# A SEAMLESS PRODUCER MOBILITY MANAGEMENT MODEL FOR NAMED DATA NETWORKS

**AHMAD ABRAR**

**DOCTOR OF PHILOSOPHY**
**UNIVERSITI UTARA MALAYSIA**
**2025**

Awang Had Salleh
Graduate School
of Arts And Sciences

Universiti Utara Malaysia

**PERAKUAN KERJA TESIS / DISERTASI**
*(Certification of thesis / dissertation)*

Kami, yang bertandatangan, memperakukan bahawa
*(We, the undersigned, certify that)*

**AHMAD ABRAR**

calon untuk Ijazah **PhD**
*(candidate for the degree of)*

telah mengemukakan tesis / disertasi yang bertajuk:
*(has presented his/her thesis / dissertation of the following title):*

**"A SEAMLESS PRODUCER MOBILITY MANAGEMENT MODEL FOR NAMED DATA NETWORKS"**

seperti yang tercatat di muka surat tajuk dan kulit tesis / disertasi.
*(as it appears on the title page and front cover of the thesis / dissertation).*

Bahawa tesis/disertasi tersebut boleh diterima dari segi bentuk serta kandungan dan meliputi bidang ilmu dengan memuaskan, sebagaimana yang ditunjukkan oleh calon dalam ujian lisan yang diadakan pada : **23 September 2024.**
*That the said thesis/dissertation is acceptable in form and content and displays a satisfactory knowledge of the field of study as demonstrated by the candidate through an oral examination held on:*
***23 September 2024.***

| | | |
|---|---|---|
| Pengerusi Viva: *(Chairman for VIVA)* | **Assoc. Prof. Dr. Yuhanis Yusof** | Tandatangan *(Signature)* |
| Pemeriksa Luar: *(External Examiner)* | **Assoc. Prof. Dr. Mohamad Nazim Jambli** | Tandatangan *(Signature)* |
| Pemeriksa Dalam: *(Internal Examiner)* | **Prof. Ts. Dr. Suhaidi Hassan** | Tandatangan *(Signature)* |
| Nama Penyelia/Penyelia-penyelia: *(Name of Supervisor/Supervisors)* | **Dr. Ahmad Suki Che Mohamed Arif** | Tandatangan *(Signature)* |
| Nama Penyelia/Penyelia-penyelia: *(Name of Supervisor/Supervisors)* | **Dr. Khuzairi Mohd Zaini** | Tandatangan *(Signature)* |

Tarikh:
*(Date)* ***23 September 2024***

# Permission to Use

In presenting this thesis in fulfilment of the requirements for a postgraduate degree from Universiti Utara Malaysia, I agree that the Universiti Library may make it freely available for inspection. I further agree that permission for the copying of this thesis in any manner, in whole or in part, for scholarly purpose may be granted by my supervisor or, in their absence, by the Dean of Awang Had Salleh Graduate School of Arts and Sciences. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to Universiti Utara Malaysia for any scholarly use which may be made of any material from my thesis.

Requests for permission to copy or to make other use of materials in this thesis, in whole or in part should be addressed to:

Dean of Awang Had Salleh Graduate School of Arts and Sciences
UUM College of Arts and Sciences
Universiti Utara Malaysia
06010 UUM Sintok

# Abstrak

Rangkaian Data Bernama (NDN) ialah senibina Rangkaian Berorientasikan Maklumat (ICN) yang direka untuk menyokong mobiliti sumber kandungan. Walaupun ia berkesan dalam mengendalikan mobiliti pengguna melalui penempatan cache kandungan, mobiliti pengeluar masih menjadi cabaran. Apabila pengeluar berpindah lokasi, penghala NDN masih mengarahkan permintaan ke lokasi asal, menyebabkan kehilangan paket Interest, kos isyarat yang tinggi, dan peningkatan kependaman peralihan. Masalah ini menjejaskan prestasi rangkaian dan kadar penghantaran data, sekali gus mendedahkan jurang dalam pengurusan mobiliti NDN. Kajian ini meneroka penyelesaian yang berkesan untuk meningkatkan mobiliti pengeluar, memastikan penghantaran kandungan yang lancar dan dioptimumkan dalam persekitaran rangkaian yang dinamik. Oleh itu, kajian ini bertujuan untuk mencadangkan Model Pengurusan Mobiliti Pengeluar (PMMM) untuk menangani cabaran mobiliti pengeluar yang berkaitan dan menyediakan laluan yang optimum. PMMM menggabungkan paket pengurusan mobiliti, termasuk Paket Pemberitahuan Mobiliti (MNP) dan Paket Kemaskini Mobiliti (MUP), dan mengubah suai proses penghantaran standard untuk menyokong paket pengurusan mobiliti ini dengan berkesan. MNP digunakan untuk memaklumkan rangkaian dan pengguna tentang mobiliti pengeluar, membantu mengurangkan kehilangan paket berlebihan dan kos isyarat yang tinggi. Sementara itu, MUP mengemaskini lokasi pengeluar dalam rangkaian, memaklumkan pengguna tentang ketersediaan pengeluar, dan mewujudkan laluan komunikasi yang optimum. Siri eksperimen mengesahkan bahawa PMMM meningkatkan prestasi rangkaian dengan mengurangkan kependaman peralihan, kos isyarat, dan kehilangan paket, serta meningkatkan pengoptimuman laluan dan kadar penghantaran data. Berbanding dengan IBM, PMSS, dan KITE, PMMM mengurangkan kependaman peralihan sehingga 24%, memastikan peralihan yang lebih lancar apabila pengeluar berpindah lokasi. Ia juga mengurangkan kos isyarat sehingga 31%, sekali gus mengurangkan beban rangkaian. Selain itu, pengoptimuman laluan meningkat sebanyak 25%, membolehkan penghantaran data yang lebih cekap. Kehilangan paket berkurang sebanyak 44% berbanding KITE dan 32% berbanding PMSS, memastikan penghantaran data yang lebih boleh dipercayai. Akhirnya, PMMM meningkatkan kadar penghantaran data sebanyak 17% berbanding KITE dan 12% berbanding PMSS, memperkukuh kestabilan rangkaian. Penemuan ini membuktikan bahawa PMMM berkesan dalam menangani cabaran mobiliti dalam NDN. Peningkatan ketara ini menyerlahkan potensi besar PMMM untuk penerapan masa depan, terutamanya dalam konteks teknologi termaju seperti Internet of Things (IoT), Internet of Medical Things (IoMT), dan rangkaian mudah alih generasi keenam (6G).

**Kata Kunci**: Rangkaian berpusatkan maklumat, Pemodelan analitik, serahan, Paket pengurusan mobiliti.

# Abstract

Named Data Networking (NDN) is an Information-Centric Networking (ICN) architecture designed to support content source mobility. While it efficiently handles consumer mobility through content caching, producer mobility remains a challenge. When a producer relocates, NDN routers still direct requests to the original location, causing Interest packet loss, high signalling overhead, and increased handoff latency. These issues degrade network performance and throughput, highlighting a gap in NDN's mobility management. This study explores efficient solutions to enhance producer mobility, ensuring seamless and optimized content delivery in dynamic networks. Therefore, this research aims to propose a Producer Mobility Management Model (PMMM) to handles the associated producer mobility challenges and provides the optimal path. The PMMM incorporates mobility management packets, including the Mobility Notification Packet (MNP) and the Mobility Update Packet (MUP), and modifies standard forwarding processes to support these mobility management packets effectively. The MNP is used to inform the network and consumers about producer mobility, helping to reduce excessive packet loss and high signalling costs. Meanwhile, the MUP updates the producer's location within the network, notifies consumers of the producer's availability, and establishes an optimal communication path. A series of experiments confirm that PMMM improves network performance by reducing handoff latency, signalling costs, and packet loss, while enhancing path optimization and throughput. Compared to IBM, PMSS, and KITE, PMMM reduces handoff latency by up to 24%, ensuring smoother transitions when producers relocate. It also lowers signalling costs by up to 31%, reducing network overhead. Additionally, path optimization improves by 25%, leading to more efficient data routing. Packet loss decreases by 44% compared to KITE and 32% compared to PMSS, ensuring reliable data delivery. Finally, PMMM increases throughput by 17% over KITE and 12% over PMSS, improving network stability. These findings demonstrate that PMMM effectively addresses mobility challenges in NDN. This significant improvement highlights the PMMM's immense potential for future deployment, especially in the context of advanced technologies such as the Internet of Things (IoT), the Internet of Medical Things (IoMT), and sixth-generation (6G) mobile networks.



**Keywords**: Information-centric networking, Analytical modelling, Handoff, Mobility management packets.

# Acknowledgement

In the name of Allah, the Most Gracious, the Most Merciful, the Giver of Wisdom:

“The ink of the scholar is more sacred than the blood of the martyr.”

— Prophet Muhammad (peace be upon him)

I am deeply grateful to my esteemed supervisors, Dr. Ahmad Suki Che Mohamed Arif and Dr. Khuzairi Mohd Zaini, for their invaluable guidance and support throughout this remarkable journey. Your encouragement and professional oversight have been instrumental in my growth and success. The space you provided for exploration and learning has profoundly enhanced my understanding and sharpened my critical thinking skills. I sincerely appreciate your dedication, and may the Almighty bless you with continued wisdom, strength, health, and prosperity.

I would also like to express my heartfelt appreciation to the staff of the School of Computing (SoC) at Universiti Utara Malaysia (UUM) for their invaluable assistance throughout my academic journey. Your dedication and willingness to help have made a significant impact on my experience.

I extend my sincere gratitude to Dr. Ahmad Suki Che Mohamed Arif and the Research Innovation and Management Center (RIMC) at UUM for providing me with the opportunity to receive the Fundamental Research Grant Scheme (FRGS). I would also like to thank RIMC for appointing me as a Graduate Research Assistant (GRA), which has allowed me to explore my research interests and deepen my knowledge in the field. This role has been instrumental in enhancing my learning experience and fostering my development as a researcher.

I am profoundly grateful to my wonderful parents, whose unwavering love and encouragement have been the foundation of my achievements. Their selfless sacrifices and unwavering belief in my potential have inspired me to relentlessly pursue my dreams. The depth of my gratitude for them is beyond what words can convey.

I wish to extend my heartfelt appreciation to my friends, Dr. Muhammad Ali Naeem and Dr. Waqar Hafeez, for their invaluable support in my research. Your insightful feedback, collaborative spirit, and shared knowledge have enriched my work significantly. Thank you for being there through the highs and lows, and for your steadfast friendship during this journey.

Lastly, I want to acknowledge the entire InterNetWorks Research Laboratory (IRL) team at UUM. You have become my academic family, and it has been an honor to collaborate with you. Your unwavering motivation and support have been my anchor during the most challenging times of my studies, and your camaraderie has played a crucial role in my accomplishments.

# Table of Contents

# List of Figures

# List of Tables

## List of Abbreviations

| | |
|---|---|
| **4WARD** | Forward |
| **4G** | Fourth Generation |
| **AS** | Autonomous System |
| **BU** | Binding Update |
| **BA** | Binding Acknowledgement |
| **BT** | BitTorrent |
| **CAGR** | Compound Annual Growth Rate |
| **CCN** | Content-Centric Networking |
| **CDSBM** | Control/Data Plane Split Based Mobility |
| **CBM** | Caching Based Mobility |
| **CDN** | Content Distribution Network |
| **COAST** | Content-Aware Searching retrieval and sTreaming |
| **COMET** | COntent Mediator architecture for content-aware nETworks |
| **COMIT** | Active Content Management at Internet Scale |
| **CONET** | Content Network |
| **CONVERGENCE** | Convergence Project |
| **CR** | Content Router |
| **CS** | Content Store |
| **DNS** | Domain Name System |
| **DNSBM** | Domain Name System Based Mobility |
| **DONA** | Data-Oriented Network Architecture |
| **DPDR** | Data Packets Delivery Ratio |
| **DRM** | Design Research Methodology |
| **DS-I** | Descriptive Study-I |
| **DS-II** | Descriptive Study-II |
| **EB** | Exabyte |
| **EUFP7** | European Union Research and Innovation program |
| **FIB** | Forwarding Information Base |
| **GreenICN** | Green Information Centric Networking |
| **HIP** | Host Identification Protocol |
| **IBM** | Indirection Based Mobility |

| | |
|---|---|
| **ICN** | Information Centric Networking |
| **IETF** | Internet Engineering Task Force |
| **IP** | Internet Protocol |
| **IRTF** | Internet Research Task Force |
| **LISBM** | Locator/Identifier Split Based Mobility |
| **LFBL** | Listen First Broadcast Later |
| **MI** | Mobility Interest |
| **MU** | Mobility Update |
| **MobiNDN** | Mobility Support Architecture for Named Data Networks |
| **MIPv4** | Mobile Internet Protocol Version 4 |
| **MIPv6** | Mobile Internet Protocol Version 6 |
| **NDN** | Named Data Networking |
| **NetInf** | Network of Information |
| **NACK** | Negative Acknowledgement |
| **NS-3** | Network Simulator version 3 |
| **NS-2** | Network Simulator version 2 |
| **ndnSIM** | Named Data Networking Simulator |
| **NFD** | NDN Forwarding Daemon |
| **OMNeT++** | Objective Modular Network Testbed in C++ |
| **OPML** | Optimal Provider Mobility in Large-Scale |
| **POA** | Point of Attachment |
| **PMSS** | Producer Mobility Support Scheme |
| **PSI** | Public Subscriber Internet |
| **PIT** | Pending Interest Table |
| **PSIRP** | Publish-Subscribe Internet Routing Paradigm |
| **PURSUIT** | Publish Subscribe Internet Technology |
| **PS** | Partial Separation |
| **PACK** | Prefix Update |
| **PS** | Prefix Update Acknowledgement |
| **PMC** | Publisher Mobility Support |
| **PNPCCN** | Proactive Neighbor Pushing in Content-Centric Networks |
| **PS** | Prescriptive Study |

| | |
|---|---|
| **RFC** | Request for Comment |
| **RH** | Resource Handler |
| **RP** | Rendezvous Point |
| **RD** | Rendezvous Domain |
| **RC** | Research Clarification |
| **RTT** | Round Trip Time |
| **SAIL** | Scalable and Adaptive Internet Solution |
| **SMM** | Scalable Mobility Management |
| **SDC** | Software Define Controller |
| **TCP** | Transmission Control Protocol |
| **TCP/IP** | Transport Control Protocol/Internet Protocol |
| **TS** | Total Separation |
| **TRIAD** | Translating Relaying Internet Architecture Integrating Active Directories |
| **UCL** | University College London |
| **URL** | Uniform Resource Locator |
| **UDP** | User Datagram Protocol |
| **US** | United States |
| **UUM** | Universiti Utara Malaysia |
| **VNI** | Visual Networking Index |
| **IoTs** | Internet of Things |
| **IoE** | Internet of Everything |
| **IoMTs** | Internet of Medical Things |
| **MANET** | Mobile Ad hoc Network |
| **VANET** | Vehicular Ad hoc Network |
| **6G** | Six Generation |

# CHAPTER ONE

# INTRODUCTION

This research is intended to resolve and contribute a solution to enhance the producer mobility support for Named Data Networking (NDN). Producer mobility is where the source of data moves to a new location, but the reference of Interest packets forwarding is still pointed to the previous location of the producer. The change of the producer location induces various issues such as long handoff latency, high signalling, Interest packet loss, and inefficient delivery path. This chapter aimed to highlight the issues or research gaps in the producer mobility domain then to propose a solution. This chapter is organized into different sections that initiate with Section 1.1 in which we cover the background of the study to provide comprehensive knowledge and fundamental issues of the Internet architecture. In Section 1.2, the research motivation is explained wherein it defines the NDN features, benefits and issues are discussed. In Section 1.3, the problem statement that provides the key issues of producer mobility in NDN architecture. In Section 1.4, research questions derived from the problem statement to specify the basic issue that needs to be addressed in producer mobility. Section 1.5 defines the research objectives to propose an efficient solution for NDN producer mobility problems. In Section 1.6, significance of the study and benefits of the present study are explained. In Section 1.7, scope of the study is presented to provide the logical conclusion and performance measurement of this research. Lastly, Section 1.8, describes the organization of the thesis that reveals the outline of this proposal.

## 1.1 Background of the study

The design of the Internet architecture was developed and introduced in 1960s. When the primary target was resource sharing. Owing to the relevant target, the few computing resources were interconnected to each other and started to exchange the information in the network [1]. The usage of the Internet has surged in recent times, becoming an essential part of our daily lives. Originally established to meet the needs of an information communication system, the Internet now serves as a vital resource for connectivity and information exchange [2]. With the rapid and revolutionary growth in advanced mobile devices, the Internet is transitioning from a PC-based computing system to a mobile-centric model. This shift has led to a significant increase in the number of Internet users, resulting in heightened demand for computing resources. However, the current Internet architecture has not fully met the evolving needs of consumers [3, 4]. This gap becomes particularly relevant when considering broader applications such as the Internet of Things (IoT), 6G technology, and smart cities. As more devices become interconnected, the demand for robust, high-speed Internet will escalate. IoT relies on seamless connectivity to function effectively, while 6G promises to enhance communication speeds and reduce latency, enabling real-time data exchange. Additionally, the development of smart cities will depend on a reliable and efficient Internet infrastructure to support various systems, from traffic management to energy distribution. Addressing these challenges in Internet architecture is essential to fully realize the potential of these transformative technologies [5, 6].

According to the Cisco Visual Networking Index (VNI) report, at the end of the year 2018, the total global Internet users has increased to 3.9 billion and from 2018 to

2023, the total global Internet users projected to 5.3 billion [7] as shown in Figure 1.1.

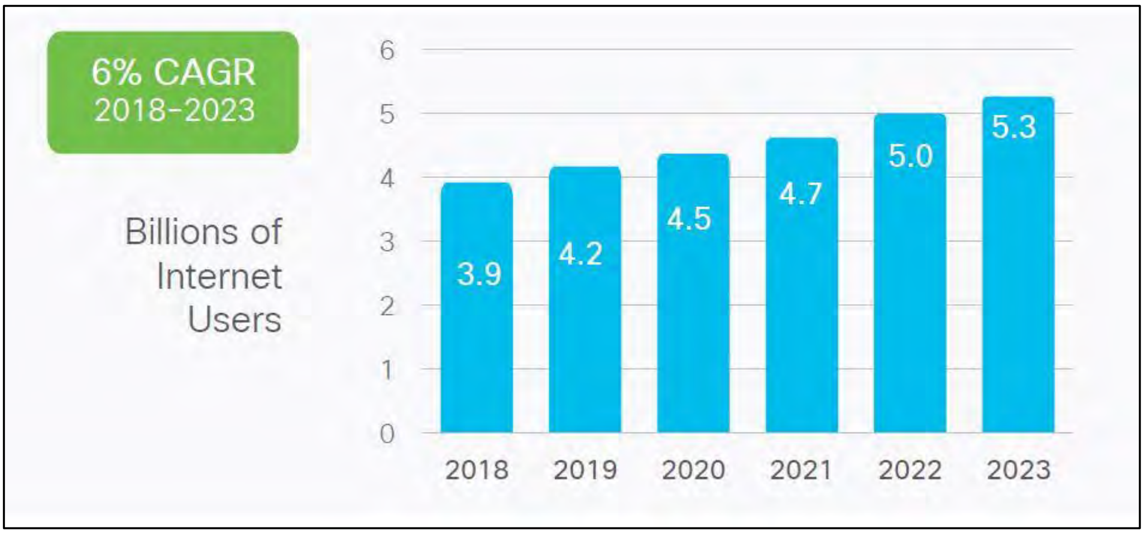



*Figure 1.1.* Global Internet User Growth [7]

The VNI statics showing the growing trend from 3.9 to 5.3 billion of Internet users at 6 percent in Compound Annual Growth Rate (CAGR) [7]. Thus, according to VNI report, the rapid increment of the global Internet user growth for the upcoming years will induce more complications and burden the Internet.

As per year, VNI statics by 2023 shows the global mobile devices and connection will be increased up to 17 billion at 10 percent in CAGR [7] as shown in Figure 1.2. However, the VNI report shows the increasing trend of global mobile devices and connection growth that will be induce more challenging works in the current Internet.

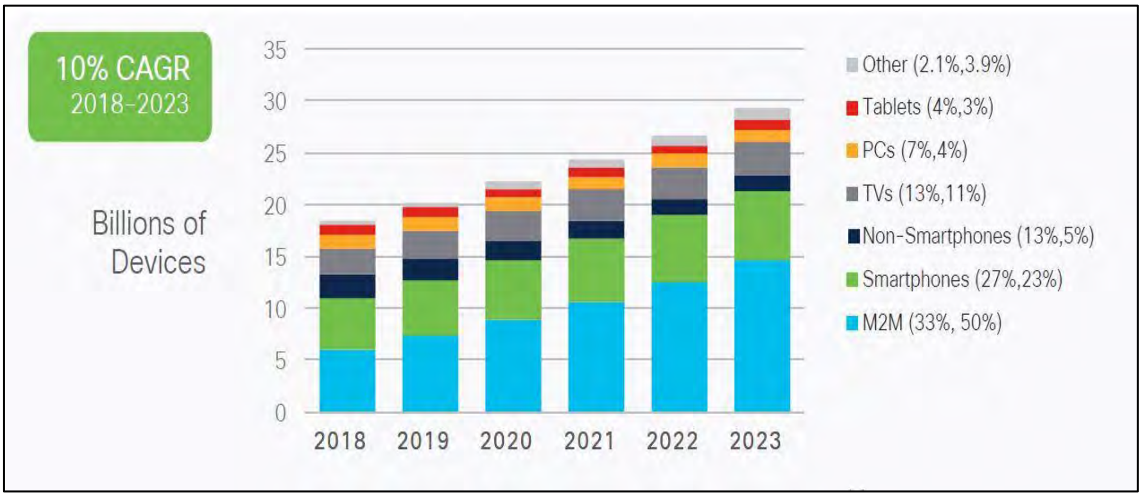



*Figure 1.2.* Global Mobile Devices and Connection Growth [7]

The current location-based (TCP/IP) Internet architecture usually supports end-to-end communication system. For the content retrieval, the data dissemination requires the name resolution and locations for both sender and receiver. First, name resolution supports location (i.e., IP address) with identifiers for content (i.e., Uniform Resource Locator [URL]), and secondly, Interest Data transmission is location-based due to the fact the consumer send Interests to provider and provider forwards required content to the consumer on the bases of location [8]. Moreover, mobility has become a more essential part of the future Internet.

According to the VNI report, the excessive demand for Internet services and data. The future Internet is becoming more mobilized. The excessive demand for Internet services and data that has increased the usage of Internet from the last decade. In addition, advanced development in smart devices and their excessive usage leads to high data traffic and the flash crowd on the Internet. For this reason, researchers acknowledged and highlight the growing problem in IP-based network architecture such as does not support proper device mobility. Due to unsupported mobility, it influences other problems in the network such as unnecessary bandwidth consumption, data unavailability issue, content scalability trouble, inefficient content distributive problem, and does not serve good caching capabilities. Moreover, it creates long-standing challenges in forwarding, routing, privacy, authenticity, and security [9]. Therefore, the current Internet will be insufficient to meet the user needs and difficult to achieve the desired level of information because of unsupported mobility.

The present communication system of the Internet creates several limitations in terms of mobility. The reason is that receiving content is firmly attached to its locations. By referring to Figure 1.3, the shows the current Internet communication scenario between consumer and server along with the Content Router (CR). The consumer is connected to CR1 using the public IP address 217.91.19.1 and is downloading content in chunks. The content is being downloaded from the server with the IP address 168.1.89.7. When the initial request for content arrives at the server, a unique socket is created by the network to establish communication between the consumer and the server, combining their respective IP addresses. Subsequently, the consumer begins downloading the content from the server in the form of chunks. However, during the communication process, the consumer gets disconnected from CR1 and interrupts the content downloading when it reaches 70% completion. The consumer then relocates and connects to CR2, where it makes a new request to the server and obtains a new public IP, which is now 218.19.91.2. The network establishes a new content communication path between the consumer and the server by creating a new socket, referred to as socket 2. Unfortunately, instead of resuming the download from where it left off, the new socket between the consumer and the server with the new public IP starts the content downloading from scratch. This means that the consumer has to re-download the entire content instead of completing the remaining chunks.

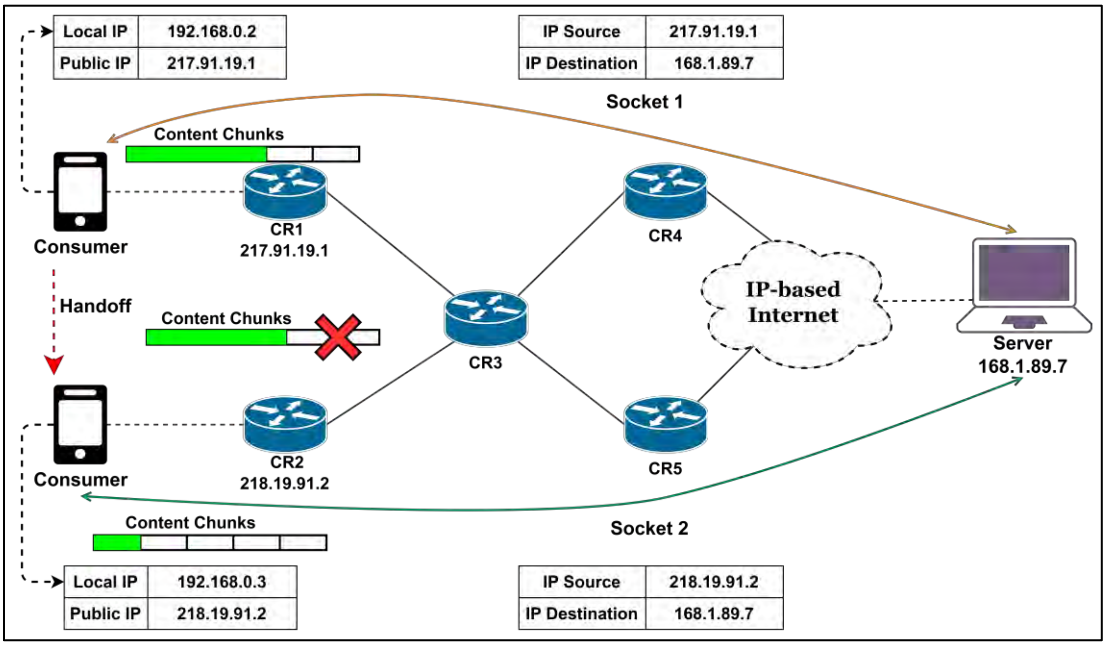



*Figure 1.3.* The IP-based Content Communication Architecture

Thus, whenever an Interest packet is sent for retrieving content it demands location addresses [8]. These Interests are strongly linked to addresses, indicate the particular content location information, despite the fact the consumer concerned to get content as expeditiously as possible rather than its location or wherefrom it's retrieved. To directly solve this issue is need to exchange "where" with the "what" [10].

Far beyond, if the additional copy for required content is placed at the network router close to the consumer, the consumer does not require to send Interests over the main content provider. Consequently, it will minimizes the usage of network traffic and supports the resource mobility [11]. Hence, it requires intensifying changes for efficient, distributive, scalable and cost-effective network architecture. For this reason, the Information-Centric Networking (ICN) was introduced for the betterment of current Internet architecture as a cost-effective distribution and scalable [12]. To control mobility effects in communication services such as bandwidth utilization, and content distribution across the Internet, researchers developed an efficient ICN architecture.

ICN aims to replace the current Internet architecture and ensures better services in the future to conquer the drawbacks in the current Internet. Therefore, the core idea of ICN is to replace the current IP-based Internet with content-based technology because the user's in ICN concern about data rather than its physical location in the network [13]. For this purpose, ICN architecture based on content-centric nature where each content identified by its unique name rather than IP. In ICN, the user generates the request (Content Name: ILab.my/video) to fetch Data. So, the first part of request is "ILab.my" shows the unique content source rather than the IP address and the second part "video" shows the content or Data.

To seamless the consumer and producer mobility in the IP-based network has the need for high-cost network manager for controlling mobile nodes. As a node, changes its location topologically and physically due to which node lost the link from communication system and node disconnected from the network.

### 1.1.1 Named Data Network Architecture and Mobility

Internet Research Task Force (IRTF) aims to bring excellent functionalities on the Internet and exclude the current Internet architecture. The reason is that the current IP-based Internet is surrounded by long-standing issues with uncertainty in solution that seems IP-based architecture will be very difficult to handle these critical issues in the future. For this instance, ICN architecture is introduced to improve the future Internet and to maintain mobile devices. ICN presents Named Data Networking and is considered as the most appropriate project for the future networks. Named Data Networks (NDN) is an efficient project of ICN, funded by the US future Internet architecture program, which is an advanced version of Content-Centric Network (CCN) [12]. NDN has developed from the ICN that influences many other Internet architectures [13]. NDN is the most prominent architecture of ICN that employs as promising and proficient architecture for future networks. Therefore, IRTF more focuses on NDN because of its functionalities and advanced features.

NDN Internet architecture planned as a clean-slate project in the light of ICN that draws attention towards the thoughtful complication in IP-based architecture and the attention to replace the current network into a content-centric nature. According to some researchers' point of view, NDN is a provision and has improved version that is basically derived from CCN architecture. In NDN architecture, Interest and Data packets are used for Data communication. The consumer uses the Interest packet, and the producer uses the Data packet for communication. In NDN architecture, Content Store is used for caching content, Pending Interest Table is used for the record of Interest packets, Forward Information Base is used for Interest and Data packet forwarding. The consumer in NDN sends an Interest packet to the producer, which contains a name that indicates the desired content. The producer, after receiving the consumer Interest packet, forwards Data packets in the reverse direction of Interest packet [14].

NDN supports opaque names in the network through which routers do not recognize the meaning of a name. NDN uses hierarchical names that represent the piece of content and allows routing to scale. For routing and forwarding purpose NDN utilize packets on the name, which no need IP addresses and potentially reduces the burden on the network. Additionally, NDN enhances scalability in the routing system. As a common networking protocol, NDN supports various applications, including Video on Demand (VoD), while adapting to diverse network environments. It enables a content retrieval service where consumers can effortlessly access uniquely named content, referred to as "Data packets," in response to "Interest packets"—a significant shift from the traditional source-to-destination addressing used in current network architectures. In the NDN framework, Data packets operate independently, allowing for seamless forwarding and retrieval [15]. This approach is particularly beneficial for the Internet of Things (IoT), where a myriad of devices constantly generates and request data. NDN's ability to efficiently handle content retrieval can improve the performance and scalability of IoT systems, enabling devices to access relevant information quickly without the overhead of traditional addressing schemes. By facilitating direct content access, NDN can support the vast number of interconnected devices in IoT ecosystems, making it easier for them to communicate and share data in real-time, ultimately enhancing the functionality and responsiveness of smart applications. Moreover, NDN architecture provides multipath routing, load balancing, control Interest duplication, routing security, reduce communication inefficiencies, and complex configuration. However, NDN still has surrounded by several serious issues such as mobility support, application development, authenticity, privacy, and security, etc.



In recent years, exponential growth in mobile devices and networking connections, some researchers, industry, academics, organization, and individuals working to accomplish the mobility of mobile devices were connected in the network and trying to offer well mobility support model [16]. Although, mobility is the most significant area in NDN that permits mobile nodes to change its location from one point of attachments (PoA) to other PoA without minimum hand-off delay and interruption in content availability. PoA is a means of connecting point that connects the mobile node in the network. Hence NDN mobility is classified into the consumer and the producer mobility [1].

## 1.2 Research Motivation

In network communication systems, users focus on exchanging content rather than its source. The availability of this content is crucial, especially with the growing number of mobile nodes, some of which act as content providers. As mobile devices proliferate, ensuring content availability becomes increasingly challenging during mobility. Content provider mobility is particularly significant, as it can disrupt network communication and render content undeliverable. While mobile content consumers can easily resend requests to retrieve content, disruptions caused by mobile providers lead to persistent issues such as content unavailability, excessive bandwidth consumption, inefficient distribution, scalability challenges, and difficulties in content forwarding. Addressing these challenges is essential for maintaining effective communication in mobile networks.

In NDN, mobility is divided into two concepts, the consumer and the producer mobility [17]. In NDN, consumer-side mobility is supported more effectively through the inherent caching mechanisms within the network. When a mobile consumer requests content, the network delivers it from the producer while simultaneously caching it at intermediate routers. This design allows for smoother content retrieval as the mobile consumer moves. When the consumer relocates, it connects to the nearest router, which can then serve previously cached content. To access this content, the consumer simply sends an Interest packet. This seamless process reduces latency and enhances the overall efficiency of content delivery, leveraging the caching capabilities of the NDN architecture [18, 19]. As a result, the consumer mobility is supported seemingly in the absence of the content providers through routers caching making the content available.

In NDN, the producer is responsible for managing and delivering content to consumers. Producer mobility facilitates the content provider's ability to relocate while ensuring uninterrupted content distribution through intermediate routers. Additionally, producers update their location information with minimal handoff time, ensuring that content remains accessible to consumers and intermediate routers alike. This seamless mobility enhances the overall efficiency of content delivery in the NDN architecture [1]. However, in NDN the producer mobility is still unsupported [17, 20-22]. The unsupported producer mobility in NDN makes content unreachable for its consumers because after the producer handoff the consumers still follow the producer's old location FIB's that make the producer unavailable for the consumers. Moreover, producer mobility entirely affects the network that creates an inefficient routing path, makes the content undeliverable, increases bandwidth consumption, causes the Interest and Data packet loss and forwarding issues [23, 24].

In NDN, producer mobility is the most important part of mobility that needs improvements for uninterrupted communication. As the Producer receives the consumer Interest packet, it forwards the Data packets to the consumer. By referring to Figure 1.4, when the producer handoff from the Content Router (CR3) to CR4, in this situation, the consumer Interests still follows the old path and Interest packets are still forwarded towards CR3. In the absence of producer at CR3, there is a depraved effect in the network and it faces different issues such as Interest packet loss, long handoff latency, less scalability in routing table size, unnecessary bandwidth consumption, the movement of Interest towards old producer location, lack of significant scalability [1, 25]. Also, frequently updating the routing table causes excessive bandwidth utilization and creates high signalling overhead [1, 24, 26, 27].

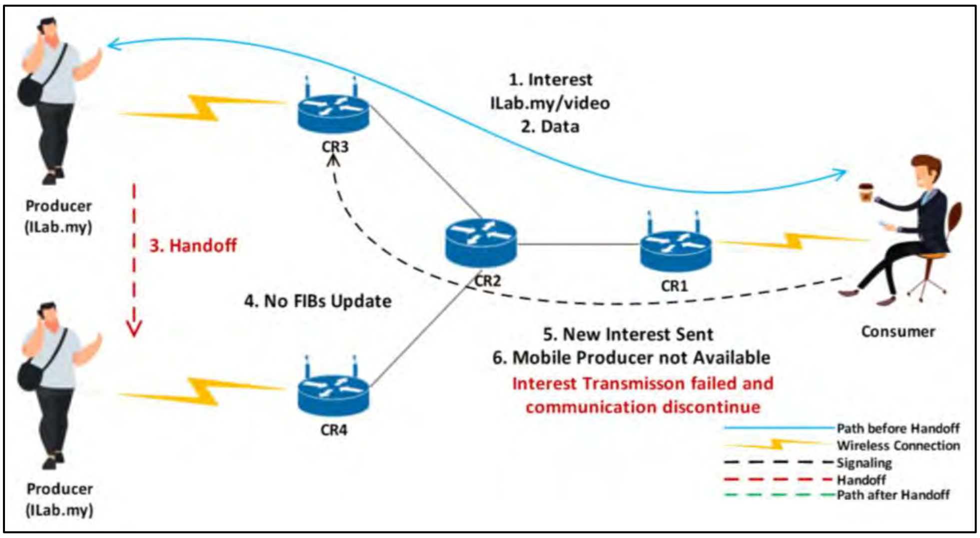



*Figure 1.4.* Producer Mobility in NDN

In NDN architecture several researchers proposed various approaches to support the producer mobility. In the NDN approach of Indirection Based Mobility (IBM), many researchers proposed different methods to support the producer mobility. In IBM, whenever the content producer moves from old location to new location, the producer registers or updates its available content prefixes to the immobile anchor [28-30], or home agent [31, 32], or indirection point [31, 33, 34] that processes the Interest packets and forwards it to the producer. In IBM, the consumer retrieves content from the producer by using triangular path. The schemes as like DNS Based Mobility (DNSBM), Locator/Identifier Split Based Mobility (LISBM) and Control Data plane Split Based Mobility (CDSBM) uses the Mapping system or Rendezvous Server or DNS Server for content communication. In addition, the schemes apply the encapsulation and de-capsulation processes in the original packets, that may lead to more complicated operation and consume more time. Further, the Caching Based Mobility (CBM) caches the content for communication that creates more delays, signalling and support specific Interest for specific content. However, IBM solution does not provide an optimal path because it follows the triangular routing scenario by using the producer old location router as a home agent. Therefore, the consumer retrieves content from the producer by a non-optimal path which raises more delays in the content retrieval and produces indirection point or anchor or home agent router failure. Moreover, it creates, inefficient data paths, invoke the Interest fall back issue and more signalling cost as compared to the normal NDN architecture.

### 1.3 Problem Statement

One of the interesting proposals, known as the Producer Mobility Support Scheme (PMSS) [35] was designed to minimize producer mobility issues in NDN architecture. The core components of this solution include the Mobility Interest (MI) packet, which employs a broadcasting strategy, and the introduction of immobile anchors within the network topology. The MI packet carries producer binding information related to its location prefix, while the broadcasting strategy facilitates the dissemination of this packet information throughout the network. When the producer relocates to a new location, it transmits an MI packet from its current location to the immobile anchor following the producer handoff process. The immobile anchor broadcasts the producer current location information packet in the whole network and updates the routers' FIBs. However, frequent movement of the mobile producer results in the continuous broadcasting of MI packets to update location information within the network. This leads to high signalling overhead and increased bandwidth consumption. Furthermore, the solution unable to accommodate incoming Interest packets during long handoff processes, causing these packets to be routed to the producer's previous location based on outdated FIBs. Additionally, when a consumer's Interest packet is lost, the consumer must retransmit the packet to retrieve the same content, further degrading network throughput. This approach of Interest retransmission is not optimal for supporting mobility, as it introduces additional delays and reduces overall network performance when accessing content [36]. Furthermore, when the producer broadcasts its new location prefix to update all routers' FIBs in the network, this process leads to significant handoff delays and incurs substantial bandwidth costs [25].

Another interesting solution is known as the Optimal Provider Mobility scheme (OPML) [27] that was proposed to handle content provider's mobility problems such as high cost, non-optimal routing path, and long handover latency. To manage provider mobility effectively, the scheme alters standard router operations and employs specialized mobility management packets designed for a fast handover mechanism. These packets gather information about neighbouring routers prior to the producer's handover. Additionally, the scheme removes the old route and establishes a new one, ensuring an optimal path for both Interest and Data packets. It also enhances the Interest and Data packets by incorporating extra fields, facilitating their delivery to the precise location. However, the path optimization process, which involves deleting and creating new paths for Interest and Data packets, are time-consuming process and incurs significant signalling costs and latency. Additionally, the fast handover mechanism adds complexity and requires more time when the producer moves to routers beyond neighbouring ones, increasing the risk of Interest and Data packet loss. In comparison to the original NDN architecture, the proposed scheme complicates mobility, leading to challenges in delivering Interest and Data packets while also consuming more time and degrades the overall network performance. As a result, producer handoffs within the network contribute to Interest packet loss, and the need for Interest retransmissions.

In summary, recent studies have identified significant issues stemming from producer mobility, such as Interest packet loss, Interest retransmissions, low throughput, and long handoff latency. While various approaches utilizing mobility management packets have been proposed, they continue to experience considerable challenges. This research seeks to tackle these critical problems and enhance network performance by introducing a novel Producer Mobility Management Model (PMMM). The PMMM aims to optimize handoff processes, improve throughput, reduce Interest packet loss, lower signalling costs, and optimize the data packet delivery path.

## 1.4 Research Questions

i. How can long handoff latency in producer mobility be improved to minimize signalling cost and ensure path optimization?

ii. How can producer mobility be effectively managed to enhance throughput and minimize Interest packet loss during the handoff process?

iii. What method would be most suitable for effectively implementing and evaluating the proposed model in NDN?

## 1.5 Research Objectives

i. To proposed and formulate the PMMM analytical model that improves the handoff latency to minimize signalling cost and ensures the path optimization.

ii. To design mobility management packets and forwarding strategy that manages the producer mobility to enhance the throughput and minimize the Interest packet loss during the handoff process.

iii. To implement the proposed mobility model by using simulator and evaluate the performance with the previous works in the NDN network simulation environment.

## 1.6 Significance of the Study

The proposed PMMM effectively addresses producer mobility challenges by providing seamless availability of content to consumers and intermediate routers, without relying on a centralized node or creating triangular routing paths in the network. PMMM utilizes a mobility management packets and a forwarding strategy, significantly reducing issues such as Interest retransmission and handoff time. By providing producer location information, it ensures content availability while overcoming critical challenges like high signalling costs and Interest packet loss.

In contrast, traditional solutions depend on a centralized router, known as a home agent or indirection point, to redirect incoming consumer requests to the producer. This approach leads to triangular routing paths, which can diminish network throughput. Additionally, the handoff process in these traditional methods involves the home agent to update producer mobility, resulting in excessive signalling costs and increased latency. PMMM eliminates the need for such triangular routing by establishing optimal paths through mobility management packets, thereby addressing single points of failure and reducing handoff latency and signalling costs. As a result, findings indicate that PMMM is well-suited for supporting communication among IoT devices, offering lower latency and reduced signalling cost.

## 1.7 Scope of the Study

This research focuses on managing and improving producer mobility within NDN. The proposed model offers an efficient solution for handling producer mobility in NDN architecture. It aims to minimize the Interest packets loss and reduce handoff latency by utilizing mobility management packets alongside a forwarding strategy. Additionally, these mobility management packets overcome the high signalling overhead and ensure updates the producer mobility across the network and to the consumers. However, this study is specifically limited to addresses producer mobility and does not cover consumer mobility, which is inherently supported by the caching mechanisms present in NDN routers. The NDN architecture is categorized into system applications, system services, and system architecture, with system services encompassing privacy, forwarding, mobility, caching, and routing. Thus, the primary scope of this research is to provide a solution for managing producer mobility, introducing the PMMM, as illustrated in Figure 1.5. The evaluation of the proposed PMMM is conducted through both simulation and analytical methods to assess its performance effectively.

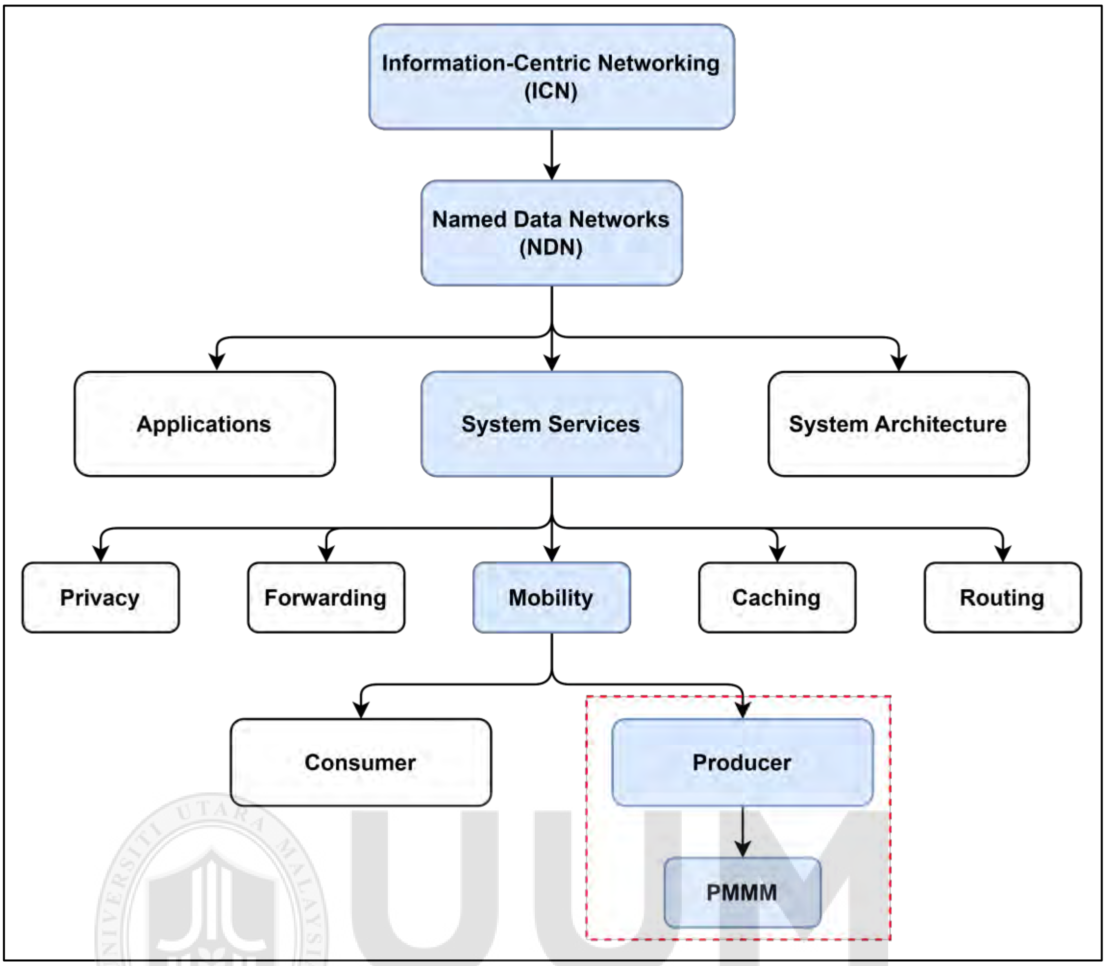



*Figure 1.5.* Scope of the Study



### 1.8 Organization of the Thesis

This thesis is organized into seven different chapters which are the following:

**Chapter One** starts with the introduction of Named Data Networks (NDN). It explains the importance of producer mobility and issues surrounded by NDN due to producer mobility. More specifically, this chapter highlights the research motivation, problem, objectives, significance, and scope of the study related to this research.

**Chapter Two** provides a comprehensive exploration of the NDN paradigm, offering in-depth insights into packet dissemination within this paradigm. It also delves into the intricacies of content dissemination between consumers and producers during mobility in an NDN environment. Furthermore, the chapter presents a thorough examination of various solutions for producer mobility, categorizing them based on their working mechanisms and technical distinctions. In addition, it critically analysis previous research endeavours on producer mobility in NDN, aiming to propose a novel mechanism.

**Chapter Three** discusses the use of Design Research Methodology (DRM) to drive this research. It outlines the various stages of DRM that are employed to attain the research objectives at an optimal level. Furthermore, within this chapter, a conceptual model for producer mobility is meticulously crafted. Additionally, it delves into the selection of the most effective performance evaluation techniques, tools, methods, and metrics for measuring the performance of the conceptual PMMM model.

**Chapter Four** introduces a comprehensive proposal for an analytical model of a PMMM, which serves to accomplish research objective. The chapter highlights the significance of mobility management packets and the modified forwarding as influential factors within the PMMM analytical model. The model is formulated utilizing the hop count technique and subsequently implemented, validated, and compared against the existing IBM approach along with the KITE and PMSS. The objective of this investigation is to address the data path stretching problem, minimize handoff latency, and reduce signalling costs.

**Chapter Five** deliberates the design of PMMM (Producer Mobility Management Mechanism) to accomplish the research objective. Likewise, it also explains the proposed mobility management packets and extended forwarding within the PMMM. As a result, the proposed mobility management packets and extended forwarding are extensively discussed in NDN.

**Chapter Six** presents the performance evaluation of the proposed PMMM by comparing it with the other solutions using various parameters. To access the effectiveness of the research from multiple perspectives and network topologies, a simulation environment is employed.

**Chapter Seven** serves as a concluding chapter, providing a comprehensive summary of the study conducted. It highlights the key findings, contributions, and implications of this research. Additionally, the chapter offers insightful suggestions for future research directions to further advance the field.

# CHAPTER TWO

# LITERATURE REVIEW

This chapter delivers detailed knowledge about the background of the NDN and provides the comprehensive knowledge of NDN. Also, it comprehensively explains the fundamentals of producer mobility. It discusses the NDN knowledge to support understanding the producer mobility, while another part of this chapter is discussing critically the other solutions on producer mobility or the related issues. It also identifies and highlights the research problems such as increasing handoff latency, high signalling cost and long data path delivery in the producer mobility. Furthermore, this chapter gave a well-developed taxonomy on producer mobility in NDN paradigm. Moreover, it systematically classifies the producer mobility solutions in several approaches based on their different technical methods and characteristics that clearly differentiates the different existing research approaches.



## 2.1 Information-Centric Networking

The present Internet architecture is based on an end-to-end communication system that uses Transmission Control Protocol/Internet Protocol (TCP/IP). Therefore, the usage of IP addresses is increasing dramatically due to the increasing trend in mobile devices and massive data demand that may cause high burdens to the network. To manage this situation, a new architecture known as Information-Centric Networking (ICN) has been introduced to optimize the network. ICN aims to replace the current Internet architecture and ensure better services by countering the weaknesses of the existing Internet such as scalability, forwarding, routing, mobility, availability, security, privacy and trust [37]. Therefore, the core idea of ICN is to replace the current IP-based Internet with content-based technology because the users in ICN are concerned about data rather than its physical location in the network [13]. For this purpose, ICN architecture is based on content-centric nature where each content is identified by its unique name rather than IP. Furthermore, the IP-based network requires the high-cost network manager for monitoring the mobility, forwarding, routing, security, and privacy in the mobile devices.

### 2.1.1 Mobility Significance and Limitations

To conclude and synthesize, TCP/IP have been developed by merging various modules in which mobility is considered as a core factor for actualizing the TCP/IP manageability. With the drastic demand for mobile devices, mobility has become the most significant segment of the communication network. According to the VNI report, there is an excessive demand for Internet services and data due to innovation in mobile devices. The future Internet is set to become more mobilized. The superabundance of Internet services and data has also increased Internet usage over the last decade. In addition, advanced developments in smart devices and their excessive usage led to high data traffic and the flash crowd on the Internet. For this reason, researchers acknowledge and highlight the growing problem in IP-based network architecture as it does not support proper device mobility and refers to unsupported mobility. Unsupported mobility adversely affects other issues in the network, such as unnecessary bandwidth consumption, data unavailability, content inaccessibility, poor security, inefficient routing and forwarding updates, inadequate content distribution, and unsatisfactory caching capabilities [9, 38]. Therefore, the current Internet may not meet the user needs and experience problems because of the unsupported mobility. Of the ICN projects, the Named Data Networks (NDN) promises to be the most intelligible and efficient architecture. The NDN is a successor to the ICN, which has inspired a wide range of Internet architecture.

## 2.2 Named Data Networks in a Nutshell

The NDN is a well-known efficient project of Information-Centric Networking funded by the US future Internet architecture program [12]. NDN is an advanced version of the Content-Centric Network (CCN) under the canopy of Information-Centric Networking [13]. The core idea of ICN is to replace the current Interest host-based IP address with the information-based naming scheme. It aims is to bring in the magnificent functionalities, features and architectural properties to develop uninterrupted superior communication network. Correspondingly, various ICN projects are developed that is based on content-centric nature instead of IP based network. Among all the ICN projects the NDN seems more understandable and an efficient project. The NDN has developed from the ICN which influences many other Internet architectures.

The NDN architecture hourglass keeps the same shape as in IP, but the intention of its thin waist replaces from IP packets to the data or content chunks directly without emphasizing the location of the data or content chunks as shown in Figure 2.1. Moreover, it changes the network communication trend from packet delivery on location-based system to retrieve data by its identified name. According to architectural principles' guide, the NDN architecture focuses on the universal network layer in the hourglass and supports the security and global connectivity within its architecture. Furthermore, its design provides the separation of forwarding and routing plane. Also, it provides the self-regulation in the network traffic and flow-balance during data delivery [8, 15].

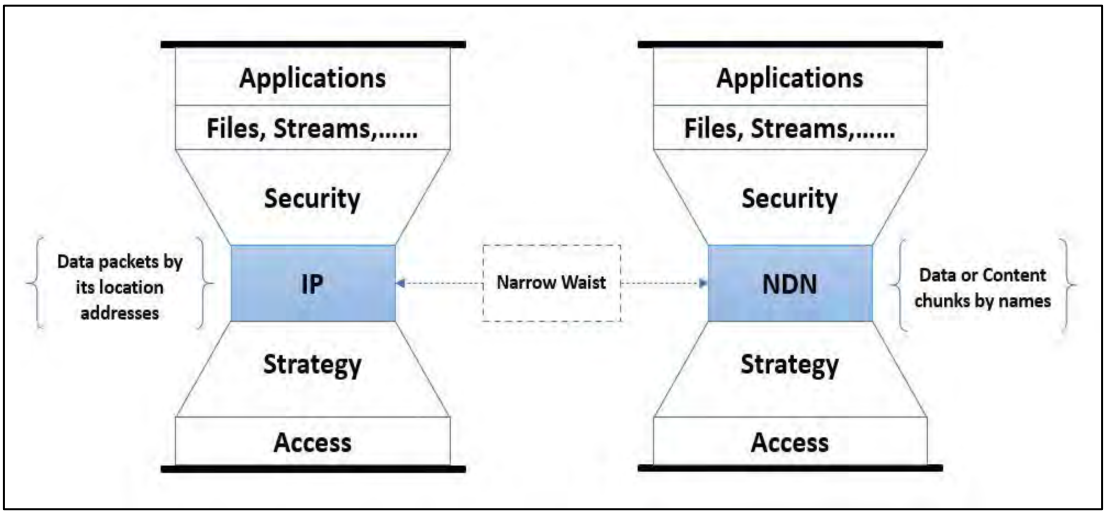



*Figure 2.1.* Comparing IP and NDN Hourglass Architecture

Being a common networking protocol, NDN maintains all applications such as Video on Demand (VoD) and the network environment. NDN provides the best-effort packet delivery service by using the network layer protocol including physical channels such as Ethernet wires, and User Datagram Protocol (UDP) or Transmission Control Protocol (TCP). The tunnel works as a logical connection over the existing Internet.

In NDN, names are designed globally unique and human-readable hierarchically structured and sometimes are assumed same as URLs to build a strong relationship between the context and data elements [39]. Due to the fact that it allows the content retrieval service, it supports to retrieve uniquely named content from the network. For the content retrieval and communication in NDN, it consumes two types of packets, “Interest packet” and “data packet” [15] as shown in Figure 2.2. Both, Interest and data packets, contain the name that identifies the content. Furthermore, the consumer in NDN uses the Interest packet for content retrieval. For this purpose, the consumer places the name of content in the name field of the Interest packet and sends it into the network. The data packets belong to the producer that are sent to the consumer in response of the Interest packet. The content such as video frames, text file chunks and temperature sensor readings are all the forms of data that can be retrieved.

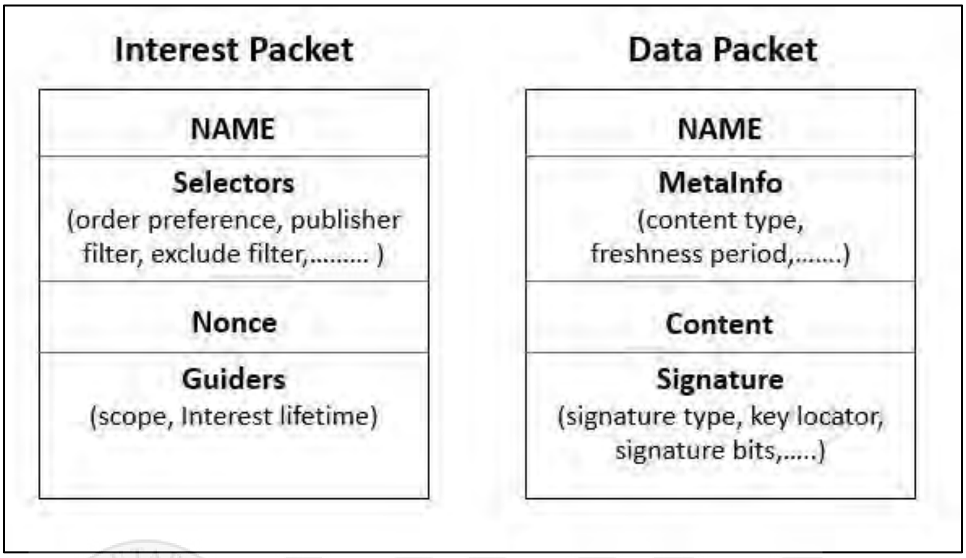



*Figure 2.2.* Interest and Data Packet in NDN Architecture [40]

NDN uses unique names for the content communication. It provides numerous functions to router that keeps the record of all packets' state. In NDN, content packets are independent, whereby they can be easily forwarded and retrieved effortlessly. To forward the Interest and data packets in NDN, it manages three different types of data structures that have different functions and responsibilities: Forwarding Information Base (FIB), Pending Interest Table (PIT) and Content Store (CS) as shown in Figure 2.3. The FIB is used for outgoing interface(s) that contains the information names through which the incoming Interest packets are forwarded to the most appropriate content source. The PIT is used for incoming interface(s) that records the incoming Interest packets with the content names and their incoming interface(s), it is also responsible for storing unsatisfied Interest packets that are forwarded for retrieving content. The CS is a local cache in the router that is used to stores the contents corresponding to their content name [23].

| Content Store (CS) | |
|---|---|
| Content Name | Cached Content |
| *IrLab.com/ndn.mp4/v2/s1* | -------------- |
| | |

| Pending Interest Table (PIT) | |
|---|---|
| Incoming Interface | Content Name |
| *0* | *IrLab.com/ndn.mp4/v2/s3* |
| | |

| Forwarding Information Base (FIB) | |
|---|---|
| Outgoing Interface | Name Prefix |
| *0,1* | *IrLab.com* |
| | |

*Figure 2.3.* Data Structure in NDN Architecture [23]

The consumer and producer play a vital role in order to exchange the content between them. The consumer refers to content requester while the producer refers to content provider. The consumer content communication is supported by the CS. When a consumer sends an Interest packet (*IRL.my/sun.mp4/v3/s2*) in NDN, the CS in the router assess the availability of the requested content. The content is forwarded to the consumer immediately on its availability otherwise, the Interest packet is transferred to the PIT. The PIT serves to verifies the Interest duplication in order to prevent the Interest looping in the network. The PIT adds the Interest interface if it is duplicated and does not further forwards to the FIB to avoid unnecessary network traffic. While if the PIT receives the Interest packet first time, it stores the Interest incoming interface corresponding to requested content name and further forwards to the FIB. The FIB contains the list of content provider name prefix corresponding to the outgoing interface. The FIB finds the best matching entry and forwards the Interest to the most appropriate provider path as shown in Figure 2.4. In a situation, if there is no source name found in FIB, the Interest packet is dropped, and the consumer gets the Negative Acknowledgement (NACK) [41]. When the request content reaches to the router, it searches for the related Interest in the PIT. If the related Interest found in the PIT, the content is acknowledged by the PIT which is known as loop hit. The content is cached in CS and forwarded to the consumer. If the related Interest for incoming content is not found in the PIT which is known as lookup miss. The content is dropped at the router level and content is tagged as an unsolicited content. However, the content availability and content distribution challenging task due the mobility.

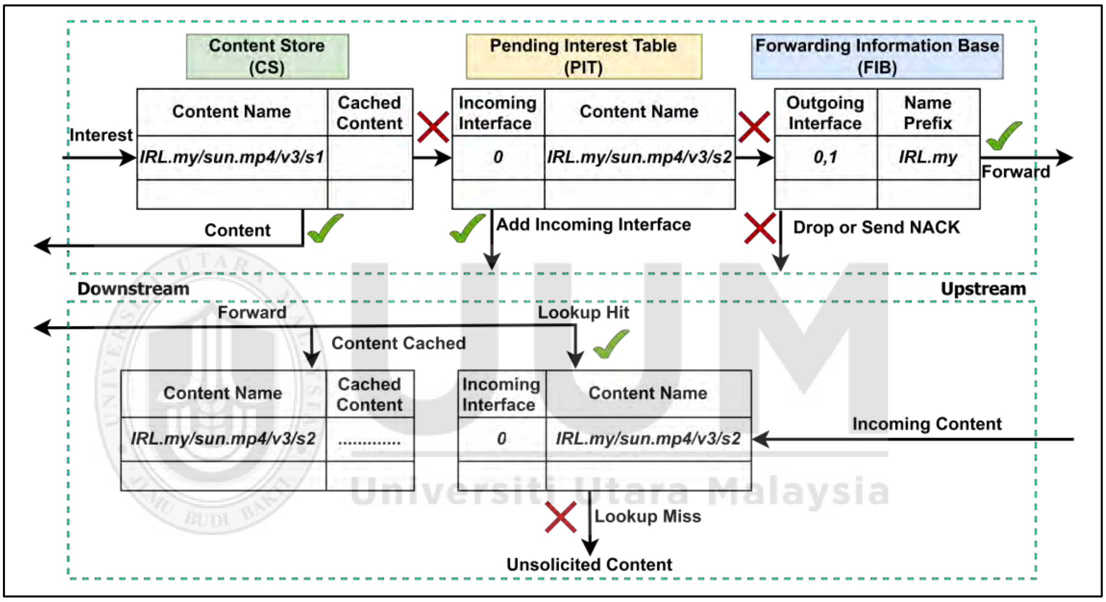



*Figure 2.4.* Forwarding Process in NDN [30]



### 2.3 Mobility in Name Data Networking

NDN is the clean-slate architecture of ICN that achieves data integrity, authenticity, and confidentiality. It supports the named content rather than the thin waist of the networking stack of the IP architecture. Naming becomes the most important segment of application design of NDN that certifies the support for mobility, content distribution, multicast and delay-tolerant networking [42]. To summarize and synthesize, all of the ICN projects have been developed by combining various modules in which mobility is considered the most dominant component for actualizing the ICN manageability [43]. From the several surveys on ICN designs it has been seen that the benefits of forwarding, routing, content retrieval, scalability and caching cannot achieve advantages without supporting mobility. With the constantly in growing proliferation of mobile devices, it becomes a fundamental necessity to discover an efficient technique to support mobility. The unsupported mobility addresses the various issues in ICN and substantial research challenges need to be resolved such as efficiency, trust, consistent routing, security, privacy, content availability, routing and practical deployment [17].

By default, ICN is proposed to handle IP weakness and mobility, but faces many challenges in NDN with regards to mobility support. In NDN, mobility allows the mobile devices to change their location between different access points either without any interruption and content availability delay or with minimal handoff.

In a host-centric communication environment, every point of access for each network device needs an IP address to exchange data with one another and there is no guarantee for further persist of an on-going connection. Therefore, after the relocation of the mobile device, it requires a new IP address for continuing their communication. Moreover, to support this situation, some researchers proposed a solution for Mobile IP and Host Identification Protocol (HIP), but these mobility approaches do not directly deal with the present mobility issues. These solutions are based on indirection point and topological information for traffic redirection [44]. However, NDN supports the data access by content names rather than IP addresses that enable mobile devices to have superior content access without repeatedly acquiring an IP address to continue their communication.

NDN users access content by its name, therefore, it supports multiple network interfaces by sending interest instead of host-centric network that assists host multi-homing [45] where the individual application is required to establish individual connections as in Bluetooth [18]. For multiple interfaces, users need a different IP address to communicate and establish a TCP connection. Consequently, in NDN, without any notice of application, the consumer request can be freely multiplexed over a number of different interfaces [26].

In the NDN environment, whenever a mobile device moves, it does not need to establish connection again to data source for communication. The current Internet architecture supports connection-oriented sessions through which mobile devices propagate in the network and requires to re-establish TCP connection for communication [18]. However, Mobility helps mobile nodes to freely change their location between different access points without interruption in the content minimal hand-off and availability delay. Hence, NDN mobility is classified into two categories, the consumer and the producer mobility [1, 25].



### 2.3.1 Consumer Mobility in NDN

NDN influences the receiver-driven [27] communication architecture. For this purpose, it uses two kinds of message packet [35]: Interest and data packets [46]. In NDN, the consumer that needs to retrieve content just sends an Interest packet from its current location in the network. After receiving the Interest packet, it delivers the consumer request to the appropriate data source that can forward the required content. When the consumer Interest packet reaches the NDN router for content retrieval, firstly, the content router checks its own CS if the required content is available in its CS, then, it immediately forwards the content to the consumer.

Otherwise, the Interest is forwarded to the next router depending on the FIBs and the entry is stored into PIT that stores all pending Interests packets which has not satisfied yet and waits for the content of predefined time [42]. In case of the consumer mobility, if the consumer handoffs in the network before receiving the requested content, when handoff process completes, the consumer retransmits the Interest packet to get the remaining content which is already cached in common router or intermediate routers in between the old and new location. Through which it is easy to retrieve the content and send it to the consumer by using following its reverse forwarding path [13].

In this scenario, the consumer can efficiently get remaining data packet by sending Interest or re-Interest for the same content again [45, 47] and mobility is smoothly resolved within the minimal delay [48]. Thus, in NDN, the consumer mobility issue is inherently solved through the assistance of network routers caching or sending again an Interest after the completion of handoff process or the consumer stable relocation [1, 49].

By referring to Figure 2.5, it shows the consumer mobility scenario. During the content communication, the consumer handoffs from CR3 to CR4. The remaining content is cached in the common router CR2 that is common between CR3 and CR4. When consumer completes handoff and attaches it to CR4, the consumer re-Interests for the remaining content and easily gets the content from CR2. In this way, the consumer mobility is supported through caching the content between intermediate or junctional routers.

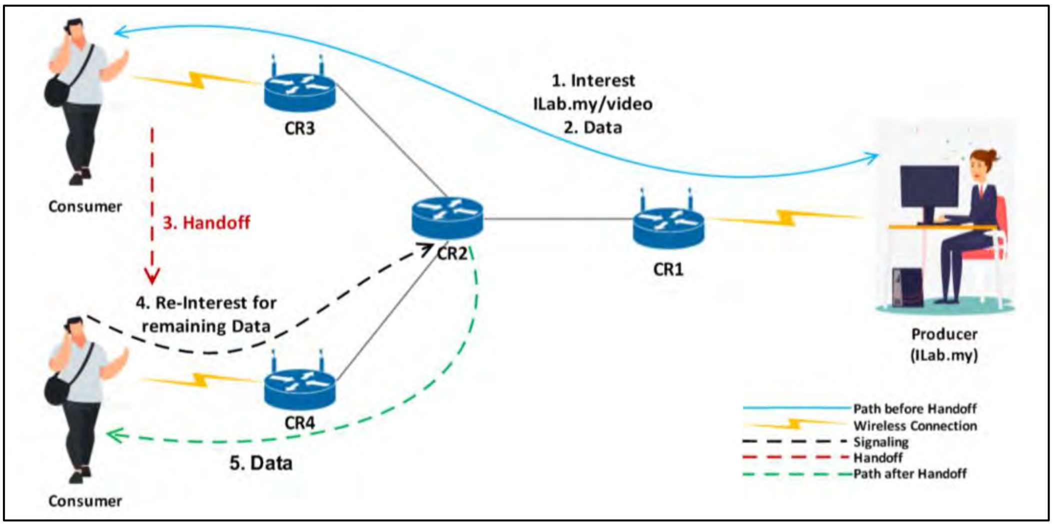



*Figure 2.5.* Consumer Mobility in NDN

### 2.3.2 Producer Mobility in NDN

In NDN architecture, the producer refers to the source that provides the content in the direction of the consumer Interest. Although in NDN, content name is decoupled from its location, however, the content name is not separated from its location. By referring to Figure 2.6, the content name is coupled in its location by directly inserting it into FIB [1]. The consumer in the network generates an Interest packet for the content from its location towards the connected router. Then, the NDN router is decided on behalf of the FIB where it can be forwarded to an appropriate content provider. Generally, FIB has the list of long Prefixes addresses for the next router or provider through which it can be easy to estimate the optimal path to retrieve related content, and forwards the consumer Interest packet to the provider or CS.

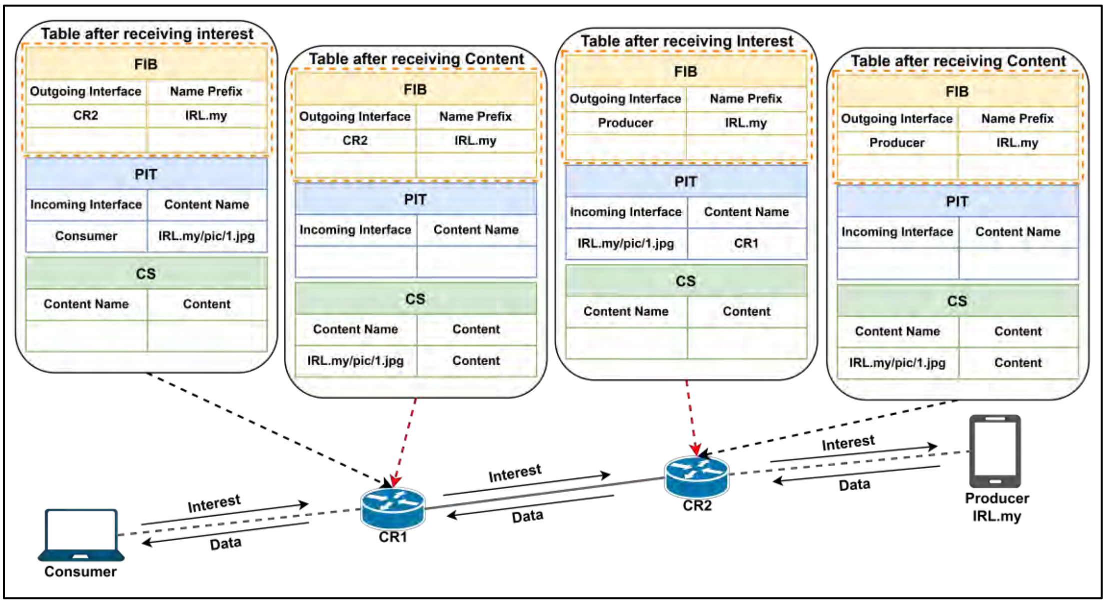



*Figure 2.6.* The FIB in NDN architecture

By referring to Figure 2.7, the content provider from old content router 3 (CR3) on receiving the consumer Interest packets satisfies the content needs on availability of the content. If the content provider moves and connects to the new location router CR4, in this state, the producer needs to update the FIB's of all content routers (CRs) in the network [13]. Otherwise, the consumer Interest arrives at the old location router CR3 and finds no content due to the unavailability of the producer. In NDN, the movement of the producer is untraceable for the consumer. As a result, the producer mobility faces high overhead [13], long handover latency and high packet loss [49]. Therefore, the consumer communication is blocked until the updates of the producer prefix domain name in the network [34].

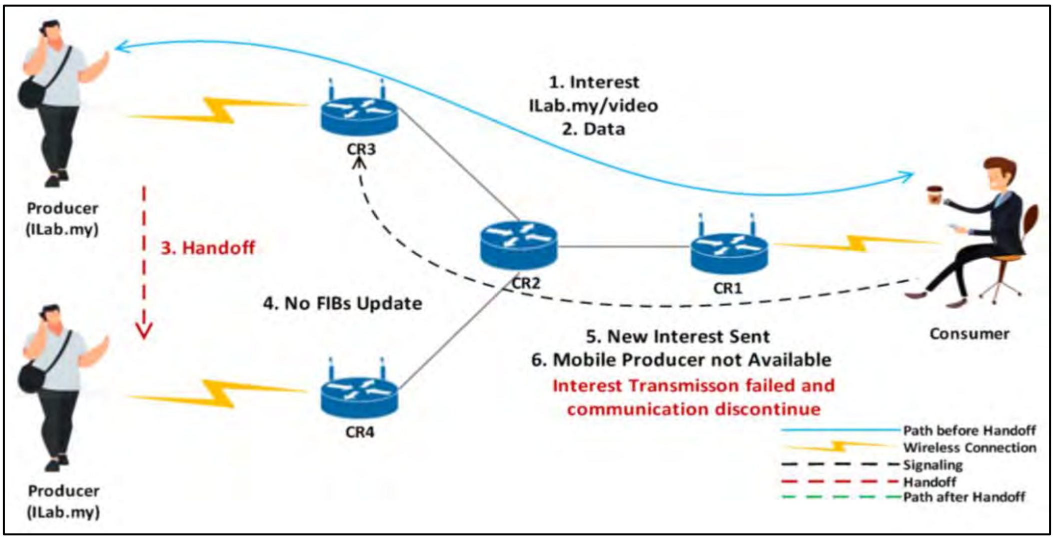



*Figure 2.7.* The Producer Mobility in NDN

In producer mobility, just after relocation of the producer, the producer requires to update its name prefixes in FIBs for further communication. For this reason, NDN uses Listen First Broadcast Later (LFBL) protocol to apply mobility in ad-hoc networks [13]. Therefore, in NDN, after the completion of producer handoff process, it utilizes a common flooding strategy and broadcasts the specific Interest packet to update all prefix information in serving related routers [17, 50]. However, this solution produces high signalling and has no strategy to recover the lost Interest packets during the producer handoff process and incoming Interest packet of old locations[6].



## 2.4 The Producer Mobility Approaches in NDN

Many researchers carried out different studies that present different concepts and schemes to support the producer mobility in NDN. In some research, the producer mobility is categorized into different concepts depending upon their ideas as well as functionalities. Zhu et al. [51] identifies three different concepts used by some researchers and the fundamental concept is to solve the producer mobility issues. Further, it presents different producer mobility concepts that can be directly applied to solve mobility issues. The presented concepts are, the consumer Interest broadcasts to all available faces, the consumers retrieve data by using efficiently designed data storage by the mobile producer, and the consumer can fetch data by using the DNS server that stores mapping between the producer identifier and its locator. Moreover, for the fast data retrieval, the consumers utilize multiple interface data such as Wi-Fi and 4G.

In some other research, the producer mobility solutions are categorized into different classes to easily determine benefits and drawbacks in presented solutions. Due to this fact in [52], the researchers divided the producer mobility support approaches, kinds of literature into rendezvous point-based mobility support approach (RBMA) and indirection point-based mobility support approach (IBMA). Similarly, Saxena et al. [18], categorized the producer mobility support approaches into the locator-free approach and the mapping-based approach. Moreover, Feng et al. [1] divided producer mobility into Partial Separation (PS) and Total Separation (TS) depending on their specific characteristics.

Therefore, this research plans to divide the literature into five different approaches as Indirection Based Mobility (IBM), Locator/Identifier Split Based Mobility (LISBM), Caching Based Mobility (CBM), DNS Based Mobility (DNSBM), and Control Data plane Split Based Mobility (CDSBM). All these approaches are different in terms of their functionalities and specifications. The main goal of this division is to identify the benefits and drawbacks of the producer mobility support schemes. These approaches can be further divided into two distinct types of solutions: router-based approaches and server-based approaches.

### 2.4.1 Router-based Approaches

IBM, LISBM, and CBM are categorized as router-based solutions because they manage producer mobility through the use of routers alone. In these approaches, routers play a crucial role in tracking and directing data from mobile producers to consumers, thereby ensuring efficient communication and resource management.

#### 2.4.1.1 Indirection Based Mobility

Indirection-Based Mobility (IBM) is an approach that provides the producer mobility support in NDN. The concept of this approach is adopted from MIPv4 and MIPv6 that is used to support mobility in IP based architecture. According to this approach, a fixed router named as a home agent or home router, is used to redirect traffic to appropriate data sources. In NDN, home agent or home router records the binding information between the content prefix and its location that is efficiently used to redirect the Interest Packets to producers after the handoff process. When the producer relocates or changes its location, the incoming Interests route unavailability of the content provider and the Interest packets may be lost. The producer, after handoff, registers its content prefix to fix home router or Indirection point that provides the appropriate direction to incoming Interest towards the available producer. The Interest is redirected from home router to the producer by using tunnelling and encapsulation process. The Interest packets are encapsulated at the home router and forwarded to the producer. The producer decapsulates the Interest and encapsulates the data, forwards to the home router, and then home router forwards the data to the consumer as shown in Figure 2.8. Many researchers adopt the Indirection point technique and provide different solutions to reduce the producer mobility issues in NDN architecture. In a study [33] proposed an indirection approach to overcome the producer mobility issues in NDN. For this purpose, to efficiently support the producer mobility, the indirection point technique is utilized in NDN that adopts the same idea of mobile IP.

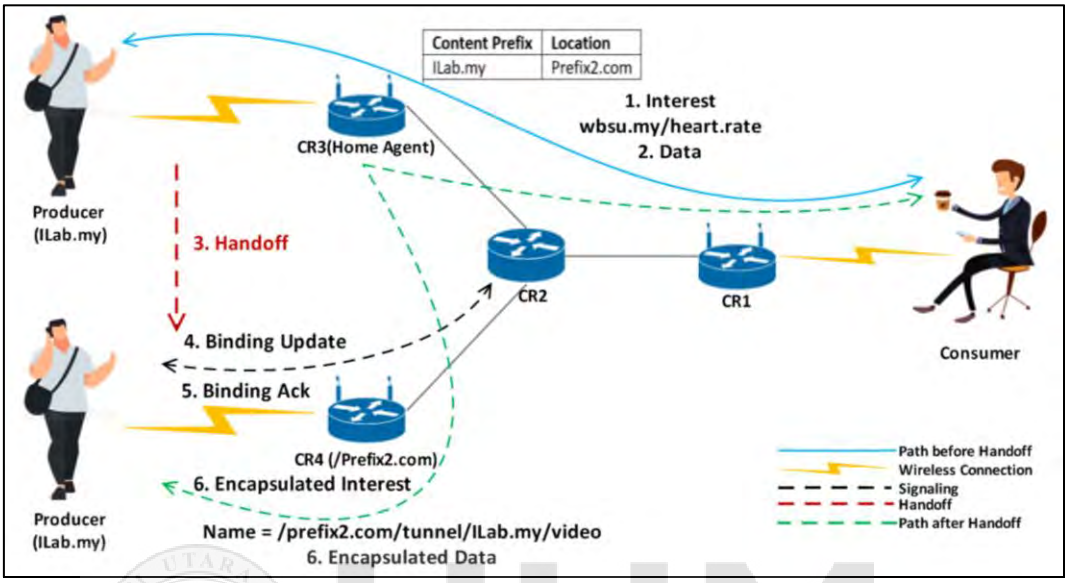



*Figure 2.8.* Operational Representation of IBM in NDN

The indirection point refers to a home repository which maintains the binding information between target prefix and source prefix. Target prefix that reflects the mobile source prefix under which it serves data and source prefix identifies its location or current point of attachment. The mobile producer registers its target prefix and source prefix to an indirection point or home repository. When the producer changes its location, it updates its new binding information to an indirection point or home repository and removes the out-dated binding information.

When an Interest arrives at home repository with its target prefix, first it tries to retrieve content from its cache. If the required content is not cached, it starts the longest prefix matching of the Interest name corresponding to the target prefixes and finds the best source prefix from the binding table. Upon finding out the source prefix, the home repository encapsulates the original Interest and forwards it to the mobile producer. When the producer receives the encapsulated Interest, it decapsulates the Interest and finds the required data. Thereafter, the required data is encapsulated and is sent to the home repository, and the home repository decapsulates the data and forwards it to the consumer [33]. In this way, the consumer retrieves data in minimal time. However, this proposed scheme uses the triangular path.

To handle the producer mobility issues and make possible routing path for forwarding the Interest packet and retrieval content, the indirection approach has been proposed in [31], and the same technique has been used in [33]. To support the producer mobility, the proposed scheme in [31] uses the intermediate Content Routers (CRs) and home domain Content Router ($CR_h$). When the producer relocates, it sends prefix updates (PU) message that travel through the CR and reaches the $CR_h$. In response, the producer gets prefix update acknowledgment (PACK) message from $CR_h$ that creates the new path from old to the new domain of the producer current location. Afterward, the incoming Interest packets are encapsulated at $CR_h$ and are forwarded towards the available producer's new location, and upon reaching the Interest, they are de-capsulated at the producer and the data is encapsulated at the producer side. Thereafter, data packets are forwarded to the $CR_h$. At $CR_h$, data is de-capsulated and sent to the consumer. Intermediate routers between the path of the producer and $CR_h$ must decapsulate the data and cache them into their Content Store (CS) by its original name prefix. However, this scheme also follows the triangular routing as in mobile IP. The Interest or data packets move from the home content router that creates an issue to a single point of failure for $CR_h$.

To handling the producer mobility issues and minimizing the handoff latency in [34] involves the rendezvous point in two ways, first, rendezvous point is used as naming server, and the second as a relay server. The rendezvous work as a naming server tracks the location of all the producers. When the consumer sends an Interest to the producer, it does not get any response in predefine time of Interest. In this situation, the consumer sends a query to the rendezvous server to get a new location of the producer. Thereafter, the rendezvous server sends the producer a new location information, and the consumer sends the Interest to the new location of the producer again to retrieve data. On the other side, the rendezvous point as relay server provides the same services as in indirection point that imparts between the consumer and the producer to reduce latency and communication. The indirection server maintains the location of the producer in the network so that the producer must notify its location information in the indirection server. When the consumer sends an Interest to the producer, it moves to the producer through the given direction of the indirection server. To handle the producer mobility when the producer needs to move, it sends an indication to the indirection server about its mobility immunization, from that point the incoming Interest is buffered at indirection server. When the producer completes its mobility and updates its location information to indirection server, thereafter, indirection server redirects the buffered interest towards the producer to retrieve content. By using this technique, the indirection server minimizes the latency upon rendezvous server to extreme latency that is 226ms and the lowest to be 200ms [34]. This shows indirection server is more efficient to support mobility in comparison with rendezvous server. However, all the Interest or data move through the indirection server that creates the single point of failure issue. Furthermore, it faces longer RTT as compared to rendezvous server.

Therefore, a new technique introduced in [34] known as Interest forwarding, in which, when the mobile producer needs to handoff, it notifies the mobility event to its access router. Then, the access router buffers a new incoming Interest during the producer mobility after the mobile producer handoff completes, it is attached to new access router. A virtual Interest is sent to old access router that passes through intermediate routers and updates the FIBs. When virtual Interest arrives at the old access router, the buffered Interest is forwarded to the new access router, and data directly sent to the consumer as the PIT found in intermediate routers in response. The Interest forwarding technique shows better results and lessens the latency issues as compared to rendezvous and indirection server. However, applying the Interest forwarding technique in some topologies creates triangular routing that reflects to a single point of failure problem. Furthermore, the access routers need an efficient modification to process virtual Interest and for buffering the incoming Interest during the producer mobility.



Han et al. [32], proposed a scheme namely Publisher Mobility Support in CCN (PMC) to handle the producer mobility issue without changing its original architecture. The PMC scheme reflects the similar idea of indirection-based mobility and updates the FIB by using Interest data packets. For this reason, the PMC scheme maintains two kinds of FIB in their routers for mobility support. The first, called ordinary FIB entry, is maintained by routing protocol and the second, called mobility entry, is used as the information for the mobile producer and is updated by the PMC protocol in router. In normal situation when the producer is not mobile, all Interest follows the original FIB entry.

In PMC, the publisher introduces two reserved names to update the publisher mobility information. When the publisher moves from home router to a new location, it sends an Interest that moves from publisher's new location (POA) to home router through the intermediate routers and establishes path by updating the mobility entries in routers with high priority. When the consumer sends an Interest, it will automatically move towards the publisher and retrieve content. In the same way, when publisher relocates from old location (POA) to the new location (POA), it sends an Interest to, both, home and old location routers to updates mobility entries. Furthermore, it establishes path towards the publisher's new location with high priority and updates the FIB for incoming interests. However, PMC scheme produces high delays because the Interest packet must travel to home and old location routers before reaching to the mobile publisher. In addition, mobile publisher sends Interest to, both, home and old location routers to update mobility entries which may lead to high signalling.

In NDN, a PIT based scheme is introduced to support the consumer and the producer mobility which is known as KITE [29]. For this reason, the KITE scheme supports the producer mobility by using two efficient features. First, the locator-freeness, in which location of the mobile producer is transparent for all nodes and any node can be communicated with the mobile producer, and the second is the scenario-awareness which provides the efficient mobility support to application program according to their requirements or scenarios. Furthermore, to keep the track of the producer mobility, KITE uses the PIT entries that is created by the traced Interest and tracing Interest. The mobile producer issues a traced Interest to immobile anchor router, and the corresponding node sends the tracing Interest to immobile anchor for the content retrieval. The immobile anchor forwards the tracing Interest to the mobile producer location by chasing through the PIT trace of producer and the content is forwarded to the corresponding node through the way of immobile anchor.

Therefore, the main disadvantage in KITE scheme is that it generates the long forwarding path as compared to normal NDN because all the Interests transfer from the immobile anchor. Due to this fact, path is not optimal in KITE.

Further, Kim et al. [28], proposed the on-demand anchor-based mobility scheme that follows the similar scenario of IBM to control the producer mobility issues. The proposed scheme considers the anchor router in the network that natively supports the consumer Interest packets, and for mobility management, it uses the Mobility Update (MU) packet that contains the producer name prefix. When the produce moves from old location to the new location, it simply sends the MU packet to anchor router except for the old location. When the consumer sends an Interest packet, it follows the FIB and reaches to the old location, if the producer is not available then Interest packets are redirected towards the anchor router. When the producer completes relocation, it sends MU packet to anchor router and receives the consumer Interest packets. This scheme shows the better performance and reduces the Interest packet retransmission as compared to the KITE scheme [29]. However, the proposed scheme does not determine the anchor selection method and creates the inefficient data forwarding path issue. In general, an Indirection based mobility approach provides the best effort to control handoff latency. However, the approach follows triangular routing in the network.

Do et al. [27], proposed a solution to support the producer mobility which is known as the Optimal Provider Mobility scheme (OPML). The proposed scheme aims to handle content provider's mobility issues such as high cost, non-optimal routing path, and long handover latency. The scheme replaces the normal router operation to control special mobility management packets that are used for a fast handover mechanism to support the provider mobility. The special mobility management packets are used to obtain the information about the neighbor router before the producer handover. Also, it creates a new route and deletes the old route that provides an optimal path for the Interest and data packets. The scheme adds extra fields into the Interest and data packets that makes it reachable for the packets to the producer new location. However, the path optimization process deletes the old path and creates a new path for the Interest and data packets. The optimization process utilizes more time that leads to high signalling cost and latency. The Fast handover mechanism utilizes more time and creates complexity because, when the producer moves to other routers rather instead of the neighbour router, it may lose the Interest packets. The proposed solution makes mobility more complex in terms of providing Interest and data packet and consumes more time and bandwidth.

Moreover, Hussaini et al. [35], introduced the Producer Mobility Support Scheme (PMSS) that is designed to minimize the producer mobility issues in NDN architecture. The scheme uses the Mobility Interest (MI) packet with broadcasting strategy and introduces immobile anchor in the topology. MI packet comprises the producer binding information that provides the producer location prefix. The broadcast strategy is used to spread the MI packet information into the whole network. When the mobile producer completes its handoff process and is attached to the new location, it sends an MI packet from its current location to immobile anchor. The immobile anchor broadcasts the MI packet information into the whole network that updates the routers' FIBs. However, during the producer long handoff process, the consumer Interest packets follow the producer's old location FIBs, and the Interest reaches to the producer old location. The consumer Interest packet gets dropped due to unavailability of the producer, and the consumer retransmits the Interest packet for content retrieval. The Interest retransmission is not an efficient solution to mobility because it decreases the overall performance of the network and utilizes more bandwidth [36]. Moreover, the uninterrupted mobile producer handoffs and broadcasts the location information in the network which causes high signalling cost and trapping of the consumer Interest packet to the old location and utilizes the extra bandwidth. Further, the broadcast storm in the network causes redundancy, contention, and collision [53].

A proposed solution to address producer mobility in a sustainable digital society focuses on minimizing communication delays between IoT devices [30]. This mechanism utilizes edge routers, Mobility Notification (MN) packets, and immobile anchors to effectively manage producer mobility. When a producer relocates to a new location, it sends an MN packet to the immobile anchor, which then broadcasts the producer's new location throughout the network. During this transition, the edge router reroutes incoming Interest packets to the immobile anchor, where these packets are temporarily cached. Once the producer updates its location, the cached Interest packets are redirected to the new location, allowing data packets to be delivered seamlessly. However, this solution can result in a long path stretch ratio in large networks, leading to increased signalling overhead and a higher likelihood of packet loss.

From the literature review, two proposals stand out as particularly noteworthy: OPML and PMSS. The OPML scheme is compelling due to its focus on path optimization, the use of specialized mobility management packets, and a fast handover mechanism designed to address provider mobility challenges, such as high signalling costs, suboptimal routing paths, and long handover latencies. However, it does have drawbacks, including increased signalling complexity resulting from path optimization and additional time and bandwidth consumption associated with fast handovers. On the other hand, the PMSS scheme is intriguing because it combines MI packets with a broadcast strategy to enhance producer mobility. Yet, it also presents challenges, such as consumer Interest packet loss, issues with Interest retransmissions, high signalling overhead, and excessive bandwidth consumption.

The different producer mobility support schemes analysis in IBM is presented in Table 2.1 and summarized the method, delivery path, merits, and demerits of each scheme.

Table 2.1

*Indirection Based Mobility Approach Schemes*

| Scheme | Method | Path | Merits | Demerits |
|---|---|---|---|---|
| An Indirection Approach [33] | Use the home router as a home repository to maintain source prefix and target prefix. | Triangular | Increase data delivery for consumer. | Uses Encapsulation and decapsulation that creates more delays. |
| Device Mobility Management [31] | Provides the home domain router that tunnels the redirected Interest and data packets. | Triangular | The producer Update and acknowledge its new prefix to home domain router. | Home domain router tunnelling uses the encapsulation and decapsulation as in Mobile IPv6. |
| Rendezvous point as naming server [34] | Allocates the location management server that tracks the location of the mobile producers. | Optimal | To some extent, the naming server supports the producer and consumer. | The Rendezvous server can provide an outdated location that may lose Interest packet that induces high handoff latency. |
| Rendezvous point as relay server [34] | The relay server caches the Interest packet until the related content provider reached. | Triangular | Decrease the Interest and data packet loss. | The data and Interest packets exchange through the relay server that creates a single point of failure. Increase the average Round Trip Time (RTT). |
| Interest Forwarding [34] | The home access router buffers the Interest packets and forwards the packets as received the producer location information. | Triangular | Virtual Interest updates the access router on the path between consumer and producer that avoids routing table explosion. Shows less handoff latency. | Increase the path stretch ratio and decrease the quality of service. |

| | | | | |
|---|---|---|---|---|
| Publisher Mobility Support (PMC) [32] | Make the ordinary FIB for producer mobility entry and original FIB when the publisher is not mobile and use the Home Router (HR). | Triangular | Provides the path for both Interest and data packet. | Interest packet travels to HR and old location before reached to the publisher that shows high delays. |
| KITE [29] | Assigns an Immobile anchor and introduces the forwarding mechanism by using traced and tracing Interest. | Triangular | Locator free and scenario are aware that support both consumer and producer. | All Interest and data move from an Immobile anchor that produces Single point of failure and long forwarding path. |
| On-demand Anchor-based Mobility [28] | Use an anchor node to forward Interest packet and Update (MU) packet to update anchor about the produce prefix. | Triangular | Reduce handoff | The inefficient data forwarding path. Increases the path starch. |
| Optimal Provider Mobility scheme (OPML) [27] | Special mobility management packets use for path optimization and fast handover mechanism to support the provider mobility. | Optimal | Provides the best route for consumer Interest and data packet. | Path optimization consumes more bandwidth. Fast handover produces high signalling cost and latency. |
| Producer Mobility Support Scheme (PMSS) [35] | Allot an Immobile anchor in the topology and Mobility Interest (MI) packet with broadcast in network. | Optimal | Lesser the handoff latency and update the producer location information to whole network. | Interest packet loss and consume extra bandwidth. Broadcast storm causes redundancy, contention, and collision. |
| Handle Producer mobility in Sustainable Digital Society [30] | Uses the edge router, immobile anchor, and Mobility Notification (MN) packet. | Sub-optimal | Overcomes the Interest packet loss and increases the data packet delivery. | Increases the path stretch ratio and high signalling in the larger network. |



#### 2.4.1.2 Locator/Identifier Split Based Mobility

Locator/Identifier Split Based Mobility (LISBM) is an approach that endeavours to support the producer mobility and based on the split identifier and locator. For this purpose, a unique locator field is added to the home router. The home router manages the mapping between the content prefix of a mobile producer known as an identifier and its current location that is known as a locator. When the mobile producer decides to change its location from old to the new location and completes the handoff, the producer sends its new location information to the home router and the home router updates the location information corresponding to the content prefix or identifier. The home router modifies the Interest packets by adding the current location of the producer and forwards it to the new location of the producer as shown in Figure 2.9.

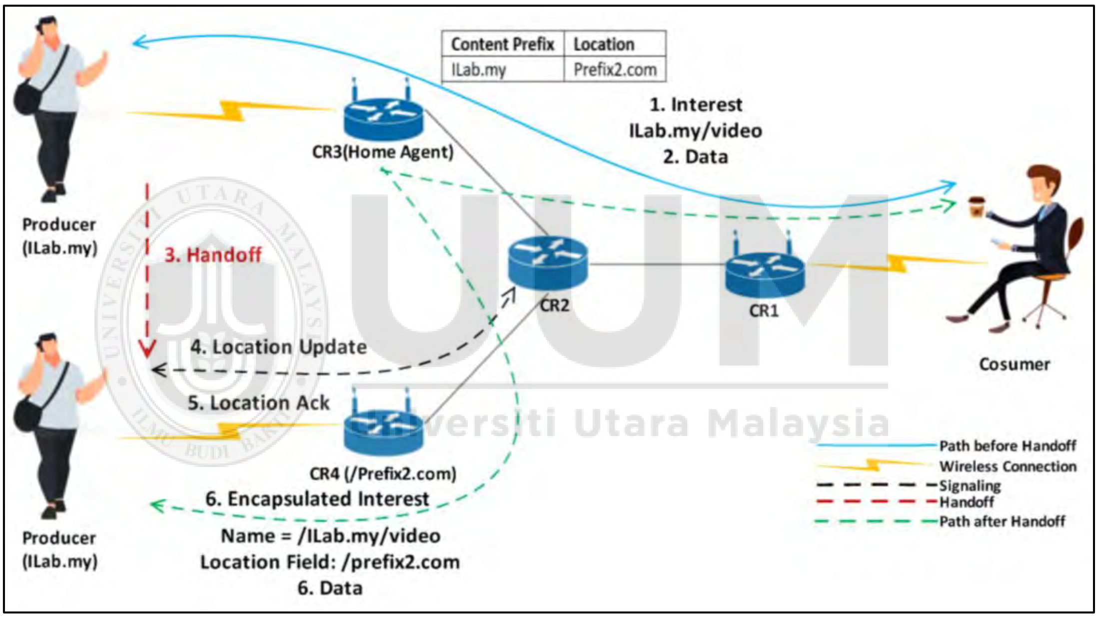



*Figure 2.9.* Operational Representation of LISBM in NDN

The idea of locator/Identifier Split [54] was proposed to support the producer mobility that is similar to the mobile IP. The scheme uses the mobility anchor that avoids the encapsulation and modifies the normal Interest packet by adding an optional location name field. When the Interest packet is forwarded and received by the router, the router checks its cache and provides the related required content. If the copy of the content is not available in the router cache, the router will normally forward the Interest to the producer. In a situation, when the location name is added into the Interest packet, it performs two lookups at a caching router which are the content name and location name to check either Interest needs to be forwarded to next hop according to the location name corresponding to its forwarding table. However, the packet delivery cost becomes more complex and increases the lookup time due to the several mobile producers.

A scheme has been designed to enhance the seamless producer mobility in NDN [52] that efforts to continue the interrupted communication after the handoff process and avoid sending an Interest packet to the producer's old location. For this purpose, the scheme modifies each access router as a unique topological layer in NDN. Also, it enhances extra functionalities in the access router like caching and forwarding the Interest packet on behalf of source and modifies it by adding an optional field in the original NDN packet. Meanwhile, it updates the access router original FIB entries by adding mobility status and current locator of the source. As a result, it supports the consumer to continue its interrupted communication and reduce the handoff cost and lessen handoff latency. Further, the locator/identifier split based mobility provides a better result as compared to IBM and DNSBM that show too large handoff latency. However, it decreases the performance by increasing the number of mobile nodes and reduces the performance as compared to IBM and DNSBM. Moreover, this solution shows a high cost in the wide network where the distance between the old and new access routers increases.

Do et al. [27], proposed a scheme that provides the solution to control several issues in the mobile content producers in NDN such as high cost, non-optimal routing path, long handover latency. For this vision, this scheme introduces the new mechanism that establishes the optimal path before the handover occurs. In the mechanism, some special mobility management packets are designed. To create the special mobility packets, this scheme modifies the original Interest and data packets. Also, it enhances the normal router operations that controls the special packets. Meanwhile, each boarder router is modified by adding some extra information to know about its neighbour router. When the producer moves from the current router to the neighbour router, the current router uses the neighbour information and forwards the unsatisfied Interest packets by an optimal path. This optimal path forwards the upcoming Interest packets to the producer's new location content router. In this way, the proposed scheme seems cost-efficient and provides a fast handover solution to support the producer mobility. However, the solution changes all the routers that are unrealistic in worldwide deployment. Moreover, it is not suitable for large networks and a group of producers.

Further, Rui et al. [55] designed the producer mobility support scheme for real-time multimedia delivery. The focus of the scheme is to provide the continuous multimedia transmission and seamless service. The scenarios are developed in the scheme to minimize the handover delay and maximize the consumer experience. For this purpose, two scenarios, ProCache and ProPull, are developed to provide the continuity in transmission during the producer convergence time. In the ProCache scenario, the producer caches the subsequent contents for incoming Interest Packets before the handoff. This basic idea of this technique is a proactive cache called ProCache. In the ProPull scenario, the producer sends the special packets to its connected access router to get the router name before its handoff. Once the producer completes its handover and connects, it pulls Interest packets from old location to new location that is known as ProPull. Moreover, it efforts to decrease the Interest drop rate and delay. However, the producer in the scheme uses special packets before and after handoff that produce high signalling.

Another, interesting study by Yan et al. [56] proposed hybrid network mobility support in NDN to handle the producer mobility. To support the producer mobility in NDN, the proposed scheme adopts the idea of NEMO (NEwork Mobility) as in current TCP/IP. The scheme controls the Mobile Node (MNN) through Mobile Routers (MR) and Mobile Agent (MA). The MNN is located under the authority of the MR. When the MR moves and attaches to new PoA of Access Router (AR) in the inter-network known as inter-NEMO then the MR and new AR exchange their location information. The Packet Update (PU) are forwarded, and Packet Acknowledgement (PACK) received from the AR to MNN's HA and previous AR to notify the movement behaviour. Afterwards, a Binding Update Table (BIT) are created at the intermediate routers, AR, and HA that contains (mobile node; current PoA; Face number) information. The BIT entry works as preliminary FIB. For this purpose, the consumer Interests firstly go through from BIT, if it finds the matching entry then the Interest is forwarded to MNN, otherwise, it starts lookup for matching entry into the FIB. In this way the MNN mobility is controlled by the MR. However, the PU and PACK produces the signalling in the whole network. Moreover, continuous movements of MR and excesses updates may loss the Interest packets and increases the lookup time for Interest packets.

Table 2.2 contains the various analysis on producer mobility support schemes under LISBM approach and expresses the method, delivery path, merits, and demerits of each scheme.

Table 2.2

*Locator/Identifier Split Based Mobility Approach Schemes*

| Scheme | Method | Path | Merits | Demerits |
|---|---|---|---|---|
| Global Source Mobility [54] | Uses the mobility anchor and modify the normal Interest by adding location name field. | Triangular | Provides the support for Interest packet. | Increase the packet delivery cost and Interest lookup time for appropriate source. |
| Locator Based Mobility [52] | Modify the access router FIB's and NDN packets. | Triangular | Provides the interrupted contents and lessen the handoff latency. | Creates high cost in the wide network and increase the distance and hop count. |
| ProCahe and ProPull for real-time multimedia delivery [55] | In ProCache, caches the content for upcoming Interests. In ProPull, use special packets to get name for next router. | Optimal | Lessening the handover delay and increases the packet delivery. | Special packets increase the signalling. |
| Hybrid Network Mobility [56] | Creates Binding Update Table (BIT) at Home Agent, previous and intermediate routers. | Optimal | Updates the location information in the network. | PU and PACK creates high signalling. Excessive updates for producer may loss Interest packets and increases lookup time. |

### 2.4.1.3 Caching Based Mobility

Caching Based Mobility (CBM) is another approach that develops to support the producer mobility in NDN. The CBM endeavours to support the producer mobility through the content-centric nature of NDN. According to this approach, the consumer firmly interested in the content and send Interest to the producer in order to retrieve the content. When the producer moves, the consumer Interest unable to reach the producer location due to not updated with the new location of the producer. Additionally, the consumer Interest directed towards the producer's old location and dropped after expires its predefined time. The main idea of CBM is to caches the content to its neighbour router before the producer handoff. The producer caches the content at the neighbour router according to the popularity of content or the most interesting content by the consumers. The producer before its handoff, sends the queries to its neighbour router and collects the information and calculates the popularity of content or search for the most interesting content among the contents. After the calculation, the producer selects the appropriate neighbour router and caches the most interesting content at the neighbour router. Whenever the producer moves, the content is available for the consumers as shown in Figure 2.10.

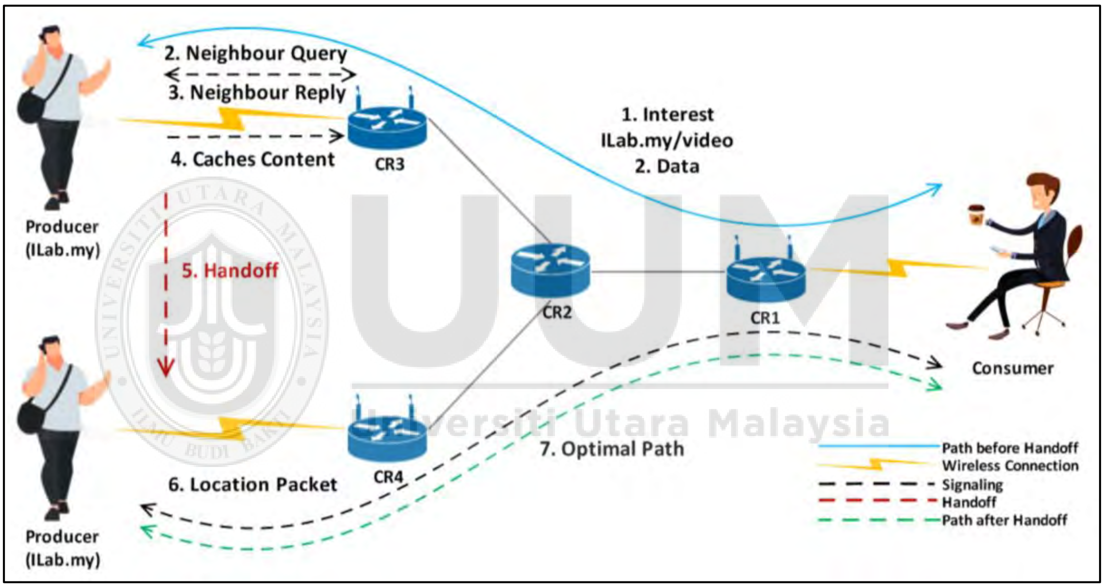



*Figure 2.10.* Operational Representation of CBM in NDN

Woo et al. [57] develops the Proactive Neighbor Pushing CCN (PNPCCN) scheme to support and enhance the provider mobility in CCN. When the provider handoff, the location information changes, and the router FIBs are no longer able to access the content provider. For further communication, all the routers in the network perform an extra task to update the routing information that increases the cost for altering routing information. The PNPCCN scheme focusses to solve a critical issue that is produced due to provider mobility. In PNPCCN, the provider caches the requested content to the neighbour router before its move. Moreover, the provider caches the content depending on its popularity and rarity which known as transfer probability. The popularity of the contents is calculated and caches the highest popular content to the neighbouring routers. The rarity refers to the surrounding condition, the provider verifies the duplication of the contents to the neighbouring routers. If the neighbouring routers have the same contents, then the contents do not need to cache. When the provider moves, the consumer effortlessly retrieves the popular contents from the neighbour routers rather than the provider. However, the scheme supports the specific contents during the provider mobility and the consumer request for unpopular contents may lose. The scheme creates more signalling cost to scan the content duplication from the neighbouring routers. Further, the calculation of the content for transfer probability and pushing the content towards the neighbour router creates more delays in the network. Also, the scheme does not update the current location information of the producer.



Another, Lehmann et al. [58] introduced the producer mobility support in NDN through proactive data replication. The scheme concentrates to minimize the impact of the producer's unavailability and make the content available for the consumer through content-centric mechanisms. When the producer moves, the consumer's Interest unreachable to retrieve content due to unavailable of the producer in a network. The scheme gets the benefit through the content-centric nature of NDN and focuses on the availability of content rather than the producer. The scheme uses the data replication strategy that increases the availability of content and reduces the influence of the producer inaccessibility. Further, the scheme uses the content push operation and content placement policy to make the content available. In a content push operation, the producer generates the content and suggest the users to request for the generated content. The users request to the producer and obtain the generated content before its mobility. Moreover, the scheme uses the content placement policy that caches the content copies in the network. Thus, the content copies are inversely proportional to the availability of the producer in the network. However, the content placement policy generates and caches the excessive copies of the content that consumes unnecessary routers cache and produces redundant contents in the same network. Additionally, the content push operation creates more signalling and overheads. Furthermore, the scheme focusses on the availability of content rather than to control the producer mobility.

Farahat et al. [59] presented a proactive caching scheme to support producer mobility in NDN. This scheme introduces to control the problems during the producer convergence time such as Interest packets drop and Interest retransmission. The main idea of this scheme is to predict the producer location pattern and cache the most requested data before the producer handover. For this purpose, the scheme adopts the ProCacheMob. ProCahceMob is used to predict the future expected content Interests for the mobile producer and cache the contents for future Interests before the producer handover. This may lead to control over the Interests drop and retransmissions. Moreover, it improves the network efficiency and decreases the consumer delay during the producer mobility that is produced due to Interest packets drops. However, this scheme does not provide an optimal path for some scenarios that induce high signalling overhead.

Korla et al. [60] proposed an interesting solution to assist the producer mobility in NDN. To support the producer mobility, the scheme caches the selected content at router in the network. For this reason, the scheme enhances the router function by adding content name, trendiness, and frequency. In addition, it introduces the control messages GETT (short for GET Trendiness) and REPT (short for REPort Trendiness) to get the information about its nearest routers. When the producer wants to handoff within the domain, it broadcasts the GETT query with the names of its available data objects to each edge router. The edge router owns receiving the query checks the data object if it is already cache than the GETT will be discarded, otherwise, the edge router calculates the trendiness of the data object and sends a REPT message to the producer. The producer calculates the trendiness of content by receiving values in REPT message and caches the highest trendiness content among all contents. Further, the messages are used to delete the producer old prefix and update the new prefix in the FIB. However, the scheme broadcasts the messages which increase the cost of handoff signalling and latency. Moreover, the consumer request for high trendiness cached content is satisfied by the router but the rest of the requests may be lost.

Swaroopa et al. [11] proposed a FAVE Cache Strategy for producer mobility in content-centric networks. The producer is the source that provides the content to satisfy the consumers Interest. When the producer is under mobility, it is very challenging to control mobility by using alternative internet design. For this purpose, the proposed scheme gains some benefits from the NDN architecture and support the producer mobility through caching approach. The producer broadcasts the message to its neighbour in order to get the values of cri and fri. The cri search for the same prefixes in CS of the router, in other words, the cri search for the maximum cached content for the given prefix in the router. The fri measures the frequency of occurrence for a specific prefix at a router CS. By obtaining the values of cri and fri from neighbors' router, the producer selects the appropriate neighbour router for caching content by calculating the cost of the cri and fri values. The calculation involves the weight of each prefix and set the prefix priorities based on their weights. After All producer caches the complete content at the selected router based on the result of these values. When the producer moves and the consumer similar Interest reached at the router, it can retrieve content without chasing the producer. However, the scheme supports the content for a specific prefix. Additionally, only a similar request for specific content can retrieve, the rest of the Interest packet loss due to the unavailability of the producer and content. Moreover, the broadcast in the network consumes more signalling and creates overheads.

The different producer mobility support schemes analysis in CBM is summarized in Table 2.3 and express the method, delivery path, merits, and demerits of each scheme.

Table 2.3

*Caching Based Mobility Approach Schemes*

| Scheme | Method | Path | Merits | Demerits |
|---|---|---|---|---|
| Proactive Neighbor Pushing [57] | Caches the most popular content to the neighbour router. | Optimal | Popular content easily retrieved by consumers without any delay. | Does not indicate the producer mobility. Transfer probability and pushing content creates more signalling. Interest packets for less popular contents may loss. |
| Proactive Data Replication [58] | Caches the various content copies in network. | Optimal | Make specific content available for the consumer. | Does not control the producer mobility. Content push operation and excessive copies for content induce high signalling and overhead. |
| Proactive Caching [59] | Optimally cache the contents for future expected Interests. | Sub-optimal | Cached content easily retrievable in minimal delay for the consumers. | Generate extra network overhead and the Interest rather than the cached content cause lose. |

| | | | | |
|---|---|---|---|---|
| T-light movement [60] | Higher trendiness and frequency content caches to all routers. Broadcast GETT and REPT messages. | Optimal | Higher trendiness and frequency content effectively retrieved by its consumers. | Broadcasts messages increase cost of handoff signalling. Request for cached content is satisfied but the rest of the requests may lose. |
| FAVE Cache Strategy [11] | Broadcasts cri and fri messages to neighbor. Caches the selected content at the selected router based on the result of cri and fri. | Optimal | The consumer similar request for specific content is to be retrieved. | Specific content can retrieve, the rest of the Interest packet lose. Broadcast produces more signalling and overheads. |

### 2.5 Server-based Approaches

DNSBM and CDSBM are classified as server-based solutions. These approaches rely on servers to manage producer mobility, providing a centralized point for tracking and maintaining connections. By leveraging server capabilities, these solutions can offer enhanced features such as load balancing, data caching, and improved mobility.



#### 2.5.1 DNS Based Mobility

The DNS-Based Mobility (DNSBM) is a technique used to support the producer mobility in NDN. The scheme involves the mapping server, DNS server, and rendezvous server to keep track the producer mobility in the network. These all servers maintain the mapping between the content identifier with locator. Each mobile producer has a namespace or stable identifier under which it publishes the data without its location The locator indicates the location of the mobile producer and refers to name prefix [51]. When the mobile producer relocates, and after it connects to the new location, it registers the new name prefix to server. When the consumer sends an Interest packet and does not get any response due to the unavailability of producer, the consumer sends a query to DNS server to get the producer new location for content name. The DNS server sends the forwarding hint to the consumer which provides the reachability to the producer's new location with new name prefix. The consumer sends the Interest according to the provided forwarding hint and efficiently arrives to the producer current location as shown in Figure 2.11.

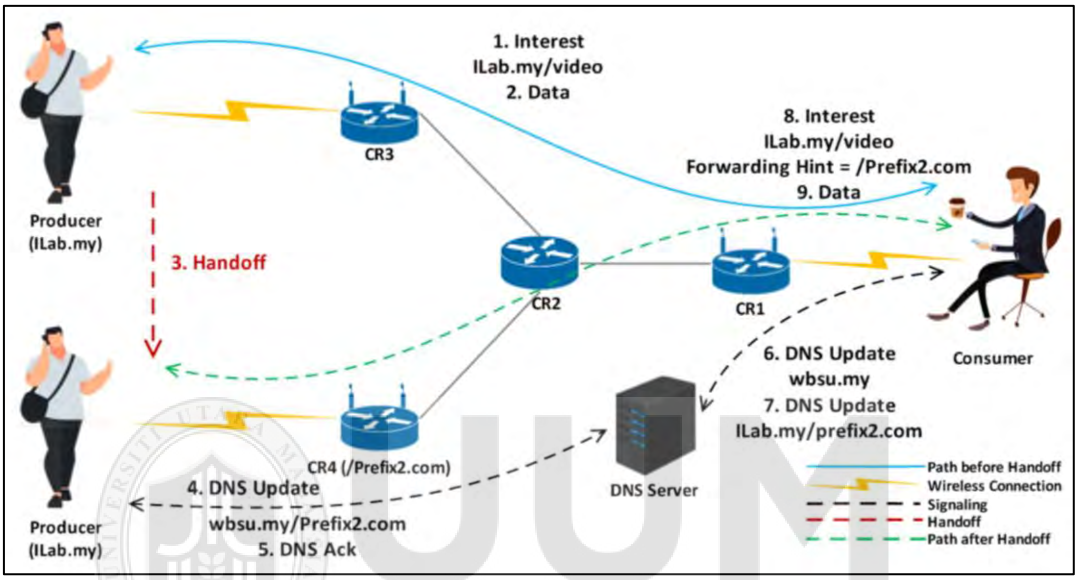



*Figure 2.11. Operational Representation of DNSBM in NDN*



Kim et al. [34] proposed a solution to support the producer mobility in NDN. The proposed scheme traces the producer location by using rendezvous server. When the producer completes the handoff, after that it updates its new location prefix to rendezvous server. Under this scheme if the consumer does not get any response in the predefine time, the consumer sends a query to rendezvous server to get the producer new location. In response, rendezvous server provides the forwarding hint to the consumer by which it sends Interest again to reach the producer current location. However, this scheme shows the maximum handoff latency around 400ms that is greater than the round time trip. As a result, the rendezvous server provides the outdated location information to the consumer.

In NDN, a solution has been proposed for the producer mobility provided by utilizing the DNS-like mapping server and using the forwarding hint to support the producer mobility [48, 61]. The mapping server keeps the location of the producer corresponding to its identifier and modifies the consumer Interest by adding locator [48]. When the producer relocates, it sends the name in the new network and withdraws its name from old network and adds its new forwarding hint in the mapping server. Therefore, the consumer gets query for the producer location and Interest moves to the exact producer location. However, all the announcements, withdrawal and adding or updating forwarding hint procedure affects the overall performance [61].

Scalable Mobility Management scheme (SMM) [62] was proposed to solve the producer mobility problems such as single point of failure, non-optimal routing path and severe scalability without tampering the original NDN architecture. The SMM provides the shortest path communication and fast handover by splitting identifier and locator. For this reason, SMM adopts three different kinds of separation mechanisms in NDN, management/routing separation, locator/ID separation, and access/core separations. According to SMM, the producer sets the location name of the stored contents like the name of access router and the producer needs to register its identifier and location into the locator/ID mapping system. When the producer handoffs and attaches to new location, it sends Interest packet, namely Binding Update (BU) to mapping server. Mapping server updates the binding and replies with Binding Acknowledgement (BA), to the producer and informs the old location router about the producer current location. However, BU and BA influence high signalling and consume more bandwidth when the producer has frequent movements.

Cluster-based device mobility management scheme [63] uses to solve the producer mobility issues in NDN. When the producer moves from the old location router to the new location router, it sends its location information to the new location router. The new location router sends the producer location information to the cluster head and cluster head updates the table and sends binding update to the producer. Thereafter, cluster head forwards the producer location information to all attached cluster head nodes and updates the producer location. However, this scheme increases more signalling that is produced by the binding update and binding acknowledgement. Moreover, this scheme increases the handoff latency which is produced by updating the process of cluster head nodes.

The Hybrid Indirection Method (HIM) is designed to minimize signalling costs during the handoff procedure [64]. This approach introduces a rendezvous server to support producer mobility and enhance the data packet delivery ratio. The rendezvous server plays a crucial role in managing producer mobility while maximizing the efficiency of data transmission. In this solution, multiple producers are utilized to handle Interest packets. When an Interest packet is sent to the rendezvous server before the producer moves to a new AP, the server forwards the data to the consumer once the producer is connected to the new AP. This method aims to ensure the timely delivery of data packets to consumers while effectively managing producer mobility. However, the solution leads to triangular routing in simple topologies, which can result in increased signalling costs and excessive packet loss in larger networks. This ultimately contributes to lower throughput and reduced packet delivery.

Table 2.4 expresses the different producer mobility support schemes analysis under the DNSBM approach and brief the method, delivery path, merits, and demerits of schemes.

Table 2.4

*DNS Based Mobility Approach Schemes*

| Scheme | Method | Path | Merits | Demerits |
|---|---|---|---|---|
| DNS-like Mapping System [48, 61] | Places the mapping sever to provide the forwarding hints for the producer location. | Optimal | Reduce the routing update cost. | Updating forwarding hints influence more delays and signalling. |
| Scalable Mobility Management scheme (SMM) [62] | Introduce management/routing, locator/ID, and access/core separations. The Binding update and acknowledgement to inform mapping server about the producer location. | Optimal | Provides scalability in forwarding plane and improve robustness of mapping server without tempering in NDN architecture. | Updating process for global mapping server high overhead cost and Interest packet lose. |
| Cluster-Based Device Mobility Management [63] | Cluster the nodes known as Cluster heads based | Optimal | Support consumer and producer mobility. Reduces the packet loss. | Increase signalling and produces the delays in contents delivery. |
| Hybrid Indirection Method [64] | Places the rendezvous server to redirects data packets | Triangular path | Increases the data packet delivery in simple topology | Increases the path stretch ratio and increases the delay. |

### 2.5.2 Control Data plane Split Based Mobility

Control Data Plane split based mobility (CDSBM) is an approach that takes part to support the producer mobility. The CDSBM efforts to provide an efficient technique to handle the producer mobility. For this aim, CDSBM is divided into the control plane and data plane to grip the producer mobility. The control plane (resource handler [65] or controller [66]) is responsible to handle the producer mobility signals. The data plane provides the facility to forward the Interest and data packets. When the producer relocates, it updates the controller or resource handler about its new location information. Subsequently, the control plane informs the producer location information to the data plane. As a result, the new Interest packets track to the producer new location as shown in Figure 2.12.

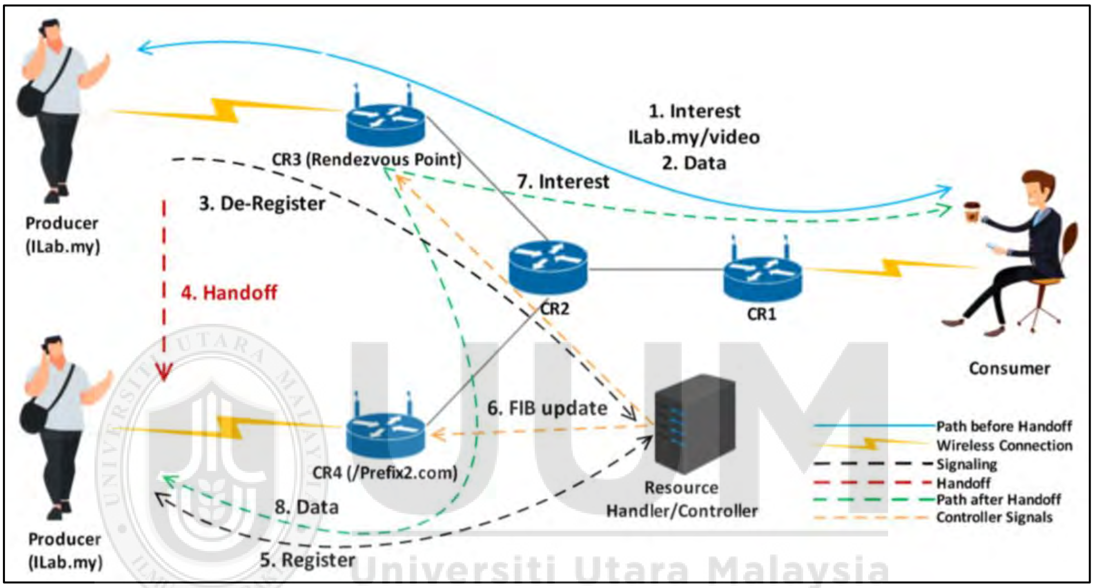




*Figure 2.12.* Operational Representation of CDSBM in NDN

Tang et al. [65] proposed the idea to support the producer mobility and efforts to control different issues such as content retrieval latency and frequent routing updates. The scheme splits the locator and identifier together with separate control and data plane. Also, it uses the global and local locator that is specified in the Interest optional location name field. Global locators identify the rendezvous domain where the mobile producer is located, and local locators specify the access router to which the mobile producer is attached in the domain. The scheme modifies the Interest packet into a location update packet that contains the mobile producer's name and its location.

The scheme network consists of many rendezvous domains (RD) and each RD has a resource handler (RH). When the mobile producer moves in RD and is attached to access router, it gets a local locator. Also, RH allocates a global locator and rendezvous point (RP). RH in the control plane is responsible for location registration and update signalling. Moreover, the RPs control the Interest and data packets in the data plane. However, the producer mobility handoff process results are analysed in both intra and inter-domain. The handoff latency and handoff signalling are very high in inter-domain as compared to the intra-domain movement.

Zhou et al. [66] proposed a mobility support architecture for NDN (MobiNDN). The scheme focuses to reduce the Interest and data packets losses. Also, it attempts to minimize the handoff delay during the mobile producer convergence time. For this reason, MobiNDN designs a centralized control system architecture in which each autonomous system (AS) is maintained by one controller. Each controller obtains the region topology and maintains the link information. Moreover, the AS and controller also communicate with each other to support mobility during handoff. The MobiNDN contains the forwarding plane and control plane. Forwarding plane provides the forwarding path for the packets including Interest and data packets. Control plane is responsible to maintain control messages and manages router action. The MobiNDN starts with initialization that includes calculation of route and recognizes the network topology information. It functions in three different stages: registration, deletion and updating. When the producer needs to publish the content, according to the first stage, the producer must register its content to the access point router. The access point router generates the FIB entry that the controller records the entry with content and broadcasts to all nodes in the network. When the producer relocates, it updates the controller about its new location. The controller removes the outdated information and updates the FIB table in the content routers that supports the Interest packets towards the producer. However, the use of registration, deletion, and updating queries shows high signalling costs in the handoff process.

Ren et al. [67] proposed a mobility management scheme to support the producer mobility in the network and resolve the lager overhead problem during the handoff process. The scheme uses the software-defined technique and develops the software define controller (SDC) that reduce the handoff overhead during the producer mobility. The idea of SDC is to separate the control and data plane that creates a binding between the content name and the interface. The mobile producer sends a handoff imitation message to attach access router before its handoff and the message is forwarded from access router to SDC. When the mobile producer is completely handoff and attached to a new access router, the SDC rewrites the routing table that contains the content name corresponding to the interface. After rewriting, the routing table is sent to access routers and access routers update their routing entry. However, the scheme increases the handoff latency. In addition, the SDC causes the bottleneck issues because all the packets move through the SDC, and single point of failure may occur.

Table 2.5 shows the different schemes analysis of the producer mobility in the CDSBM approach and illustrates the method, delivery path, merits, and demerits of each scheme.

Table 2.5

*Control Data Plane Split Based Mobility Approach Schemes*

| Scheme | Method | Path | Merits | Demerits |
|---|---|---|---|---|
| Source Mobility Management scheme [65] | Uses the local and global locator rendezvous domains and resource handler, respectively. | Sub-optimal | Updates the whole network about the producer new location. | Shows high intense handoff signalling and latency in inter-domain. |
| MobiNDN [66] | Introduce centralized control system and controller for each autonomous system. | Sub-optimal | Provides the forwarding path for Interest and data packets. | Registration, deletion, and updating consume high signalling. |
| Mobility Management Scheme Based on SDC [67] | Software Define Controller (SDC) creates binding between content name and interface. | Triangular | Reduce the handoff overhead. | Creates the delays in packets delivery and cause bottleneck issue because all packets move through the SDC. |

Several approaches have been classified based on different technological methods and multiple unique properties that distinguish them from one another. Each approach encompasses various research works that have undergone critical analysis. Through this analysis, several notable factors have been identified, including packet loss, high signalling, extra bandwidth usage, and excessive Interest retransmission. Moreover, Table 2.6 succinctly summarizes the differences between these approaches.

Table 2.6

*Summary and Comparison of Producer Mobility Approaches*

| Approach | Method | Path | Merits | Demerits |
|---|---|---|---|---|
| Indirection Based Mobility (IBM) | Home Agent/Router | Triangular | Provides forwarding path for Interest and data packets. | Uses encapsulation and decapsulation for Interest and data packets.<br>High signalling cost.<br>Interest packet loss. |
| Locator/Identifier Split Based Mobility (LISBM) | Home Agent/Router | Triangular | Forward Interest packets to the producer location. | Uses complex encapsulation and decapsulation.<br>Long Handoff latency.<br>Interest packet loss. |
| Caching Based Mobility (CBM) | Router Cache | Optimal | Popular content is easy to retrieve with minimal delay. | Interests in unpopular contents suffer the loss. |
| DNS Based Mobility (DNSBM) | DNS/Mapping/ Rendezvous Server | Optimal | Provides forwarding link and tracks the producer location. | High signalling cost.<br>Interest packets loss.<br>Single point of failure issue. |
| Control Data plane Split Based Mobility (CDSBM) | The control plane and data plane points | Triangular | Reduces the Interest packet loss. | High overhead.<br>Intense handoff signalling.<br>Single point of failure issue. |

In comparing the methodologies from previous studies with the chosen methodology in this research, we find distinct approaches that highlight both strengths and limitations. Many prior studies have relied on analytical method to gather in-depth insights into producer mobility solutions. Some researchers have employed simulation method and statistical analyses to assess performance metrics, which provides valuable data to access the performance of the solution. In contrast, our research utilizes both analytical and simulation method to analyse the performance of our model which is further explained in Chapter Three. This allows us to balance generalizability with depth, validating findings across broader contexts while capturing the intricacies of individual experiences. Our methodology enhances the validity of insights through triangulation, offering a richer understanding of both user experiences and performance metrics. Ultimately, while previous methodologies have their merits, our approach aims to provide a more balanced and comprehensive understanding of producer mobility solutions, thereby enhancing the overall rigor and relevance of the research.

## 2.6 Summary

This chapter covers in detail the background issues in NDN and discusses the producer mobility support in NDN. Also, provides a clear understanding of the producer mobility support in NDN and discusses the most relevant problems in the producer mobility. Further, explore the previous research on the producer mobility support in NDN and critically analyse the producer mobility issues in NDN under different approaches. However, by having critically analysed the previous research proposal on the producer mobility support in NDN that determines to need for a solution which manages the producer mobility issues such as long handoff latency, Interest packet loss, Interest retransmission issue and unnecessary bandwidth consumption.

# CHAPTER THREE

# RESEARCH METHODOLOGY

The intention of this chapter is to provide the fundamental efforts for conducting this research and to describe how this research can accomplish the objectives. In addition, it ensures the extensive guidelines, systematic methods, and structural planning for this research. The methodology facilitates and provides clear knowledge for the model, design, verification, and validation methods. Hence, research methodology provides extra knowledge to conduct productive research. Design Research Methodology (DRM) is adopted to explain this study in order to present the effectiveness of each phase. This chapter has several sections that start from Section 3.1 which is indicating research framework approach to describe research steps. In Section 3.2, Research Clarification (RC) stage provides the deliverables and adopted methods. In Section 3.3, the Descriptive Study-I (DS-I) stage provides a detailed understanding of the current complex situation, and in order to improve the complexities of design, a conceptual model for proposed PMMM is presented. In Section 3.4, Prescriptive Study (PS) stage discusses the effective development methods used in designing the proposed mechanism for solving problems. In Section 3.5, the Descriptive Study-II (DS-II) stage is associated with evaluation approaches and performance metrics. Finally, the Section 3.6 summarized the chapter.

## 3.1 Research Framework Approach

This research aims to design a PMMM to enhance the producer mobility support in NDN. Therefore, the objective of PMMM is to reduce the most critical issues related to the producer mobility such as high handoff latency, high signalling cost, inefficient data path delivery, and less throughput. It is necessary to enhance the overall producer mobility in terms of efficient control for excessive signalling, high packet loss, non-optimal packet delivery path and long handoff latency to achieve better performance. However, it is not an easy task to resolve such challenging issues. The reason is that the existing producer mobility solutions have abilities to enhance limited issues, and the researchers are digging out an optimal solution that can lead to an optimum and proficient solution.

The primary objective of the methodology is to enhance comprehension of methods, tools, and design principles while offering guidance to improve the quality of research and achieve optimal performance. As a result, it is crucial to select an appropriate methodology that can yield improved theoretical and practical outcomes. In this context, the adoption of Design Research Methodology (DRM) is deemed suitable for conducting this study. By utilizing DRM, the understanding of methods and tools can be deepened, allowing for a comprehensive exploration of design concepts. The methodology provides a structured framework that facilitates the integration of theoretical insights with practical applications. This approach is particularly valuable in enhancing the overall quality of research outcomes. Therefore, by employing DRM, this study aims to leverage the benefits of a well-defined methodology, enabling a more rigorous and systematic investigation. The use of DRM will contribute to the achievement of superior results, both in terms of theoretical advancements and practical implications.

DRM is a systematic approach, method, and a set of step by step guideline that is used to develop more effectiveness in designing research [68]. It leads to achieve a better understanding to develop research flow and makes it easy to define step by step method for the research. Further, it provides information in the form of selecting the most appropriate tools to obtain more effective, rigorous and efficient performance [69]. Also, features of DRM seem more beneficial in terms of practicality and for research purposes. Moreover, in the scientific methodology of computer sciences, it provides a brief explanation for conceptualization, modelling, simulation, and experiment [70]. In summary, DRM is particularly suited for research objectives that prioritize innovation, user engagement, iterative development, and the integration of theory with practice. Its structured yet flexible nature ensures that the research can effectively address complex challenges while remaining responsive to user needs and contextual factors. This alignment makes DRM the optimal choice for achieving meaningful and impactful outcomes this research. Owing to the advanced functionalities in DRM, it has been selected for conducting this research in order to achieve our research objectives.

DRM has been classified into four different stages.

- Research Clarification (RC)
- Descriptive Study-I (DS-I)
- Prescriptive Study (PS)
- Descriptive Study-II (DS-II)

This research provides a concise explanation of each stage within the DRM framework and its relevance to the study. The DRM framework effectively captures the interplay between methods, approach, and deliverables, as depicted in Figure 3.1. The main process cycle of DRM is represented by light arrows connecting the stages, while the bold arrows indicate the methods employed and the resulting deliverables. By following this framework, the research ensures a systematic and comprehensive approach to design research. Each stage is succinctly described, highlighting its significance in the overall DRM process. The light arrows visually demonstrate the flow and progression between the stages, emphasizing their interconnectedness. Conversely, the bold arrows draw attention to the specific methods utilized within each stage and the corresponding deliverables they produce.

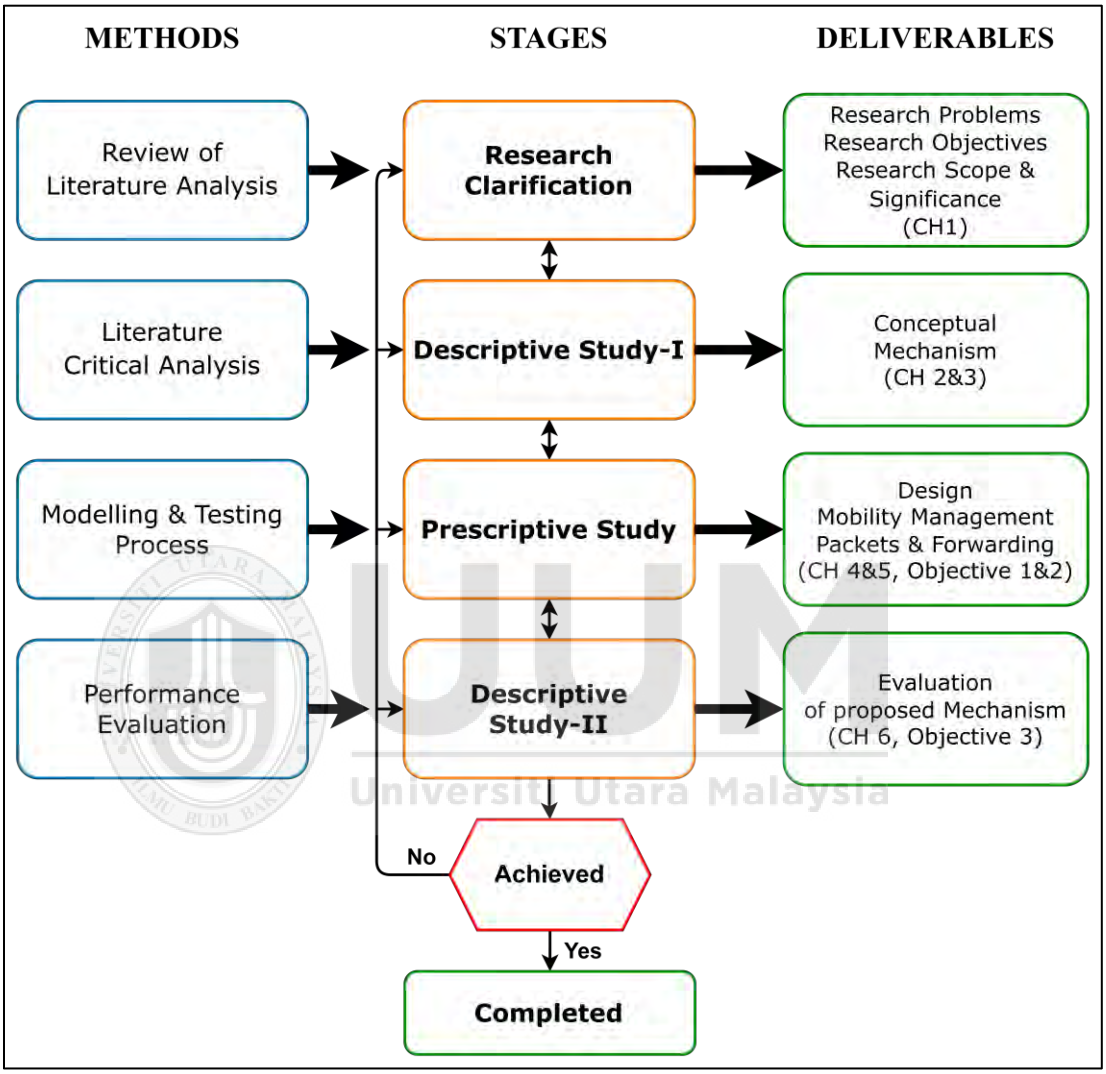



*Figure 3.1.* Research Framework Approach [68]

A key limitation of DRM is its broad nature, which may not effectively address unique research questions or specialized problems, leading to a lack of focus on specific design challenges. To mitigate this, the research was framed within a defined context with specific objectives. Targeted research questions were formulated, allowing the application of DRM to be tailored to distinct challenges for more relevant insights and solutions.

### 3.2 Research Clarification

The DRM begins with the Research Clarification (RC) stage, which serves to clarify and establish the overall research plan. This stage comprehensively outlines the aim of the study: to design a producer mobility management model that addresses challenges such as high handoff latency and signalling issues. The objective is to enhance throughput and support path optimization during and after the producer handoff process, ultimately creating an optimal communication path. The RC phase consists of six iterative steps, as illustrated in Figure 3.2. These steps ensure a thorough understanding of the research context and objectives, setting a solid foundation for the subsequent phases of the methodology.

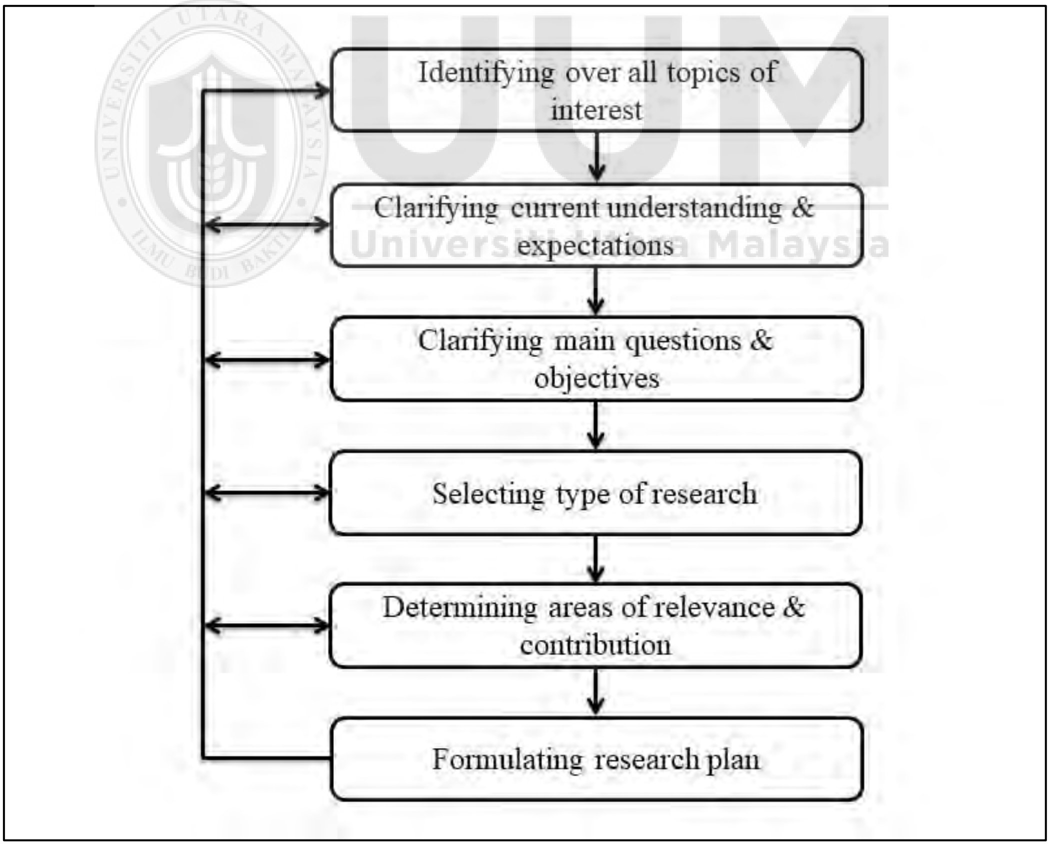



*Figure 3.2.* Research Clarification (RC) [68]

The RC stage includes several key deliverables, as outlined in Chapter One. These deliverables present a comprehensive research plan that begins with the foundational concepts and motivation for addressing producer mobility in NDN. Through an in-depth exploration of producer mobility, we identify critical research challenges, including high signalling overhead, prolonged handoff latency, reduced throughput, and non-optimal communication paths. Moreover, this stage clearly articulates the research questions, objectives, significance, and scope relevant to producer mobility in NDN. This structured approach ensures that the research is well-defined and focused, providing a solid basis for the subsequent phases of the study.

### 3.3 Descriptive Study-I

In the DRM, the second stage following the completion of RC is known as Descriptive Study-I (DS-I). This phase focuses on gaining a deep understanding of the current landscape within the research area. DS-I involves conducting empirical studies and a thorough literature review on producer mobility, which is critically analysed to extract meaningful insights.



Through this comprehensive analysis, we gain valuable perspectives on producer mobility management and explore existing solutions within the context of producer mobility in NDN. The DS-I phase comprises five iterative steps that facilitate the development and refinement of the conceptual model, as illustrated in Figure 3.3. These steps are essential for enhancing the model's performance and ensuring it effectively addresses the challenges identified in the previous stages.

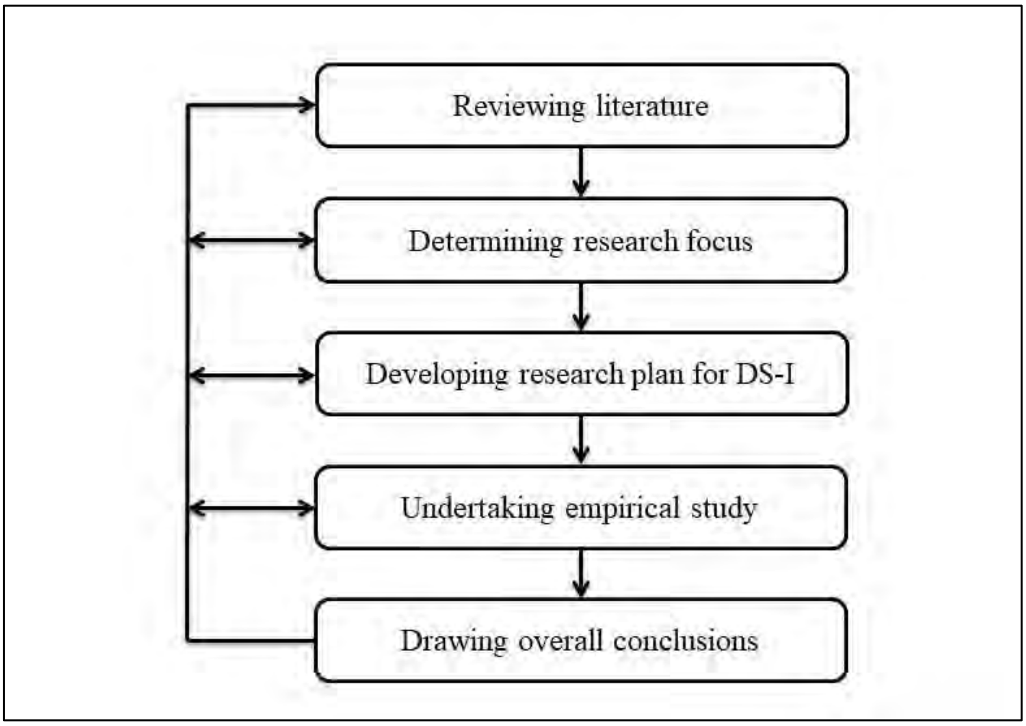



*Figure 3.3.* Descriptive Study-I (DS-I) [68]



The DS-I stage has the following deliverables steps for this research:

- Conduct a systematic and comprehensive study of existing producer mobility support solutions.
- Critically analysed the current mechanisms for supporting producer mobility to identify their strengths and weaknesses.
- Uncover significant challenges experienced in producer mobility and propose a new conceptual model designed to efficiently manage producer mobility in NDN.

### 3.3.1 Conceptual Model of PMMM in NDN

By proposing the performance model and critically analysing the existing solutions of the producer mobility in NDN, some factors are identified that need to be improved such as Interest packets loss, handoff latency, packet delivery ratio and throughput. Therefore, a Producer Mobility Management Model (PMMM) to enhance the producer mobility in NDN is proposed to improve the present situation and maximize the performance as compared to existing producer mobility solutions. The proposed PMMM conceptual model is shown in Figure 3.4.

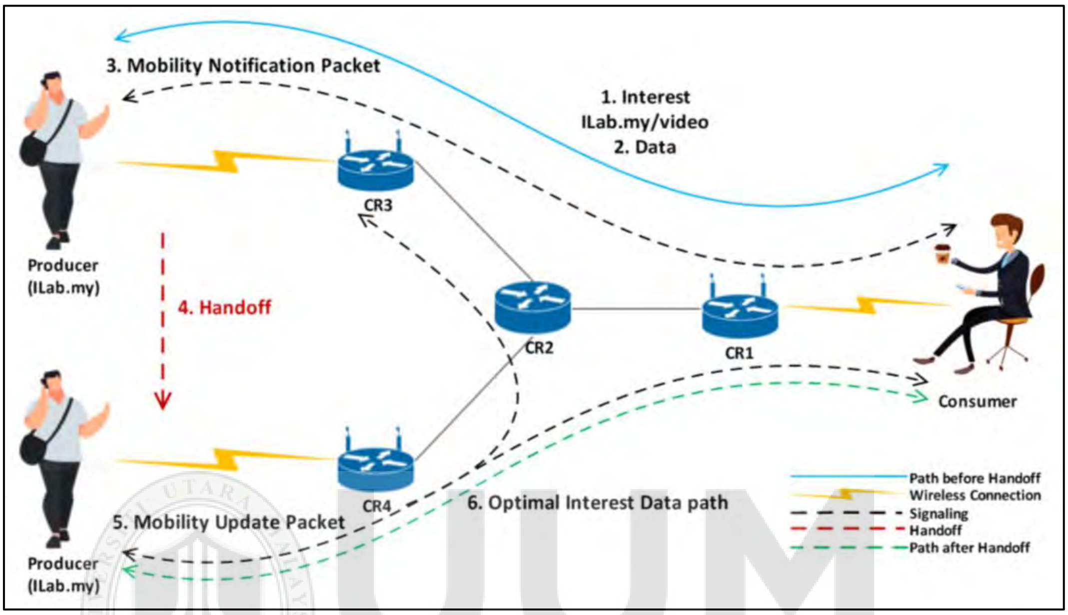



*Figure 3.4.* The Proposed Conceptual Model of PMMM



From Figure 3.4, When the consumer in the network sends an Interest packet, the Interest packet checks the initial router R1 CS. If the requested content is cached in the router, it forwards the content immediately, otherwise, Interest follows the FIBs and is forwarded to the next router. Further, the Interest looks up all on-path routers' CS before reaching to the producer location. Therefore, if the content is available, it forwards the content. Otherwise, Interest follows each router FIBs and moves to the producer location router. If the producer is available in the network, the Interest retrieves content easily. In a condition, if the producer is not available or in a state of handoff, the Interest waits for the producer until its time expires that leads to Interest packet loss and more latency. Moreover, the consumer retransmits the Interest to the retrieved content that leads to unnecessary packet loss, high signalling, and downgrades the overall network performance.

In brief, as an outcome of addressing producer mobility in NDN, the conceptual model of PMMM designs to describe the expected desires by proposing a model. In order to reduce packet loss, high signalling cost, and triangular routing in producer mobility, this research designs a model that will overcome the mentioned issues. The design consists of mobility management packets that help to notify the consumer and network about the producer mobility and availability as well as lessen in the aforementioned producer mobility issues. Moreover, modify the NDN forwarding data structure by adding two different fields to differentiate between the normal Interest data packets and mobility management packets.

By referring to Figure 3.4, according to the conceptual model, to manage producer mobility, when the producer disassociates from its current location router CR3, a Mobility Notification Packet (MNP) moves towards the consumer location CR1. The consumer on receiving the MNP packet pauses the Interest packet generating event according to the MNP instruction. After the completion of the handoff process, the producer associates to a new location router at CR4. The producer in association at CR4 sends Mobility Update Packet (MUP) to update the producer availability and enable the consumer to send Interest packet in network. Thus, the consumer Interest packet moves from CR1 to the producer's new location router CR4 that shows an optimal route.

By referring to Figure 3.5, that shows the working of PMMM and the extend data structure of NDN on each router. To notify the consumer about the producer's accessibility or presence in the network, the producer sends an MNP packet with a status value of 0 and a packet type of "mobile" when it detects a weak signal strength. This packet is then forwarded to the consumer. When the forwarding layer encounters a packet with a status value of 0, it follows additional functions specific to handling such packets. Upon receiving an MNP packet with a packet type of "mobile," the consumer temporarily suspends the generation of Interest packets for the corresponding producer prefix.

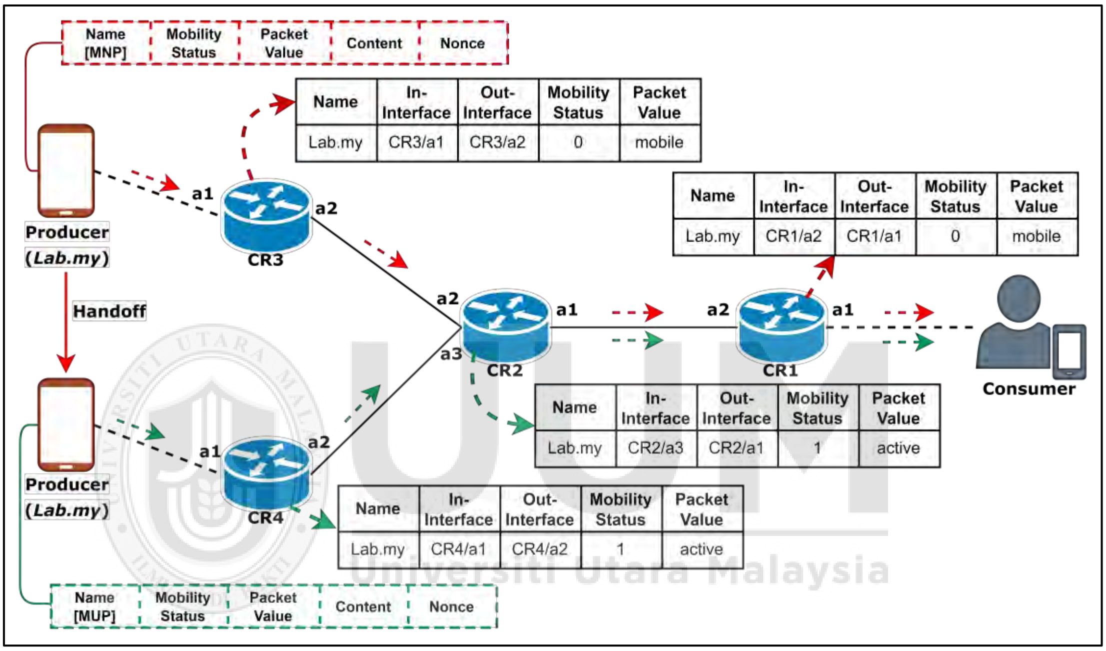



*Figure 3.5.* Mobility Management Packets Dissemination in PMMM Data Structure

On the other hand, when the producer finds a strong signal and attaches to a new access point, it broadcasts an MUP packet with a status value of 1 and a packet type of "active." This packet notifies the forwarding layer about the producer's new location. Upon receiving a packet with a packet type of "active" and a status value of 1, the forwarding layer executes additional functions to update the producer's new location information in the network. Furthermore, when the consumer receives a packet with a packet type of "active," it resumes communication for the specific producer prefix. This model enables efficient communication between producers and consumers in dynamic network environments. It allows producers to inform consumers about changes in their accessibility and triggers appropriate actions in the network to ensure seamless connectivity and data delivery.

### 3.4 Prescriptive Study

After the completion of DS-I, the third stage of DRM is known as a Prescriptive Study (PS) that is a purposeful activity with the resulting support. To achieve the objectives of this research, network modelling and simulation process are followed [71]. According to this research work, the main steps are guided into the prescriptive study as shown in Figure 3.6.

From the perspective of this DRM stage, this research encompasses several fundamental steps. It begins with the proposed PMMM to be modelled. The next step involves the development of the modelling framework, which includes problem analysis, objective determination, and a comprehensive literature review. Additionally, it incorporates analytical modelling to systematically evaluate the interactions and dynamics within the PMMM framework. This step is crucial for identifying key variables and their relationships, thereby enhancing the understanding of the model's behaviour. Furthermore, the process includes assumptions, parameters, and detailed knowledge presentation to minimize the complexities associated with the proposed PMMM model.

The next three consecutive steps focus on developing algorithms for the proposed PMMM and implementing a model that relies on selecting the most suitable simulation environment within the NDN framework. This implementation is critical for effectively testing the model's functionality and performance. Finally, the last step addresses the validation and verification of the proposed PMMM, ensuring that it meets the intended requirements and performs as expected. The key deliverables of the PS stage include:

- Chapter Four and Five
- Analytical modelling of the proposed PMMM.
- Design and implementation of the proposed PMMM.
- Validation and verification of the proposed PMMM.

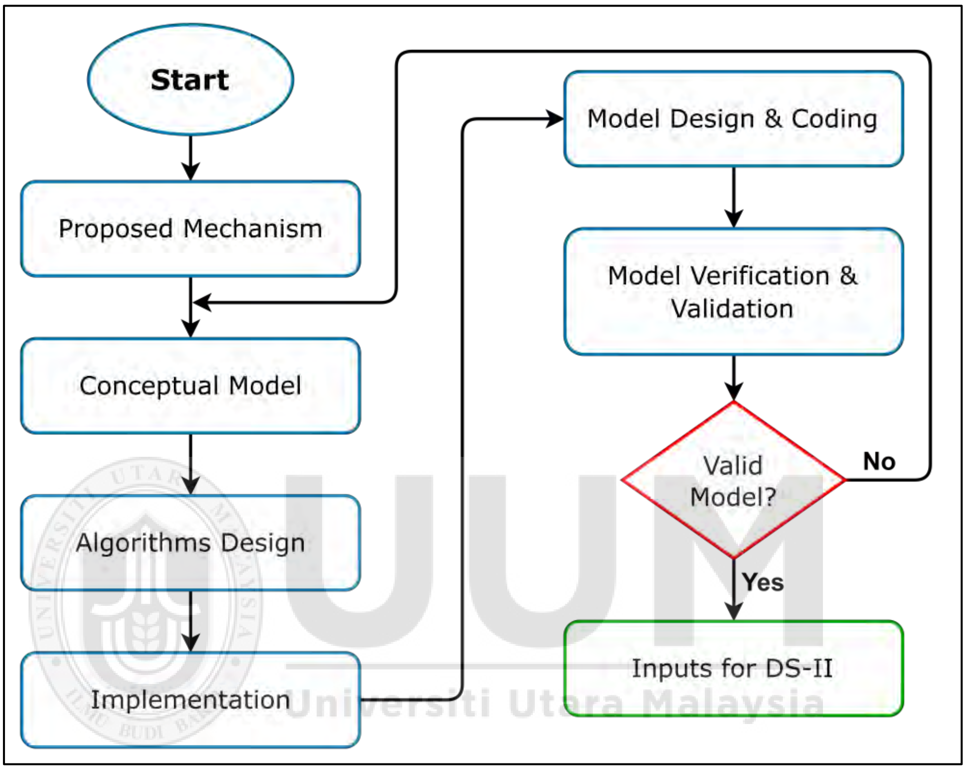



*Figure 3.6.* Prescriptive Study (PS) Steps [71]

### 3.4.1 Verification and Validation

Verification and validation are the process to verify the accuracy and precise the results for specific purposes. In addition, to ensure that it expresses in real-world entities that are appropriate to the expected goal for the proposed number of objectives. Verification is the process to examine that a prototype, parts of prototype and simulation as well as their results exactly represent the developer's explanation and accuracy of the conceptual model within its domain. While validation is to determine the prototype, parts of prototype and simulation as well as their results closely related to the real world from the perception of their expected use [72]. Simulation involves the use of computational models to replicate the behaviour of a system under various conditions. By running simulations, we can observe how a mobility management strategy performs in realistic scenarios, allowing us to identify potential issues and refine our approaches without the risks associated with real-world testing. Thus, this study has several steps that provides the correct assumptions of the PMMM model implementations. This involves evaluation of the simulation program to ensure that the conceptual PMMM exactly fulfils the requirements. For the verification of the conceptual model, we execute onto the NDN simulator that ensures the design and accuracy of the proposed PMMM. The validation is determined by the exactness in the output of the simulation model of PMMM and checks if it is working according to its intended purpose or not.

Analytical methods, on the other hand, involve mathematical modelling and analysis to derive performance metrics and validate assumptions. This approach enables us to establish theoretical bounds and predictions for system behaviour, ensuring that our simulation results align with established principles. Therefore, prior to the simulation process, the conceptual model of the proposed PMMM is analytically formulated and implemented using the Python programming language within the Visual Studio (VS) environment.

The VS facilitates the development of a tailored environment for the PMMM, enabling effective verification and validation of the conceptual model and integrated with the Python. It offers robust features for code editing, testing, and debugging, ensuring the accuracy and integrity of both the code and the design of the PMMM. This implementation process ensures the reliability and accuracy of the PMMM before proceeding to simulation.

Together, these methods provide a comprehensive framework for V&V, ensures that our findings are both robust and reliable. By combining empirical data from simulations with analytical insights, it confidently assesses the performance and effectiveness of proposed PMMM.

## 3.5 Descriptive Study-II

Upon completing the PS stage, Descriptive Study-II (DS-II) emerges as the final and most critical phase, focusing on the design of the PMMM. This stage integrates various concepts and parameters to create a robust model for the research. In DS-II, the primary emphasis is on evaluating the proposed PMMM, which entails three distinct approaches: analytical modelling, empirical measurements, and simulation. Each of these approaches plays a vital role in assessing the model's effectiveness and ensuring its alignment with the research objectives.

### 3.5.1 Performance Evaluation Approaches

In research, selecting an appropriate performance evaluation approach is the most essential part of the communication network. There are three different approaches for performance evaluation classified into analytical modelling, measurements, and simulation as shown in Figure 3.7.

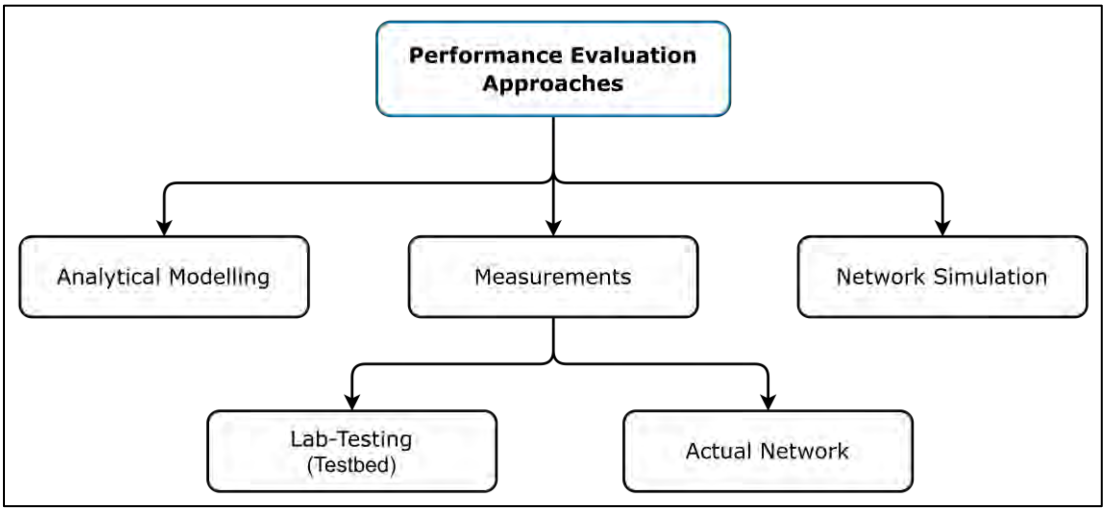



*Figure 3.7.* Performance Evaluation Approaches [73]

In the performance evaluation approach, analytical modelling serves as a technique that expresses the performance of the communication network system through mathematical equations and symbols. This method involves designing, solving, and validating the analytical model of the proposed PMMM, ensuring that it accurately captures the system's behaviour and performance characteristics. By employing analytical modelling, researchers can systematically analyse various scenarios and derive insights that inform the optimization of the PMMM. Furthermore, it examines and describes the solution for specific problems in the system [74]. This technique seems beneficial and helpful for the communication network system before the actual implementation process.

The measurement is a second performance evaluation approach that is sometimes known as an experimentation approach. This approach calculates the performance of real prototype of a communication protocol or communication network system. Generally, in this approach, researcher designs the prototype of communication network system and uses testbeds for testing purposes, and further, implements them in actual network by constructing real networks scenario to test and measure the performance of system [75].

To perform these network scenarios, the researcher needs to collect detailed information and expertise about the specific advanced network measurement software and hardware. However, building the network scenarios according to the prototype or communication network system and measuring their performance is highly time-consuming and financially more expensive in terms of money as compared to other performance approaches. In addition, testbeds are more challenging and create problems when need to modify or reconfigure.

The simulation is a well-established method for performance evaluation, commonly utilized in research and performance measurement. This approach involves creating a computerized model of a system using programming languages. The model realistically represents various devices, systems, and equipment, allowing for detailed analysis and assessment of performance metrics [76].

Simulation opens the doors for researchers and provides a more convenient platform to execute experiments and measure performances without interruption in the actual network system. In addition, it provides the facility to analyse the model performance that is a controllable, repeatable and scalable environment [77]. Moreover, simulation is efficient in terms of finding bugs or errors in designing and economical in terms of money as well as less time taking as compared to other approaches [75] as shown in Figure 3.8.

| Criterion | Analytical Modeling | Simulation | Measurement |
|---|---|---|---|
| Time Required | Less | Medium | High |
| Tools | Analysts | Computer languages | Instrumentation |
| Accuracy | Less | Moderate | High |
| Trade-off evolution | Easy | Moderate | Difficult |
| Cost | Less | Medium | High |

*Figure 3.8.* Comparison Between Performance Evaluation Approaches [78]

To achieve a higher level of satisfaction with the PMMM, this research selects both analytical modelling and simulation as key performance measurement. Analytical modelling allows for a systematic examination of the PMMM's performance, while simulation provides a practical approach to test and refine the model under various scenarios. Together, these methods enhance the robustness and reliability of the PMMM, ensuring it effectively meets the desired objectives.



### 3.5.2 Network Simulators

In-network research, various simulators are used for designing models, development, prototyping, and testing purpose. Furthermore, the simulation environment provides the facility to modify the developed model as well as re-evaluate until achieving the desired results and support to analyse or explore the complex network scenarios. A variety of network simulators is developed for simulation purpose and performance measurement, but the most popular available simulators are Network Simulator Version 3 (NS-3), Objective Modular Network Testbed in C++ (OMNeT++), and NDN simulator (ndnSIM).

**Network Simulator Version 3**

NS-3 is the discrete-event network simulator which is primarily developed for research purposes on Internet and for other network communication systems [79]. NS-3 is derived from the Network Simulator Version 2 (NS-2) that has several advanced functionalities and facilities to maintain codebase. Its design assists coding style, modularity, documentation and improves scalability as well as supports C++ and Python languages. Furthermore, its architecture provides advance features in the simulation that reduces the need to port or rewrite tools and models. Additionally, it supports open-source networking software such as packet trace analysers, kernel protocol stacks and routing daemons [80].

It offers features such as log, output trace files with statistics and animation for convenient performance evaluation. NS-3 is open source free software that is effortlessly maintainable, extensible and understandable for researchers, industry and educational groups [79]. Moreover, it can be easily installable in different environments such as OS X, Linux, Solaris, and Windows OS as well as can support for either server or desktop platforms. Furthermore, it integrates with the several networking modules.

**NDN Simulator**

The ndnSIM is an open-source simulation package platform that enables the research group or user's to efficiently simulate the basic NDN protocol operations and supports to run large scale simulation experiments. It provides the network-layer experiments with congestion management, data caching, routing and packet forwarding. The ndnSIM is based on the NS-3 platform and efficiently supports the NDN network's basic design components and features by using C++ programming language. Furthermore, it enables to design simulation topologies and specify parameters such as link bandwidth and link delays. The ndnSIM can be used for available modules, NetDevice implementations, and models.

The ndnSIM combines the ndn-cxx codebases with Named Data Networking Forwarding Daemon (NFD) to understand the core NDN forwarding function and application experiments. However, the result of this integration allows researchers and developers to implement multiple simulation scenarios with different strategies and evaluate them in real-world applications [81]. Moreover, several researchers use the ndnSIM for this research area. Therefore, the ndnSIM platform is selected to implement the simulation of the proposed design.

### 3.5.3 Network Simulation Steps

This stage describes the different steps for simulation performance evaluation. Due to this reason, it has been divided into eight steps by earlier researchers. Mainly, this research follows the two stages that are pre-software stage and software stage as shown in Figure 3.9 [82].

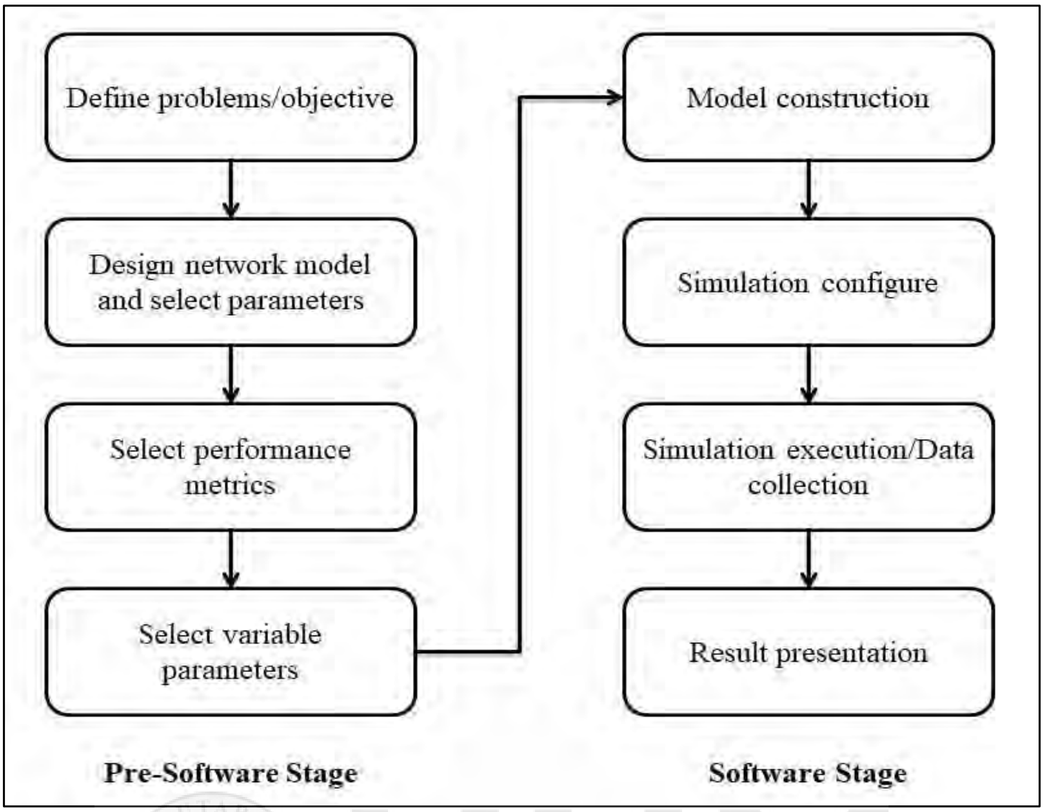



*Figure 3.9.* Simulation Steps

**A. Pre-software Stage**

This stage has four different steps.

1. To correctly define the research objectives.

2. To create a network model and define parameters: this step describes the network topology, draws on a paper, and selects the network parameters that seemed to be valid and real scenario. Further, Table 3.1 shows simulation parameters and values.

3. To choose the performance metrics for the evaluation of the proposed model.

4. To choose the variable parameter for performance metrics.

**B. Software stage**

This stage contains four consecutive steps:

1. To select an appropriate network topology and implement it into the simulator.

2. To configure the simulator according to the correct performance metrics.

3. To execute the simulator after the completion of simulation and collects the performance metrics data.

4. To interpret the presented result by using collected data.

Table 3.1

*Simulation Parameters and Values*

| **Parameters** | **Values** |
|---|---|
| Topology | Grid, Abilene |
| Mobility Model | Random Waypoint Mobility |
| Mobility Speed (ms) | 50-300 |
| Forwarding Strategy | Best Route |
| Interest packet size (bytes) | 56 |
| Data packet size (bytes) | 1024 |
| Number of the producers | 1 |
| Number of NDN routers | 16 nodes |
| Simulation time | 0.1x $N^2$ (N = Number of nodes) |
| Application | Consumer/Producer |

By referring to Table 3.1, it shows the simulation parameters and values that are taken from the previous research [28, 29, 35]. The simulation parameters and their values are carefully chosen to reflect realistic network conditions and assess their impact on performance of the PMMM. The topology, featuring both Grid and Abilene structures, provides a structured yet realistic environment for analysing routing and data transmission patterns in communication. Both topologies, which are commonly employed in benchmarking studies to accurately represent real-world conditions. Additionally, both reflect actual network environments along with relevant simulation parameters. The mobility model, specifically Random Waypoint Mobility, mimics unpredictable movement dynamics, allowing the simulation to capture how nodes behave in real-world scenarios. The mobility speed, ranging from 50 to 300 m/s, is designed to evaluate different movement scenarios, from pedestrian to high-speed vehicular, affecting route stability and packet delivery rates.

The forwarding strategy of using the Best Route is effective for ensuring efficient data delivery based on the shortest path, although it may struggle to adapt to rapid changes in network topology due to high mobility. The Interest packet size of 56 bytes minimizes overhead, enabling efficient resource use, while the data packet size of 1024 bytes balances transmission efficiency with sufficient payload, though larger packets may increase loss risk under mobility.

Having a single producer simplifies the analysis by focusing on data flow from one source to multiple consumers, while the 16 NDN routers provide a moderate level of complexity, allowing for meaningful insights into routing efficiency and congestion. The simulation time, set at 0.1 times the square of the number of nodes, ensures a thorough examination of network dynamics over multiple interactions. Finally, the consumer/producer application model closely mirrors real-world scenarios, affecting traffic patterns and ultimately influencing key performance metrics like latency and throughput. Collectively, these parameters shape the simulation's ability to reflect and analyse network performance under varying conditions.

The comparison of this research work will be with PMSS [35, 83, 84] and KITE [29, 85]. Furthermore, this stage describes the designing and implementation of the proposed model by using the ndnSIM simulator. The reason is that ndnSIM is an NS-3 based NDN simulator that is specifically designed for execution of NDN experiments in real world environment. The ndnSIM provides NDN packet format and NDN C++ library with experimental extensions. For forwarding in NDN, ndnSIM provides free source code of NFD. The ndnSIM supports the network-layer, transport layer and the link-layer protocol models such as point-to-point and wireless. Moreover, it provides visual effects, helpers to trace and track the traffic flow and the performance of NDN components. C++ and Python programming languages are available for implementation, and simulation for different scenarios. For experimental design, it starts with network topology that contains the consumer, intermediate routers, and the producer. Then, configures the FIBs, content store, forwarding strategy and installation of NDN stack. Hence, among all the simulators, ndnSIM is more suitable and fulfils all the necessities for this research work. Moreover, the previous research simulation on the producer mobility in NDN is conducted by using ndnSIM [28, 29, 35, 50].



### 3.5.4 Performance Metrics

The proposed model simulated and analysed, and its performance is compared with the KITE and PMSS. Different research proposals have used several performance metrics in the literature to measure the efficiency of the proposed model such as Interest packet loss, handoff latency, data packet delivery ratio, and throughput are popular and have more impact in the network. By focusing on handoff latency, signalling cost, Interest packet loss, data packet delivery, and throughput, the research aims to provide a comprehensive assessment of network performance in mobile environments. These metrics are interrelated and together offer valuable insights into how well the network can adapt to the challenges posed by mobility.

Ultimately, the findings able to inform the development of more robust and efficient networking protocols that enhance the performance in dynamic conditions.

### Handoff Latency

Handoff refers to a procedure that allows the mobile producers in the network to relocate by disconnecting from the current Point of Attachment (POA), and then connects to another or neighbour POA. Handoff Latency is the time interval where the mobile producer disconnects from old POA and connects to the new POA, or the time to complete the mobile producer relocation in the network is known as Handoff Latency. The shorter the time interval to complete the relocation of the mobile producer, the better in the performance.

### Signalling Cost

The handoff processes in network communication involve the transfer of packets between different network nodes or devices. During these processes, a significant number of packets are typically sent over the network to ensure seamless connectivity and uninterrupted data transmission between the transitioning devices. However, increase in the signalling cost lowers in the network performance.

### Interest Packet Loss

The number of Interest packets are lost during the consumer and the producer handoff process. The Interest Packets losses minimize the overall performance of the network. Hence, lesser Interest Packets loss in the network refers to betterment in the performance.

**Data Packet Delivery**

The total number of data packets are received by the consumers in response by sending Interest packets towards the Producer. This metric reflects its clear relationship with Interest packets loss during the handoff process. The maximum delivery of data packets leads to better performance.

**Throughput**

Throughput is the average measurement of data packets received in the time of interval during network communication. Higher throughput shows betterment in network performance.

$$\text{Throughput} = \frac{\text{Total number of the received packet}}{\text{time}}$$

### 3.6 Summary

This chapter explains, in briefly, the plan to conduct this research and ensures to achieve the objectives of this research. Through in-depth study on the producer mobility issues, it has proposed a PMMM to manage the producer mobility in NDN. Moreover, DRM is adopted for a better understanding and to conduct this research. To be more precise in this research, DRM is using four different stages: Research Clarification (RC), Descriptive Study-I (DS-I), Prescriptive Study (PS) and Descriptive Study-II (DS-II), the method and deliverable are also explained in this chapter.

RC is the first stage of DRM that addresses the research problems, research questions, research objectives, research scope and significance. DS-I is the second stage of DRM which includes designing and proposing a conceptual model. The PS is the third stage of DRM which discusses the method to design the proposed MMS scheme as well as defines the validation and verification methods. Lastly, DS-II is the fourth stage of DRM which describes the selection of valid ndnSIM simulator for this research and defines the simulation steps for performance evaluation. Moreover, it explains the performance metrics handoff latency, Interest packet loss, data packet delivery and throughput.

# CHAPTER FOUR

# ANALYTICAL MODELLING OF PRODUCER MOBILITY MANAGEMENT MODEL

This chapter delves into the formulation and exploration of the PMMM within the realm of NDN. The PMMM, visually demonstrated through the graphic representation of the DRM, is presented as a comprehensive conceptual model, systematically examined and methodically developed. The intricacies of PMMM are further dissected through a rigorous network analytical model. When a producer relocates to a new router, consumers face difficulties accessing Interest packets directed towards the content producer. This process significantly affects network performance, creating setbacks like high handoff latency, increased signalling costs, and inefficient data packet delivery. To address these complications, we've implemented a graphical depiction of DRM to propose and scrutinize the PMMM conceptual model. This model serves as an extension of well-established theories drawn from existing literature, thus offering an advanced approach towards managing high handoff latency and signalling costs. Additionally, we have applied the hop count technique to establish an analytical model of PMMM, in conjunction with IBM, PMSS, and KITE. The performance of the proposed PMMM, as well as its associated systems, has been thoroughly assessed and validated, contributing to a robust evaluation. In essence, this chapter sheds light on the design analysis of the conceptual model, the formulation of the analytical model, and evaluates the performance of the handoff process of PMMM. Furthermore, it outlines the development and execution of the model for PMMM and current schemes, thereby portraying a detailed depiction of the state of art in producer mobility management.

## 4.1 Conceptual Model Analysis

In the field of networking design, the DRM approach is highly helpful for formulating models, theories, or concepts as well as for validating tools and procedures. The DRM suggested using graphical network representations of network affecting elements for the conceptual model illustration and explanation, which consists of two alternative models. Reference and Impact models are used to describe the current and ideal scenarios for proposing support or a solution. Figure 4.1 depicts the graphical conceptual model known as the initial reference model, which presents the concept of PMMM that was obtained from the literature. The challenges that prevent producers in NDN from moving freely are depicted in Figure 4.1. The depicted figure expresses the factors that affect the producer mobility.

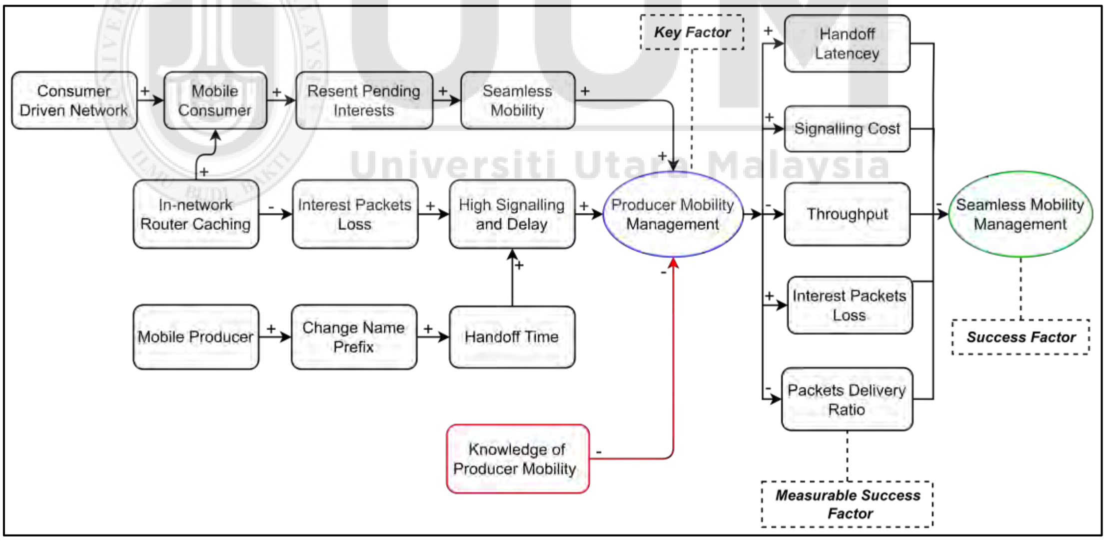



*Figure 4.1.* Initial Reference Model of Mobility Management in NDN

The initial reference model representing the existing issues in producer mobility and the impact model states the solution or a concept of PMMM in order to solve the producer mobility issues.

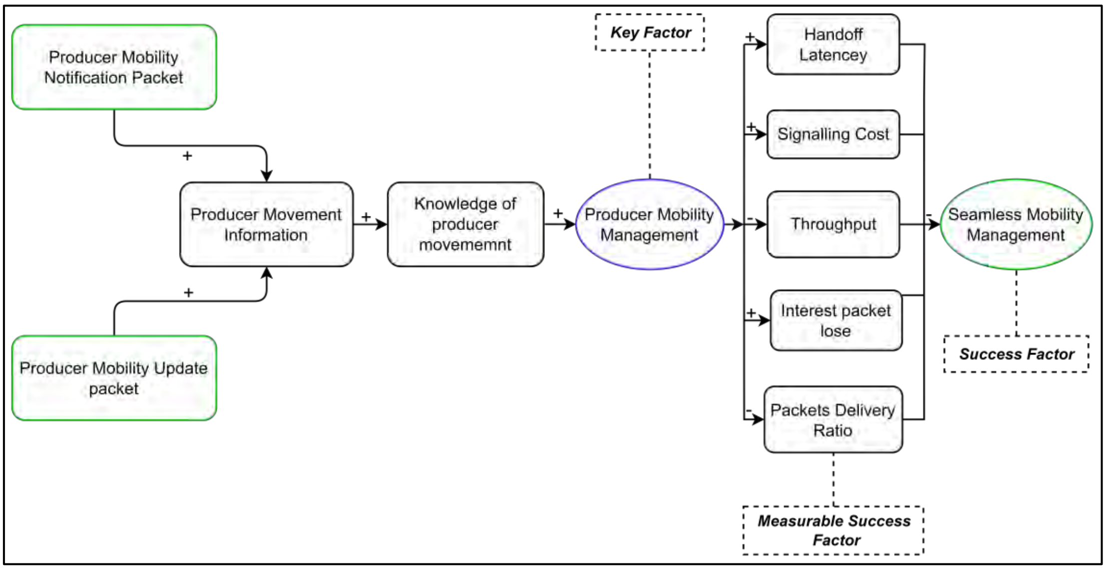



*Figure 4.2.* Impact Model Representation of PMMM Conceptual Model

By referring to Figure 4.2 that introduced to two different packets to manage producer mobility in NDN. The Mobility Notification Packet (MNP) and the Mobility Update Packet (MUP) are crucial for effectively managing producer mobility in networks, significantly minimizing signalling costs and reducing handoff latency. The MNP is initiated by the producer during relocation, serving to inform specific consumers of the producer's temporary unavailability. By doing so, it pauses ongoing requests from these consumers, preventing unnecessary retries and thus reducing signalling traffic. Once the producer connects to the new network, it broadcasts the MUP, which notifies the entire network of its new location. This prompt updating allows consumers to quickly resume their content requests, minimizing delays and enhancing the content retrieval rate. Together, the MNP and MUP facilitate a seamless transition during producer mobility, ensuring efficient communication and a better user experience by coordinating the flow of information and managing signalling traffic effectively.

The influential factor is classified into four different groups including key factors, success factor, measurable factor, and supportive influential factors. All these factors have link to one another which determines the attribute and features influenced by the relating factor. Further, the links also demonstrate how each factor was expected to have a direct impact on the others. As a result, before the formation of the analytical model, the factors for the initial reference and impact model or PMMM conceptual model will be examined.

### 4.1.1 Factor Analysis

The factor is a representation of an existing or desired state that affects other aspects of the situation. The factors are derived from experience, research objectives, literature analysis, and assumptions. Moreover, related factors reflect a particular situation that can be evaluated using quantifiable success factor. The factors are classified as follows: core factor, success factor, measurable success. The core factor is producer mobility management, which is regarded as the fundamental or key issue that this research must solve by disclosing the whereabouts to the content provider mobile producer.

The success factor that PMMM offers following the completion and accomplishment of the research goal is support for the smooth mobility. The measurable factors refer to performance metrics which are used to quantify the outcome or results of proposed producer mobility model. The metrics are presented in Chapter three which are throughput, signalling cost, Interest packet loss, data packet delivery and handoff latency. Table 4.1 and 4.2 express both the Reference and Impact models, the factors' respective impact, components, and correlation are reported in table.

Table 4.1

*Measurable Reference Model Success Factors*

| Factor | | | Impact | Components | Correlation |
|---|---|---|---|---|---|
| **Core Factor** | **Measurable Factors** | **Success Factor** | | | |
| Producer Mobility Management | 1. Handoff Latency | Seamless Mobility | High | Interest loss and high signalling | + |
| | 2. Signalling Cost | | High | Producer mobility management | - |
| | 3. Throughput | | Low | Packet delivery | - |
| | 4. Interest Packets loss | | High | Change name prefix | + |
| | 5. Data Packet Delivery | | Low | Seamless mobility | - |

Table 4.2

*Measurable Impact Model Success Factors*

| Factor | | | Impact | Attributes | Correlation |
|---|---|---|---|---|---|
| **Core Factor** | **Measurable Factors** | **Success Factor** | | | |
| Producer Mobility Management | 1. Handoff Latency | Seamless Mobility | High | Mobility Support | + |
| | 2. Signalling Cost | | Low | Mobility Support | - |
| | 3. Throughput | | High | Packet delivery | - |
| | 4. Interest Packets loss | | Low | Knowledge of Producer mobility | + |
| | 5. Data Packet Delivery | | High | Mobility Update and Notification | - |



### 4.1.2 Influencing Factor Analysis

Figures 4.1 and 4.2 depict the graphical representation of conceptual model of producer mobility management issues and potential solution in NDN. Figure 4.1 refers to the initial reference model which depicts the associated issues with producer mobility. In order to solve the associated producer mobility management issues, Figure 4.2 presents the potential solution to manage producer mobility. Additionally, the specified factor with its impact, components, and correlation influences another factor results or raises the issues towards the producer mobility management.

Influencing statements obtained from various literature. The influencing factors of current state have been analysed with respect to leading statements which are obtained from several literature. For Example, the mobility of consumers is supported by in-network caching. Additionally, it is manageable due to the consumer receiver-driven nature of communication [1-5]. While the high signalling cost and excessive Interest packet loss during high handoff latency is a major issue. While the excessive Interest packet loss and high signalling is the major issue caused by the high handoff latency [6-10]. The Table 4.3 details the influencing factors of the initial reference model which shows the causes that majorly cause in order to producer mobility issue. When the producer handoff towards the new location, it assigned a new prefix according to the new location. The consumer and intermediate router are unaware of the producer's new prefix that causes Interest packet loss and high signalling. The consumer and intermediate routers are unaware of the producer's new prefix and consumer keep sending Interest packets towards the producer old location that causes Interest packet loss and high signalling. In NDN paradigm the change of producer prefixes due to its mobility is not updated in the network [9].

Table 4.3

*Influencing Factors Analysis*

| Influencing Factor | Factor | Persuasive statements | References |
|---|---|---|---|
| Consumer Driven Network | Mobile Consumer | Smoothly support consumer mobility via receiver-driven nature of NDN paradigm. | [1, 86-89] |
| Mobile Consumer | Re-send pending Interest | Unsatisfied Interest easily retrieved by producer through consumer re-Interest. | [87, 89, 90] |
| Re-send pending Interest | Supported Mobility | Resending unsatisfactory Interest packets Interest-based leveraging and seamless support for consumer mobile mobility. | [87, 89, 90] |

| | | | |
|---|---|---|---|
| In-network caching | Interest packet loss | Control excessive packet loss through NDN in-network caching feature. | [87, 89] |
| Producer Mobility | Change of name prefix | Producer movement to new location changes in its name prefix according to new location. | [23, 41, 87] |
| Handoff time | Excessive packets loss, high signalling and delay | Long handoff latency results in excessive packet loss, high signalling and delay | [23, 27, 41, 52, 89, 91] |
| Interest packets loss | High signalling cost and delay | Excessive packet loss influences high signalling cost and delay. | [27, 41, 89, 92] |
| Seamless mobility, | Producer mobility management in NDN | Seamless mobility and decrease in high signalling and delay, and the availability of knowledge concerning producer movement. | [27, 55, 89] |
| Producer mobility management for NDN | Handoff latency, Signalling Cost, Throughput, Interest loss, Packets delivery | Supportive producer mobility management reduces the high signalling cost and delay. | [27, 55, 89] |

### 4.1.3 Impact Model Analysis

Through influential factors analysis as shown in Table 4.3, it uncovers the several related issues such as high handoff signalling, Interest packet loss, poor data delivery, and high signalling costs are the major issues which are associated with the producer mobility. Additionally, the mentioned issues also directly impact on the other parameters such as bandwidth consumption, Interest retransmission and throughput. The higher in the signalling cost influences the high usage of bandwidth and reduces the overall network performance. Therefore, the impact model proposed a model in order to manage the producer mobility. The proposed model contributes two different factors to the network to monitor the producer movement information. The factors are Mobility Notification Packet (MNP) and Mobility Update Packet (MUP). These factors highly impact the influencing key factor to manage producer mobility, as in Figure 4.2.

The new mobility management packets MNP and MUP are introduced as a supportive influential factor similar to binding update packet, forwarding hint, mobility update, tracing and traced Interest. Additionally, the normal forwarding pipeline is upgraded by adding mobility packets in order to support the mobility management packets and to differentiate between the normal packets and mobility management packets.

Table 4.4 analyses the PMMM conceptual model shown in Figure 4.2, which is portrayed as an impact model in accordance with DRM. The table shows the impact of the proposed supportive factors for the NDN's solution to the mobility of content producer. They coordinate and contribute to impact the availability of information on producer movement to facilitate smooth mobility. This factor is known as producer movement information (update). Table 4.4 highlights the causes, assertions, and impacts. A correlation between persuasive statements and anticipated effects are used to assess the influencing aspects of the desired situation. Furthermore, included are the specifics of the analysis for the impact model's supportive influencing factors.



### 4.2 Delving into Conceptual Model Analysis

Based on DRM graphical representation analysis of PMMM conceptual model described in Tables 4.3 and 4.4, this study found that producer mobility management issues in NDN are caused by producer mobility problems in NDN not knowing whereabouts of mobile producer's new location and due to change of hierarchical name prefix. The five measurable success factors Handoff Latency (HL), Signalling Cost (SC), Interest Loss (IL), Throughput (TH), and Packet Delivery (PD), which can be quantified based on the value of their linkage indicators, can also be evaluated in order to anticipate the outcome. To demonstrate the levels or degrees of influence for creating seamless mobility, the linkages in Tables 4.1 and 4.2 are denoted as + (high) and - (low).

Table 4.4

*Influencing Factors Analysis*

| Supportive Influencing Factor | Factor | Persuasive Statement | Impact/ Outcome |
|---|---|---|---|
| Producer Mobility Notification Packet | Producer dissociation information | Proposed a new MNP to notify the network about producer dysconnectivity. | Notify the producer movement. |
| Producer Mobility Update Packet | Producer association information | Proposed a new MUP to update the consumer and intermediate routers about producer new location. | Update the consumer and intermediate routers |
| Knowledge of Producer Mobility | Producer mobility information | Consumer and intermediate router received producer mobility update. | Update the consumer about producer availability |
| Modify Forwarding plane to update Mobility information | Producer mobility update | Modify the forwarding plane to assist the mobility management packets to update the consumer about producer mobility. | Monitors the producer accessibility and inaccessibility |

By adding numerical values to signify high (+) and low (-) values of the measurable success criteria, Figure 4.3 illustrates the opposing behaviour between the Reference and Impact models. The graph for the Reference model demonstrates that the throughput of data packets would expressly decline to the lower level once the measurable success factors HL and SC are increasing higher. Moreover, the outputs of HL and SC have had a direct impact on Interest packet losses, leading to subpar data packet delivery. Nonetheless, according to the graph, HL and SC should be reduced for the Impact model to achieve a high TH for data packets. Hence, minimizing or reducing HL and SC had an impact on reducing on excessive IL and would result in great data packet delivery.

However, the development of an analytical model to evaluate the handoff latency and handoff signalling cost can be used to assess the analysis of influential factors that are drawn from the literature to support the graphical conceptual model shown in Figure 4.2. As a result, the hop count approach and a well-known network analysis model are employed to create the PMMM analytical model. The integration of the impact and reference models within the analytical framework is essential for effectively addressing the producer mobility problem. The analytical framework begins by establishing relevant parameters and values that guide the analysis, focusing on their significance to the producer mobility issue. It defines various performance metrics, such as handoff latency, signalling cost, and data packet delivery, to measure the impact model's effectiveness. Through a systematic, step-by-step analysis, the framework evaluates each performance metric in relation to the parameters set in the impact model while considering the challenges highlighted by the reference model. This integration aids in identifying gaps by comparing the outcomes of the impact model against the challenges of the reference model, allowing analysts to pinpoint areas where the proposed solution may fall short.



### 4.3 Network Analysis Model

A network analysis model was developed as in [23, 27, 52, 83, 91] is shown in Figure 4.4 for the formulation and the performance evaluation of the conceptual PMMM model. For the purpose of validating and performance benchmarking this research, the proposed PMMM, and others benchmarking principal approach IBM, and existing mobility schemes as KITE and PMSS are formulated. Through the literature review for this study, the producer mobility schemes that are currently in place were grouped under the IBM methodology (Chapter Two).

The network analysis model is depicted in Figure 4.4 and consists of a few nodes, including four (4) Content Routers (CRs), a server (DNS or rendezvous), a consumer, and a mobile producer. The four CR are the C-CR that connected to the consumer, the New-CR that connected by the mobile producer after the relocation, the Old-CR that was connected to it before the relocation, and the Anh-CR functioning as the anchor node. The network link used to transmit data between the nodes is identified by the hop count parameters denoted as $a, b, c$, and $d$.

The parameters are as follows: $a$ for latency and cost of packet transmission between consumer to CR ($L_{Con\_Cr}, C_{Con\_Cr}$), and $a$ also for latency and cost of packet transmission between producer to CR ($L_{Pro\_Cr}$, $C_{Pro\_Cr}$); $b$ for latency and cost of packet transmission between Old-CR and New-CR ($L_{Old\_NCr}$ and $C_{Old\_NCr}$); $c$ for latency and cost of packet transmission between CRs ($L_{Cr\_Cr}$ and $C_{Cr\_Cr}$); and $d$ for latency and cost of packet transmission between CR and server ($L_{Srv\_Cr}$ and $C_{Srv\_Cr}$).

Moreover, Table 1. details the parameters and their values, including their notation, and description. The parameters values are $a$ = 1, $b$ = 5, $c$ = 5, and $d$ = 9 as in [23, 52, 83, 91]. Further, the notations $S_{Int}$, $S_{Data}$, and $S_{name}$, respectively indicate the sizes of Interest packets, data packets, and any signalling packets.

The $S_{Packet\_name}$ in Table 1 provides names or labels for signalling packets that used for various purposes, such as querying, acknowledging, indicating mobility, tracing, facilitating fast handoff, deleting routes, creating routes, and so on. These packets have different subscript names to differentiate between them. In the case of modified Interest packets, the size of the packet is increased by 16 bytes from the size of a normal Interest packet. This is due to the additional information contained in the modified Interest packet. Encapsulated packets, such as query, update, and reply packets contain 32 additional bytes of information compared to normal packets. This extra information used for more detailed communication between devices to stable the network connection.

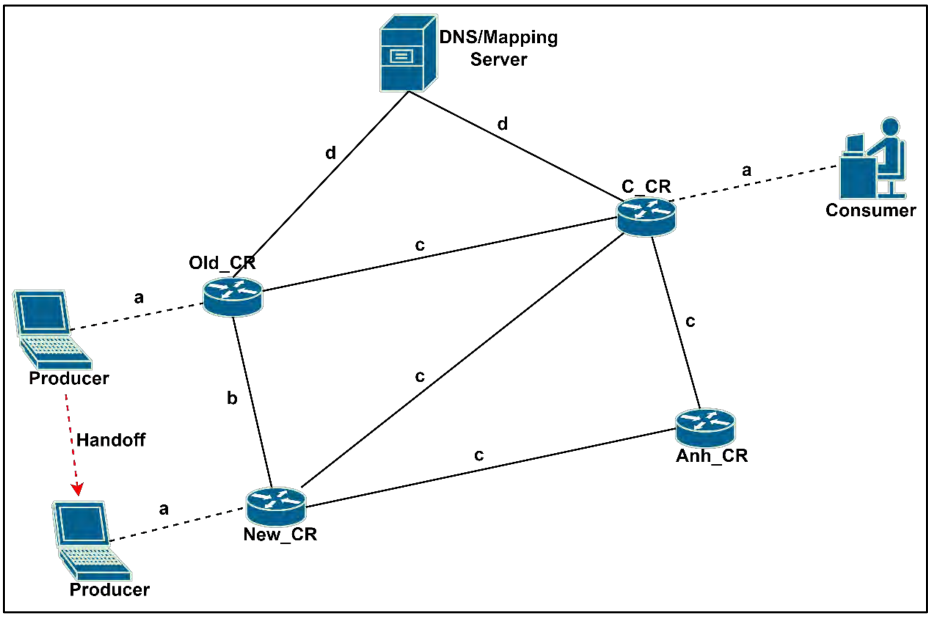



*Figure 4.3.* Network Analysis Model

The proposed PMMM, IBM, PMSS [83, 84], and KITE [29, 85] solutions incorporate the network analysis model and hop count parameters into their concept formulation. The hop count formulation is used to identify the performance of the network, which measures the handoff latency, handoff signalling cost, and packet delivery cost. The hop count technique is a significant concept for analysing various factors in networks, such as handoff latency, signalling costs, and path optimization. It effectively quantifies delays and signalling overhead, providing a practical means to evaluate the efficiency of path optimization in mobile communication. By measuring the number of hops a signal must traverse, this technique helps identify potential bottlenecks and optimize routing strategies, ultimately assist to enhance the network performance and user experience. During the development of the analytical model, several key assumptions affect the generalizability of the results. First, we rely on a simplified network topology consisting of a single producer and a single consumer to ensure model efficiency. While this arrangement facilitates clear analysis, it may not capture the complexities of larger, more dynamic networks. Additionally, we incorporate three distinct types of routers, each varying in position and operational mechanisms, to explore the impact of different routing paths. However, the limited number of routers restricts the applicability of our findings to more complex configurations. Furthermore, we assume that the results obtained from this small-scale setup can be extrapolated to larger networks, based on the premise that the underlying principles governing network performance remain consistent regardless of scale. Further, Table 4.5 explains the values that are being used for implementation.

Table 4.5

*Parameter Values of Network Analysis Model*

| Category | Notation | Parameter | Value |
|---|---|---|---|
| Packets | $S_{Packet\_name}$ | Size of signalling packet | +16 bytes |
| | $S_{Int}$ | Size of Interest packet | 40 bytes |
| | $S_{Data}$ | Size of data packet | 2000 bytes |
| Transmission Latency | $L_{Pro\_Cr}$ | Producer to CR | a = 1 |
| | $L_{Con\_Cr}$ | Consumer to CR | a =1 |
| | $L_{Srv\_Cr}$ | Server to new CR | d = 9 |
| | $L_{Old\_NCr}$ | Old CR to New CR | b = 5 |
| | $L_{Anh\_Cr}$ | CRs to Anchor | c = 5 |
| | $L_{Cr\_Cr}$ | CR to CR | c = 5 |
| | $L_{HF}$ | Time span of mobile producer after disconnection and reconnection | $l_{hf}$ |
| Signalling Cost | $C_{Pro\_Cr}$ | Producer to CR | a = 1 |
| | $C_{Con\_Cr}$ | Consumer to CR | a =1 |
| | $C_{Srv\_Cr}$ | Server to new CR | d = 9 |
| | $C_{Old\_NCr}$ | Old CR to New CR | b = 5 |
| | $C_{Anh\_Cr}$ | Anchor to CR | c = 5 |
| | $C_{Cr\_Cr}$ | CR to CR | c = 5 |

### 4.3.1 Hop Count Formulation for Handoff Latency Analysis

The hop count refers to total number of intermediate content routers through which an Interest and data packet must pass between the consumer and producer. Additionally, it measures the distance between two consecutive nodes, such as consumer, producer, content router, anchor router or server. Each content router associated with link delay, queuing delay, and bandwidth for both wired and wireless connection. Therefore, Equation (4.1) represents the total delay between two consecutive hops for wired link $L_{wd\_packet\_name}$ and Equation (4.2) shows the total delay between two consecutive hops for wireless link $L_{wls\_packet\_name}$.

$$L_{wd\_packet\_name} = \frac{S_{pn}}{B_{wd}+L_{wd}+Q_d} \tag{4.1}$$

$$L_{wls\_packet\_name} = \left(\frac{(1+q)}{(1-q)}\right) * \left(\frac{S_{pn}}{B_{wls}+L_{wls}}\right) \tag{4.2}$$



Where $B_{wd}$ and $B_{wls}$ are the bandwidth for wired and wireless link, $L_{wd}$ and $L_{wls}$ refers to link delay of wired and wireless, $Q_d$ is the queuing delay and $q$ represents the probability of link failure. The Equation (4.1) express the total wired link delay $L_{wd\_packet\_name}$ by computing the packets delay.

The packets delay includes the packet size or length $S_{pn}$ per wired bandwidth $B_{wd}$, the wired link delay $L_{wd}$, and the routers queuing time $Q_d$, are added to calculate the total wired link delay $L_{wd\_packet\_name}$ as expressed in Equation (4.1). Also, the packets delay includes the packet size or length $S_{pn}$ per wireless bandwidth $B_{wls}$, the probability of link failure $q$, and the wireless link delay $L_{wls}$, are added to calculate the total wireless link delay $L_{wls\_packet\_name}$ as expressed in Equation (4.2).

To account for the probability of a wireless communication link failing, both equations (Equations 4.1 and 4.2) for wired and wireless communication have been separated. This separation is due to the distinct operational differences between wired and wireless communications. Wired communications reserve all of the necessary bandwidth for successful communication prior to the start of packet transmission. However, in wireless communication, various factors including mobility, fading, spectrum allocation, and competing producers or consumers can degrade packet transmission. Therefore, the handoff latency is the entire amount of time that a content producer must wait between disconnecting, reconnecting, and the arrival of the first Interest packet through a new PoA. When a mobile producer moves, the producer's handoff latency can be measured when the producer disconnects from the old PoA and reconnects to the new PoA. As a consequence, the network analysis model in Figure 4.4, the parameters and values stated in Table 4.5, and the total delay for wired and wireless links represented in Equations (4.1) and (4.2) are used to build the hop count formulation of the proposed PMMM, IBM approach, PMSS, and KITE scheme solutions.

The IBM approach uses the home router or home agent as indirection point to redirects the packets towards the producer or consumer. When the mobile producer disconnects from Old-CR and connected to New-CR, it completes the $L_{HF}$ time Interval. The value of transmission latency of time interval $L_{HF}$ is represented by $l_{hf}$. The New-CR generates a binding update that consist of forwarding hint about the producer new location and forwards it towards the Old-CR that works as indirection point with the transmission latency between producer and router $L_{Par\_Cr}$, and between Old-CR and New-CR $L_{Old\_NCr}$. The indirection point acknowledges the binding update to New-CR and to producer with transmission latency $L_{Old\_NCr}$, and

$L_{Pro\_Cr}$ respectively. The consumer sends Interest packet to indirection point, the indirection point forwards the Interest packet towards the New-CR to the producer with the transmission latencies $L_{Con\_Cr}$, $L_{Cr\_Cr}$, $L_{Old\_NCr}$, and $L_{Pro\_Cr}$. After integrating the total wired $L_{wd\_packet\_name}$ and wireless delay $L_{wls\_packet\_name}$ for a wired and wireless link encountered in the formulation, Equation (4.3) is used to calculate the hop count handoff latency for IBM approach. The calculation took into account the mobile producer's overall handoff latency; it may be used to assess handoff effectiveness and measure how well the IBM technique supports seamless mobility.

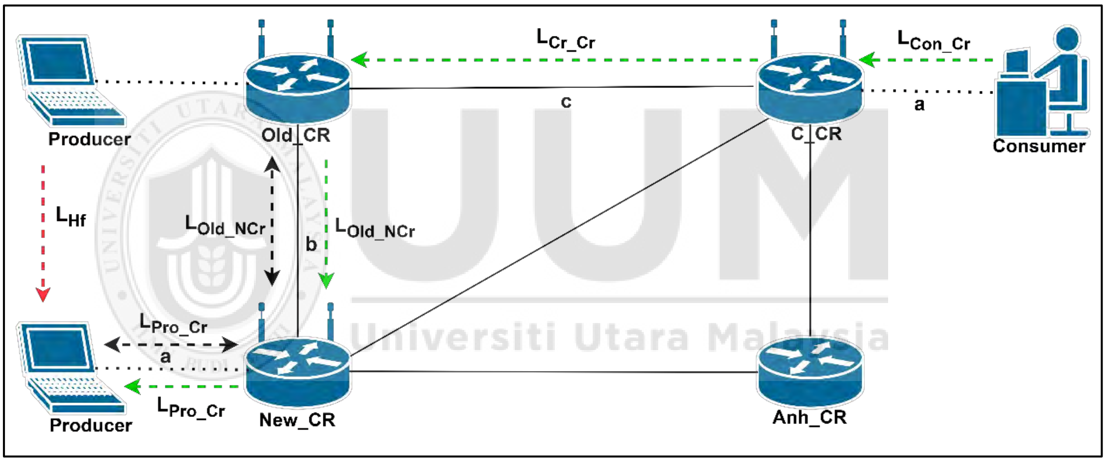



*Figure 4.4.* Handoff Latency Analysis in IBM

By referring to Figure 4.4 that shows the mobility of producer and messages patterns in IBM. After the producer handoff process, the producer sends message to New_CR, the New_CR forward message to Old_CR. While the Old_CR reply to New_CR, the New_CR further forwards the reply message to producer. The consumer sends new Interest packet to C_CR, the C_CR sends the packet to Old_CR, the Old_CR redirects the packet to New_CR and producer received the packet from New_CR.

$$L_{IBM} = HF + (Producer \rightarrow New\_CR) + (New\_CR \rightarrow Old\_CR) + (Old\_CR \rightarrow New\_CR) + (New\_CR \rightarrow Producer) + (Consumer \rightarrow C\_CR) + (C\_CR \rightarrow Old\_CR) + (Old\_CR \rightarrow New\_CR) + (New\_CR \rightarrow Producer)$$

$$L_{IBM} = L_{Hf} + L_{Pro\_Cr} + L_{Old\_NCr} + L_{Old\_NCr} + L_{Pro\_Cr} + L_{Con\_Cr} + L_{Cr\_Cr} + L_{Old\_NCr} + L_{Pro\_Cr}$$

$$L_{IBM} = l_{hf} + a + b + b + a + a + c + b + a$$

By substituting the total wired and wireless link delay in Equation (4.1) and (4.2), then:

$$L_{IBM} = l_{hf} + a \times L_{wls\_Up} + b \times L_{wd\_Up/Ack} + b \times L_{wd\_Up/Ack} + a \times L_{wls\_Up} + a \times L_{wls\_Int} + c \times L_{wd\_Int} + b \times L_{wd\_Int} + a \times L_{wls\_Int} \quad (4.3)$$

The Equation (4.4) express the handoff latency of PMSS scheme through hop count formulation. When mobile producer completes the handoff process by disconnecting form Old-CR and connected to New-CR, it completes the handoff by transmission latency time interval $L_{HF}$ which is represented by the value of $l_{hf}$. Then producer sends Mobility Interest (MI) to the New-CR, the New-CR update the mobility status and tag the MI packets to indicate the mobile producer content name with transmission latency $HL_{Pro\_Cr}$. Further, the New-CR sends the MI packet to anchor router Anh-CR, the anchor router broadcast the MI packet towards the network to update the routers with transmission latencies $L_{Anh\_Cr}$, and $L_{Cr\_Cr}$.

The consumer sends the Interest packet to the producer new location with transmission latencies between consumer to C-CR $L_{Con\_Cr}$, between C-CR to New-CR $L_{Cr\_Cr}$, and New-CR to producer $L_{Pro\_Cr}$. The hop count formulation of PMSS is presented in Equation (4.4). The equation took into account the mobile producer's overall handoff latency for the proposed PMSS. It is used to assess the effectiveness of handoffs and estimate the degree of seamless mobility support offered by the PMSS solution.

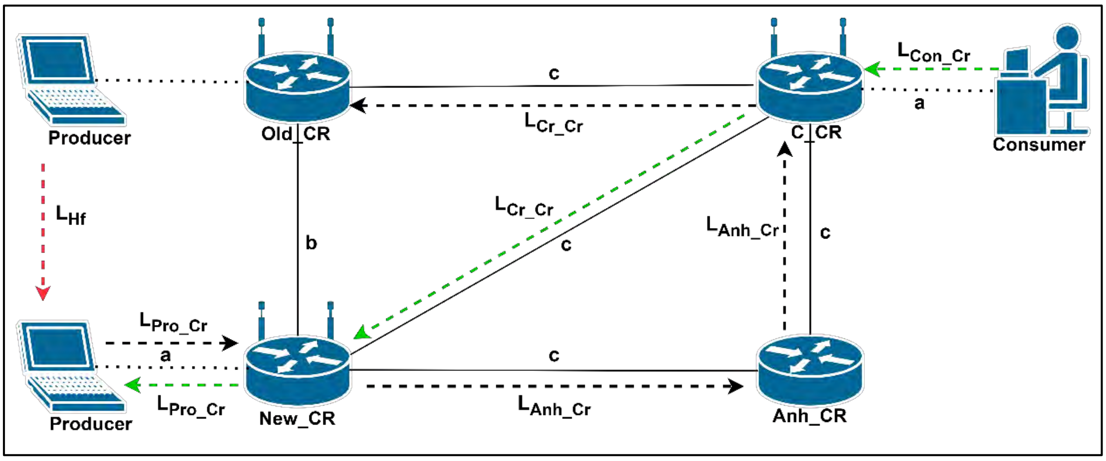



*Figure 4.5.* Handoff Latency Analysis in PMSS



By referring to Figure 4.5 that shows the producer mobility, producer, and consumer messages patterns in the network. After the producer relocation at New_CR, the producer sends packet to New_CR, the New_CR forwards the packet to Anh_CR, the Anh_CR broadcast the packet to C_CR and further it moves from C_CR to Old_CR. Hence, the new Interest packet moves from consumer to C_CR, the C_CR further forwards it to New_CR and from New_CR it reaches to producer.

$$L_{PMSS} = HF + (Producer \rightarrow New\_CR) + (New\_CR \rightarrow Anh\_CR) + (Anh\_CR \rightarrow C\_CR(Broadcast\ )) + (C\_CR \rightarrow Old\_CR(Broadcast)) + (Consumer \rightarrow C\_CR) + (C\_CR \rightarrow New\_CR) + (New\_CR \rightarrow Producer)$$

$$L_{PMSS} = L_{Hf} + L_{Pro\_Cr} + L_{Anh\_Cr} + L_{Anh\_Cr} + L_{Cr\_Cr} + L_{Con\_Cr} + L_{Cr\_Cr} + L_{Pro\_Cr}$$

$L_{PMSS} = l_{hf} + a + c + c + c + a + c + a$

By substituting the total wired and wireless link delay in Equation (4.1) and (4.2), then:

$$L_{PMSS} = l_{hf} + a \times L_{wls\_MobInt} + c \times L_{wd\_MobInt} + c \times L_{wd\_MobInt} + c \times L_{wd\_MobInt} + a \times L_{wls\_Int} + c \times L_{wd\_Int} + a \times L_{wls\_Int} \quad (4.4)$$

The hop count formulation of KITE scheme is presented in Equation (4.5). As the mobile producer completes the handoff process by disconnecting off the Old-CR and connecting to the New-CR, it completes the handoff by the transmission latency time interval $L_{HF}$, which is indicated by the value of $l_{hf}$. From the New-CR it exchanges the two different packets form the immobile anchor router to redirects the consumer Interest to the producer new location. Hence, it generates the trace Interest and trace data packets through New-CR to Immobile anchor router.

The transmission latency from producer to New-CR $L_{Pro\_Cr}$, New-CR to immobile anchor $L_{Anh\_Cr}$ and vice versa (call backs of trace Interest and trace data packet from immobile anchor). The consumer sends Interest packet to the connected router C-CR, the C-CR sends Interest to immobile anchor with transmission latencies $L_{Con\_Cr}$ and $L_{Anh\_Cr}$. The immobile anchor redirects the Interest packets to New-CR and New-CR forwards the Interest to the producer with transmission latencies $L_{Anh\_Cr}$ and $L_{Pro\_Cr}$ respectively.

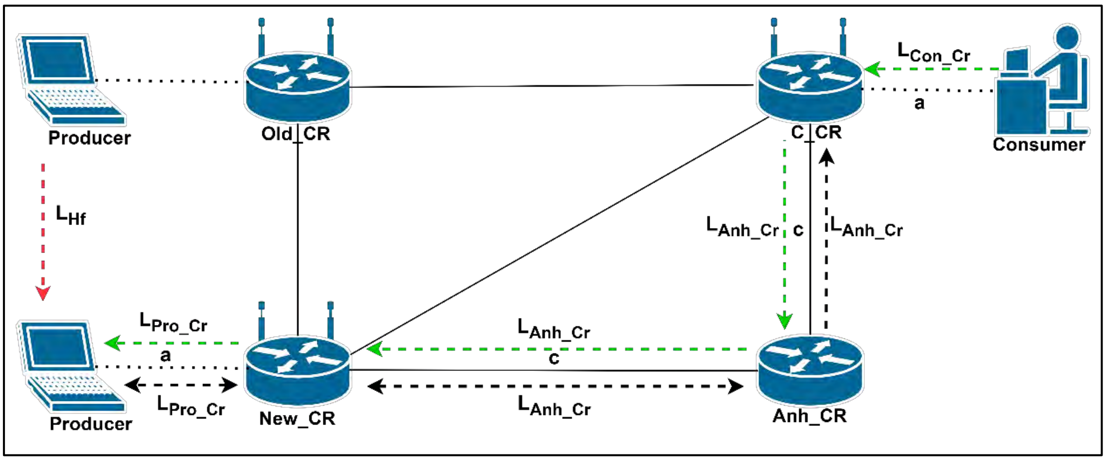



*Figure 4.6.* Handoff Latency Analysis in KITE

The Figure 4.6 shows that the producer exchanges the number of messages after the handoff process. The producer sends packet TI to New_CR, the New_CR forwards it to Anh_CR. The Anh_CR in response sends TD to New_CR, from New_CR it is received by the producer. While the consumer sends the Interest packet to C_CR, the C_CR forward the packet to Anh_CR. The Anh_CR redirects the packet to New_CR, from New_CR the packet is received by producer.

$$L_{KITE} = HF + (Producer \rightarrow New\_CR\ (TI)) + (Producer \rightarrow New\_CR(TD)) + (New\_CR \rightarrow Anh\_CR(TI)) + (New\_CR \rightarrow Anh\_CR(TD)) + (Consumer \rightarrow C\_CR) + (C\_CR \rightarrow Anh\_CR) + (Anh\_CR \rightarrow New\_CR) + (New\_CR \rightarrow Producer)$$

$$L_{KITE} = L_{Hf} + L_{Pro\_Cr} + L_{Pro\_Cr} + L_{Anh\_Cr} + L_{Anh\_Cr} + L_{Con\_Cr} + L_{Anh\_Cr} + L_{Anh\_Cr} + L_{Pro\_Cr}$$

$$L_{KITE} = l_{hf} + a + a + c + c + a + c + c + a$$

By substituting the total wired and wireless link delay in Equation (4.1) and (4.2), then:

$$L_{KITE} = l_{hf} + a \times L_{wls\_TraceIntData} + a \times L_{wls\_TraceIntData} + c \times L_{wd\_TraceIntData} + c \times L_{wd\_TraceIntData} + a \times L_{wls\_Int} + c \times L_{wd\_Int} + c \times L_{wd\_Int} + a \times L_{wls\_Int} \quad (4.5)$$

The hop count formulation of proposed PMMM is expressed in Equation (4.6). When mobile producer completes the handoff process by disconnecting from Old-CR and connected to New-CR, it completes the handoff by transmission latency time interval $L_{HF}$ which is represented by the value of $l_{hf}$. Then producer sends Mobility Update Packet (MUP) to the New-CR, the New-CR update the mobility status and broadcast the packet to the intermediate's routers with transmission latencies $L_{Pro\_Cr}$, $L_{Old\_NCr}$, and $L_{Cr\_Cr}$ respectively. Further, it updates the consumer to resumes its communication towards the producer new location with transmission latency $L_{Con\_Cr}$. The consumer sends the Interest packet from its connected router C-CR, from the C-CR the Interest packet moves to New-CR optimal path and further moves from New-CR to producer with transmission latencies $L_{Con\_Cr}$, $L_{Cr\_Cr}$, and $L_{Pro\_Cr}$ respectively.

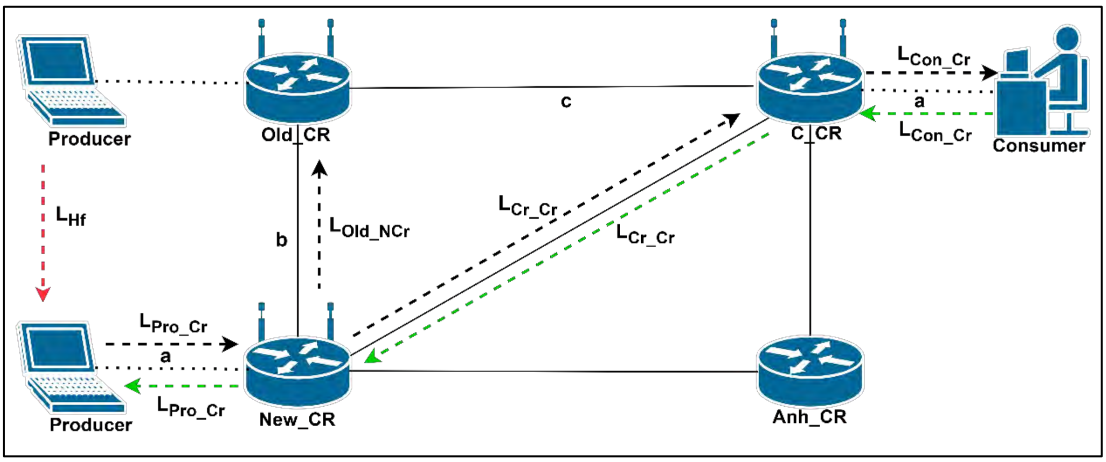



*Figure 4.7.* Handoff Latency Analysis in PMMM

The Figure 4.7 shows the packet exchange between the consumer and producer in network after the producer handoff. The producer sends the packet to New_CR, the New_CR broadcast the packet to Old_CR and also to C_CR. The C_CR further forwards the packets to consumer. The consumer sends an Interest packet to C_CR, the C_CR forwards the packet to New_CR. From New_CR the packet is received by the producer.

$$L_{PMMM} = HF + (Producer \rightarrow New\_CR) + \big(New\_CR \rightarrow Old\_CR(Broadcast)\big) + (New\_CR \rightarrow C\_CR(Broadcast)) + (C\_CR \rightarrow Consumer) + (Consumer \rightarrow C\_CR) + (C\_CR \rightarrow New\_CR) + (New\_CR \rightarrow Producer)$$

$$L_{PMMM} = L_{Hf} + L_{Pro\_Cr} + L_{Old\_NCr} + L_{Cr\_Cr} + L_{Con\_Cr} + L_{Con\_Cr} + L_{Cr\_Cr} + L_{Pro\_Cr}$$



$$L_{PMMM} = l_{hf} + a + b + c + a + a + c + a$$

By substituting the total wired and wireless link delay in Equation (4.1) and (4.2), then:

$$L_{PMMM} = l_{hf} + a \times L_{wls\_MobInt} + b \times L_{wd\_MobInt} + c \times L_{wd\_MobInt} + a \times L_{wls\_MobInt} + a \times L_{wls\_Int} + c \times L_{wd\_Int} + a \times L_{wls\_Int} \quad (4.6)$$

### 4.3.2 Hop Count Formulation for Signalling Cost

The handoff signalling cost denotes the quantity of data packets or messages exchanged between the initial sender and final recipient, encompassing all successive hops, during the handoff phase. This cost considers both directions of communication: from the source to the target, and reciprocally. For the formulation of our handoff signalling cost analysis, we employed a similar hop count methodology as previously applied in our handoff delay investigations. The Table 4.5 shows the signalling packets such as $S_{Int}$, $S_{Data}$, and $S_{packet\_name}$ and their values also presented in table along with notation. The $S_{Int}$ and $S_{Data}$ represents the Interest and data packet respectively. The $S_{packet\_name}$ refers to any signalling packet such as $S_{Up}$ for binding update, $S_{Ack}$ for acknowledgement, $S_{MobInt}$ for mobility Interest packet, $S_{TraceInt}$ for trace Interest, $S_{TraceData}$ for trace data, $S_{Encp\_Int}$ for encapsulated Interest.

The hop count signalling cost of IBM is expressed when the mobile producer sends two signalling packets $S_{Up}$, and $S_{Ack}$ to indirection point to maintain communication route. Then, the consumer sends the Interest packet $S_{Int}$ to indirection point and the indirection point tunnelled the Interest packet towards the producer location in form of encapsulated Interest $S_{EncpInt}$.

The Equation (4.7) shows the handoff signalling cost for IBM. The mobile producer sends the binding update packets towards the indirection point. The mobile producer sends binding update to New-CR, the New-CR send binding update to indirection point with signalling cost $SC_{Pro\_Cr}$ and $SC_{Old\_NCr}$. The indirection point sends back the acknowledgement by following the binding update packet reverse track from indirection point to New-CR and New-CR to producer with signalling cost $SC_{Old\_NCr}$ and $SC_{Pro\_ar}$. The consumer sends Interest packet from its connected router C-CR to indirection point router Old-CR, the indirection point redirects the Interest packet to New-CR and further forwards to producer with signalling costs $SC_{Con\_Cr}$, $SC_{Cr\_Cr}$, $SC_{Old\_NCr}$, and $SC_{Pro\_Cr}$ respectively.

$$SC_{IBM} = (Producer \rightarrow New_{CR}) + (New_{CR} \rightarrow Old_{CR}) + (Old_{CR} \rightarrow New_{CR}) + (New_{CR} \rightarrow Producer) + (Consumer \rightarrow C_{CR}) + (C_{CR} \rightarrow Old_{CR}) + (Old_{CR} \rightarrow New_{CR}) + (New_{CR} \rightarrow Producer)$$

$$SC_{IBM} = SC_{Pro\_Cr} + SC_{Old\_NCr} + SC_{Old\_NCr} + SC_{Pro\_Cr} + SC_{Con\_Cr} + SC_{Cr\_Cr} + SC_{Old\_NCr} + SC_{Pro\_Cr}$$

$$SC_{IBM} = a + b + b + a + a + c + b + a$$

$$SC_{IBM} = a \times S_{Up/Ack} + b \times S_{Up/Ack} + b \times S_{Up/Ack} + a \times S_{Up/Ack} + a \times S_{Int} + c \times S_{Encp\_Int} + b \times S_{Encp\_Int} + a \times S_{Int} \quad (4.7)$$

The handoff signalling cost of PMSS expressed in Equation (4.8). The mobile producer sends the MI packet to the anchor router. The mobile producer sends MI packet to New-CR, the New-CR sends MI packet to anchor router with signalling cost $SC_{Pro\_Cr}$ and $SC_{Anh\_Cr}$. The anchor router broadcasts the MI packets to intermediate routers and further in the network to C-CR and Old-CR with signalling cost $SC_{Anh\_Cr}$ and $SC_{Cr\_Cr}$. The consumer sends Interest packet from its connected router C-CR to optimal route router New-CR, the New-CR forwards the Interest to producer with signalling costs $SC_{Con\_Cr}$, $SC_{Cr\_Cr}$, and $SC_{Pro\_Cr}$ respectively.

$$SC_{PMSS} = (Producer \rightarrow New_{CR}) + (New_{CR} \rightarrow Anh_{CR}) + (Anh_{CR} \rightarrow C_{CR}\ (Broadcast\ )) + (C_{CR} \rightarrow Old_{CR}(Broadcast)) + (Consumer \rightarrow C_{CR}) + (C_{CR} \rightarrow New_{CR}) + (New_{CR} \rightarrow Producer)$$

$$SC_{PMSS} = SC_{Pro\_Cr} + SC_{Anh\_Cr} + SC_{Anh\_Cr} + SC_{Cr\_Cr} + SC_{Con\_Cr} + SC_{Cr\_Cr} + SC_{Pro\_Cr}$$

$$SC_{PMSS} = a + c + c + c + a + c + a$$

$$SC_{PMSS} = a \times S_{MobInt} + c \times S_{MobInt} + c \times S_{MobInt} + c \times S_{MobInt} + a \times S_{Int} + c \times S_{Int} + a \times S_{Int} \quad (4.8)$$

The KITE scheme hop count signalling cost presented in Equation (4.9). The mobile producer sends the two packets to the immobile anchor and receive data packets. The mobile producer sends trace Interest to New-CR, the New-CR sends trace Interest packet to immobile anchor router Anh-CR, the immobile anchor replies with trace data with signalling cost $SC_{Pro\_Cr}$ and $SC_{Anh\_Cr}$ twice. The consumer sends Interest packet from its connected router C-CR to immobile anchor router Anh-CR, the immobile anchor router redirects the Interest packet to New-CR and further forwards to producer with signalling costs $SC_{Con\_Cr}$, $SC_{Anh\_Cr}$, $SC_{Anh\_Cr}$, and $SC_{Pro\_Cr}$ respectively.

$$SC_{KITE} = (Producer \rightarrow New_{CR}\ (TI)) + (Producer \rightarrow New_{CR}(TD)) + (New_{CR} \rightarrow Anchor(TI)) + (New_{CR} \rightarrow Anchor(TD)) + (Consumer \rightarrow C_{CR}) + (C_{CR} \rightarrow Anchor) + (Anchor \rightarrow New_{CR}) + (New_{CR} \rightarrow Producer)$$

$$SC_{KITE} = SC_{Pro\_Cr} + SC_{Pro\_Cr} + SC_{Anh\_Cr} + SC_{Anh\_Cr} + SC_{Con\_Cr} + SC_{Anh\_Cr} + SC_{Anh\_Cr} + SC_{Pro\_Cr}$$

$$SC_{KITE} = a + a + c + c + a + c + c + a$$

$$SC_{KITE} = a \times S_{wls\_TraceIntData} + a \times S_{wls\_TraceIntData} + c \times S_{wd\_TraceIntData} + c \times S_{wd\_TraceIntData} + a \times S_{wls\_Int} + c \times S_{wd\_Int} + c \times S_{wd\_Int} + a \times S_{wls\_Int}$$

$$SC_{KITE} = a \times S_{TraceIntData} + a \times S_{TraceIntData} + c \times S_{TraceIntData} + c \times S_{TraceIntData} + a \times S_{Int} + c \times S_{Int} + c \times S_{Int} + a \times S_{Int} \quad (4.9)$$

The proposed PMMM hop count signalling cost presented in Equation (4.10). The mobile producer sends MU packet to New-CR, the New-CR broadcasts MU packet to the intermediate routers including Old-CR with signalling cost $SC_{Cr\_Cr}$, and $SC_{Old\_NCr}$. The MU packet further reaches to the consumer to activate the sending Interest packet event with signalling cost $SC_{Con\_Cr}$. The consumer sends Interest packet from its connected router C-CR to optimal route router New-CR, the New-CR forwards the Interest to producer with signalling costs $SC_{Con\_Cr}$, $SC_{Cr\_Cr}$, and $SC_{Pro\_Cr}$ respectively.

$$SC_{PMMM} = (Producer \rightarrow New_{CR}) + \big(New_{CR} \rightarrow Old_{CR}\,(Broadcast)\big) + (New_{CR} \rightarrow C_{CR}(Broadcast)) + (C_{CR} \rightarrow Consumer) + (Consumer \rightarrow C_{CR}) + (C_{CR} \rightarrow New_{CR}) + (New_{CR} \rightarrow Producer)$$



$$SC_{PMMM} = SC_{Pro\_Cr} + SC_{Old\_NCr} + SC_{Cr\_Cr} + SC_{Con\_Cr} + SC_{Con\_Cr} + SC_{Cr\_Cr} + SC_{Pro\_Cr}$$

$$SC_{PMMM} = a + b + c + a + a + c + a$$

$$SC_{PMMM} = a \times S_{MobInt} + b \times S_{MobInt} + c \times S_{MobInt} + a \times S_{MobInt} + a \times S_{Int} + c \times S_{Int} + a \times S_{Int} \quad (4.10)$$

### 4.3.3 Hop Count Formulation for Packet Delivery Cost

The packet delivery cost refers to path optimization between consumer to producer after the handoff process. Path optimization after the handoff process refers to the process of selecting the best path for data transmission between the source and destination nodes after a handoff has occurred. The packet delivery is measured after the completion of producer handoff process and the packets between consumer to producer moves through the new route of communication. Further, it includes the consumer Interest packet that's moves to producer and in response the data packet reaches to the consumer.

The packet delivery cost of IBM is presented in Equation (4.11). The packet delivery cost is calculated after the completion of producer handoff process, then the consumer sent Interest packet from the connected router C-CR, the C-CR sends the packet to indirection point Old-CR, the indirection point redirects the packet to the producer connected router New-CR and it moves to producer with transmission hop cost per packet $DC_{Con\_Cr}$, $DC_{CR\_Cr}$, $DC_{Old\_NCr}$, and $DC_{Pro\_Cr}$. The producer forwards the data packet by following the reverse path towards the consumer with transmission hop cost per packet $DC_{Pro\_Cr}$, $DC_{Old\_NCr}$, $DC_{Cr\_Cr}$, and $DC_{Con\_Cr}$.

$$DC_{IBM} = (Consumer \rightarrow C_{CR}) + (C_{CR} \rightarrow Old_{CR}) + (Old_{CR} \rightarrow New_{CR}) + (New_{CR} \rightarrow Producer) + (Producer \rightarrow New_{CR}) + (New_{CR} \rightarrow Old_{CR}) + (Old_{CR} \rightarrow C_{CR}) + (C_{CR} \rightarrow Consumer)$$

$$DC_{IBM} = DC_{Con\_Cr} + DC_{Cr\_Cr} + DC_{Old\_NCr} + DC_{Pro\_Cr} + DC_{Pro\_Cr} + DC_{Old\_NCr} + DC_{Cr\_Cr} + DC_{Con\_Cr}$$

$$DC_{IBM} = a + c + b + a + a + b + c + a$$

$$DC_{IBM} = a \times S_{Int} + c \times S_{Int} + b \times S_{Int} + a \times S_{Int} + a \times S_{Data} + b \times S_{Data} + c \times S_{Data} + a \times S_{Data} \quad (4.11)$$

The Equation (4.12) shows the packet delivery cost of PMSS. The packet delivery cost is measured after the producer handoff process, then the consumer sends the

Interest packet from the connected router C-CR, the C-CR sends the packet to the optimal router New-CR, the New-CR forwards the packet to producer that covers the transmission hop cost per packet $DC_{Con\_Cr}$, $DC_{Cr\_Cr}$, and $DC_{Pro\_Cr}$. In response the producer forwards the data packet by following the reversal path towards the consumer with transmission hop cost per packet $DC_{Pro\_Cr}$, $DC_{Cr\_Cr}$, and $DC_{Con\_Cr}$.

$$DC_{PMSS} = (Consumer \to C_{CR}) + (C_{CR} \to New_{CR}) + (New_{CR} \to Producer) + (Producer \to New_{CR}) + (New_{CR} \to C_{CR}) + (C_{CR} \to Consumer)$$

$$DC_{PMSS} = DC_{Con\_Cr} + DC_{Cr\_Cr} + DC_{Pro\_Cr} + DC_{Pro\_Cr} + DC_{Cr\_Cr} + DC_{Con\_Cr}$$

$$DC_{PMSS} = a + c + a + a + c + a$$

$$DC_{PMSS} = a \times S_{Int} + c \times S_{Int} + a \times S_{Int} + a \times S_{Data} + c \times S_{Data} + a \times S_{Data} \quad (4.12)$$



The packet delivery cost of KITE is expressed in Equation (4.13). The packet delivery cost is calculated after the completion of producer handoff process. After the handoff process, the consumer sends the Interest packet from the connected router C-CR, the C-CR sends the packet to immobile anchor router Anh-CR, the immobile anchor router redirects the packet to the producer connected router New-CR and further forwarded to producer with transmission hop cost per packet $DC_{Con\_Cr}$, $DC_{Anh\_Cr}$, $DC_{Anh\_Cr}$, and $DC_{Pro\_Cr}$. The producer forwards the data packet by following the reverse way towards the consumer with transmission hop cost per packet $DC_{Pro\_Cr}$, $DC_{Anh\_Cr}$, $DC_{Anh\_Cr}$, and $DC_{Con\_Cr}$.

$$DC_{KITE} = (Consumer \to C_{CR}) + (C_{CR} \to Anh_{CR}) + (Anh_{CR} \to New_{CR}) + (New_{CR} \to Producer) + (Producer \to New_{CR}) + (New_{CR} \to Anh_{CR}) + (Anh_{CR} \to C_{CR}) + (C_{CR} \to Consumer)$$

$$DC_{KITE} = DC_{Con\_Cr} + DC_{Anh\_Cr} + DC_{Anh\_Cr} + DC_{Pro\_Cr} + DC_{Pro\_Cr} + DC_{Anh\_Cr} + DC_{Anh\_Cr} + DC_{Con\_Cr}$$

$$DC_{KITE} = a + c + c + a + a + c + c + a$$

$$DC_{KITE} = a \times S_{Int} + c \times S_{Int} + c \times S_{Int} + a \times S_{Int} + a \times S_{Data} + c \times S_{Data} + c \times S_{Data} + a \times S_{Data} \quad (4.13)$$

The Equation (4.14) shows the packet delivery cost of PMMM. The packet delivery cost is measured after the producer handoff process, then the consumer sends the Interest packet from the connected router C-CR, the C-CR sends the packet to the optimal router New-CR, the New-CR forwards the packet to producer that covers the transmission hop cost per packet $DC_{Con\_Cr}$, $DC_{Cr\_Cr}$, and $DC_{Pro\_Cr}$. In response the producer forwards the data packet by following the reversal path towards the consumer with transmission hop cost per packet $DC_{Pro\_Cr}$, $DC_{Cr\_Cr}$, and $DC_{Con\_Cr}$.

$$DC_{PMMM} = (Consumer \rightarrow C_{CR}) + (C_{CR} \rightarrow New_{CR}) + (New_{CR} \rightarrow Producer) + (Producer \rightarrow New_{CR}) + (New_{CR} \rightarrow C_{CR}) + (C_{CR} \rightarrow Consumer)$$

$$DC_{PMMM} = DC_{Con\_Cr} + DC_{Cr\_Cr} + DC_{Pro\_Cr} + DC_{Pro\_Cr} + DC_{Cr\_Cr} + DC_{Con\_Cr}$$

$$DC_{PMMM} = a + c + a + a + c + a$$

$$DC_{PMMM} = a \times S_{Int} + c \times S_{Int} + a \times S_{Int} + a \times S_{Data} + c \times S_{Data} + a \times S_{Data} \quad (4.14)$$

## 4.4 Model Design and Implementation

The handoff latency formulation of IBM, PMSS, KITE, and PMMM are presented the in Equations (4.3), (4.4), (4.5), and (4.6). The signalling cost formulation presented in Equation (4.7), (4.8), (4.9), and (4.10). In addition, the formulation of packet delivery cost expressed in Equation (4.11), (4.12), (4.13), and (4.14). The handoff latency, signalling cost and packet delivery cost formulated equations constructed as algorithms and put into practised in the Visual Studio Code. A Visual Studio Code is Integrated Development Environment (IDE) based tool which is very comprehensive and user-friendly for Python programming development. It features an interactive prompt for executing Python programming code. The formulation is checked during the implementation process to ensure precision, formulation accuracy, and programming code correctness.

In order to validate the accuracy, evaluate, and benchmark the handoff performance of the existing approaches and proposed PMMM model, the model is evaluated using the values listed in the table of parameters (Table 4.5). The values of a hop count parameter are a = 1 and b = c = 5. Due to the differences in wired and wireless connectivity distance, the values of a, b, and c were determined. The minimum coverage range of a standard WiFi router is 50 to 100 metres, whereas the minimum coverage range of a wired cable is 100 to 550 metres. This means that wired coverage is five times greater than wireless coverage. As a result, the hop count values for the wired link between the routers are set at b = c = 5 and the wireless link at a =1.

### 4.4.1 Algorithms

The algorithms that provided a highly accurate description of the plan for solving the problem are built based on the investigation of the NDN mobility support problem. The algorithms detail various predetermined steps that incorporating the handoff latency, signalling cost, and packet delivery cost into programming codes. The formulated IBM, PMSS, KITE, and PMMM are transformed into three different algorithms by following the algorithms deterministic steps. The first algorithm helps to implementation and execution of handoff latency, while the second and third algorithms helps to executes the signalling cost and packet delivery cost respectively.

Table 4.6 demonstrates the step-by-step execution of handoff latency formulation algorithm of proposed IBM, PMSS, KITE and PMMM.

Phase 1: The step 1 and 2 declares and accept input parameters of wired and wireless link such as $B_{wd}$ and $B_{wls}$ bandwidth, $L_{wd}$ and $L_{wls}$ link delay, $Q_d$ is the queuing delay and $q$ the probability, $a, b, c$ and $d$. In addition, the step 3 assigns each scheme subscript name.

Phase 2: The step 4 to 18 executes the total wired link delay $L_{wd\_packet\_name}$ and wireless link delay $L_{wls\_packet\_name}$.

Phase 3: The step 5 to 11 computes the total wired and wireless link delays according to the normal Interest packet size $S_{Int}$. In addition, the step 12 to 18 calculates the total wired and wireless delay according to the $S_{pn}$ such as $S_{MobInt}, S_{TraceIntData}, S_{Up/Ack}, S_{Encp\_Int}$.

Phase 4: The step 19 to 29 executes the handoff latency for IBM, PMSS, KITE, and PMMM. Meanwhile, for detailed investigation into the impacts of handoff performance the step 20 and 21 is conducted to verify the transmission latency on $a, b, c$ and $d$.

Table 4.6

*Handoff Latency Algorithm*

**Algorithm 4.1: Handoff Latency**

1. **Get** $\mathrm{B_{wd}}, \mathrm{B_{wls}}, \mathrm{L_{wd}}, \mathrm{L_{wls}}, \mathrm{Q_d}, a, b, c, d$
2. **Initiate** $\mathrm{B_{wd}} = 100, \mathrm{B_{wls}} = 11, \mathrm{L_{wd}} = 2, \mathrm{L_{wls}} = 10, \mathrm{Q_d} = 5, a = 1, b = c = 5, d = 8$
3. **Let** subscript $name \rightarrow IBM, PMSS, KITE, PMMM$
4. $HandoffLatencey\_name$
5. Compute the total wired and wireless link delay
6. **for** $S_{Int} = 40$ **do**
7. **if** wired link, **then**
8. wired link delay as $\rightarrow L_{wd\_Int} = S_{Int} / B_{wd} + L_{wd} + Q_d$
9. **else** wireless link
10. wireless link delay as $\rightarrow L_{wls\_packet\_name} = ((1+q)/(1-q) * (S_{pn}/B_{wls} + L_{wls}))$
11. **end if**
12. **end for**
13. **for** $S_{pn} = 56$ **do**
14. **if** wired link **then**
15. wired link delay as $\rightarrow L_{wd\_packet\_name} = S_{pn} / B_{wd} + L_{wd} + Q_d$
16. **else** wireless link
17. wireless link delay as $\rightarrow L_{wls\_packet\_name} = ((1+q)/(1-q) * (S_{pn}/B_{wls} + L_{wls}))$
18. **end if**
19. **end for**
20. Compute the handoff latency of IBM, PMSS, KITE, PMMM
21. **for** all $a, b, c, d \in$ (0.1, 0.2, ………., 0.9) **do**
22. **for** all $a, b, c, d \in$ (5, 6, ………., 23) **do**
23. $Latencey_{name} \rightarrow Latencey$
24. $L_{IBM} = l_{hf} + a \times L_{wls\_Up} + b \times L_{wd\_Up/Ack} + b \times L_{wd\_Up/Ack} + a \times L_{wls\_Up} +$ $a \times L_{wls\_Int} + c \times L_{wd\_EncpInt} + b \times L_{wd\_EncpInt} + a \times L_{wls\_Int}$
25. $L_{PMSS} = l_{hf} + a \times L_{wls\_MobInt} + c \times L_{wd\_MobInt} + c \times L_{wd\_MobInt} + c \times L_{wd\_MobInt} +$ $a \times L_{wls\_Int} + c \times L_{wd\_Int} + a \times L_{wls\_Int}$
26. $L_{KITE} = l_{hf} + a \times L_{wls\_TraceIntData} + a \times L_{wls\_TraceIntData} + c \times L_{wd\_TraceIntData} +$ $c \times L_{wd\_TraceIntData} + a \times L_{wls\_Int} + c \times L_{wd\_Int} + c \times L_{wd\_Int} + a \times L_{wls\_Int}$
27. $L_{PMMM} = l_{hf} + a \times L_{wls\_MobInt} + b \times L_{wd\_MobInt} + c \times L_{wd\_MobInt} + a \times L_{wls\_MobInt} +$ $a \times L_{wls\_Int} + c \times L_{wd\_Int} + a \times L_{wls\_Int}$
28. **end for**
29. **end for**
30. Compute Latency for $L_{IBM}, L_{PMSS}, L_{KITE}, L_{PMMM}$
31. **return** the value of $(L_{IBM}, L_{PMSS}, L_{KITE}, L_{PMMM})$



Table 4.7 expresses the step-by-step execution of handoff signalling cost formulation algorithm of proposed IBM, PMSS, KITE and PMMM.

Phase 1: The step 1 and 2 declares and acceptance of input parameters $a, b,$ and $c$. In addition, the step 3 assigns each scheme subscript name.

Phase 2: The step 4 to 11 executes the handoff signalling cost for IBM, PMSS, KITE, and PMMM. Additionally, it includes the different size of packets $S_{Int} = 40, S_{Data} = 2000, S_{Up/Ack} = 72, S_{EncpInt} = S_{TraceIntData} = S_{MobInt} = 56$ bytes.

Phase 3: The step 13 and 14 computes the signalling cost and return the values of IBM, PMSS, KITE, and PMMM.

Table 4.7

*Signalling Cost Algorithm*

**Algorithm 4.2: Handoff Signalling Cost**

1. **Get** $a, b, c, d$
2. **Initiate** $S_{Int} = 40, S_{Data} = 2000, S_{Up/Ack} = 72, S_{EncpInt} = S_{TraceIntData} = S_{MobInt} = 56$
3. **Let** subscript $name \rightarrow IBM, PMSS, KITE, PMMM$
4. Compute the handoff signalling cost of IBM, PMSS, KITE, PMMM
5. **for** all $a, b, c, d \in$ (1, 2, ………, 10) **do**
6. **for** all $a, b, c, d \in$ (0.1, 0.2, ………, 0.9) **do**
7. $SC \rightarrow name$
8. $SC_{IBM} = a \times S_{Up/Ack} + b \times S_{Up/Ack} + b \times S_{Up/Ack} + a \times S_{Up/Ack} + a \times S_{Int} + c \times S_{Encp\_Int} + b \times S_{Encp\_Int} + a \times S_{Int}$
9. $SC_{PMSS} = a \times S_{MobInt} + c \times S_{MobInt} + c \times S_{MobInt} + c \times S_{MobInt} + a \times S_{Int} + c \times S_{Int} + a \times S_{Int}$
10. $SC_{KITE} = a \times S_{TraceIntData} + a \times S_{TraceIntData} + c \times S_{TraceIntData} + c \times S_{TraceIntData} + a \times S_{Int} + c \times S_{Int} + c \times S_{Int} + a \times S_{Int}$
11. $SC_{PMMM} = a \times S_{MobInt} + b \times S_{MobInt} + c \times S_{MobInt} + a \times S_{MobInt} + a \times S_{Int} + c \times S_{Int} + a \times S_{Int}$
12. **end for**
13. **end for**
14. Compute signalling cost for $SC_{IBM}, SC_{PMSS}, SC_{KITE}, SC_{PMMM}$
15. **return** the value of $(SC_{IBM}, SC_{PMSS}, SC_{KITE}, SC_{PMMM})$



Table 4.8 describes the step-by-step execution of packet delivery cost formulation algorithm of proposed IBM, PMSS, KITE and PMMM.

Phase 1: The step 1 and 2 declares and acceptance of input parameters $a, b,$ and $c$. In addition, the step 3 assigns each scheme subscript name for IBM, PMSS, KITE, and PMMM.

Phase 2: The step 4 to 11 executes the packet delivery cost for IBM, PMSS, KITE, and PMMM. Additionally, it includes the Interest packets $S_{Int} = 40$ bytes, and data packet $S_{Data} = 2000$ bytes.

Phase 3: The step 13 and 14 computes the packet delivery cost and return the values of IBM, PMSS, KITE, and PMMM.

Table 4.8

*Packet Delivery Cost Algorithm*

**Algorithm 4.3: Packet Delivery Cost**

1. **Get** $a, b, c$
2. **Initiate** $S_{Int} = 40, S_{Data} = 2000$
3. **Let** subscript $name \rightarrow IBM, PMSS, KITE, PMMM$
4. Compute the packet delivery cost of IBM, PMSS, KITE, PMMM
5. **for** all $a, b, c \in$ (0.1, 0.2, ………., 0.9) **do**
6. **for** all $a, b, c \in$ (0.1, 0.2, ………., 0.9) **do**
7. $DC \rightarrow name$
8. $DC_{IBM} = a \times S_{Int} + c \times S_{Int} + b \times S_{Int} + a \times S_{Int} + a \times S_{Data} + b \times S_{Data} + c \times S_{Data} + a \times S_{Data}$
9. $DC_{PMSS} = a \times S_{Int} + c \times S_{Int} + a \times S_{Int} + a \times S_{Data} + c \times S_{Data} + a \times S_{Data}$
10. $DC_{KITE} = a \times S_{Int} + c \times S_{Int} + c \times S_{Int} + a \times S_{Int} + a \times S_{Data} + c \times S_{Data} + c \times S_{Data} + a \times S_{Data}$
11. $DC_{PMMM} = a \times S_{Int} + c \times S_{Int} + a \times S_{Int} + a \times S_{Data} + c \times S_{Data} + a \times S_{Data}$
12. **end for**
13. **end for**
14. Compute Latency for $DC_{IBM}, DC_{PMSS}, DC_{KITE}, DC_{PMMM}$
15. **return** the value of ("$DC_{IBM}, DC_{PMSS}, DC_{KITE}, DC_{PMMM}$")



### 4.4.2 Model Verification

Microsoft developed Visual Studio Code (VS Code), a free and open-source coding editor. It is aimed at offering quick, lightweight, cross-platform environment for writing and debugging Python-based code. Programmers, developers, and researcher easily debug Python code right inside the editor owing to the robust built-in debugger, troubleshoot errors, and check variables. Owing to its features, the formulation of handoff latency, signalling cost, and packet delivery is implemented and verify as shown in Figure 4.8. Further, the Figure 4.9 shows the successful verification of implementation of error free code.

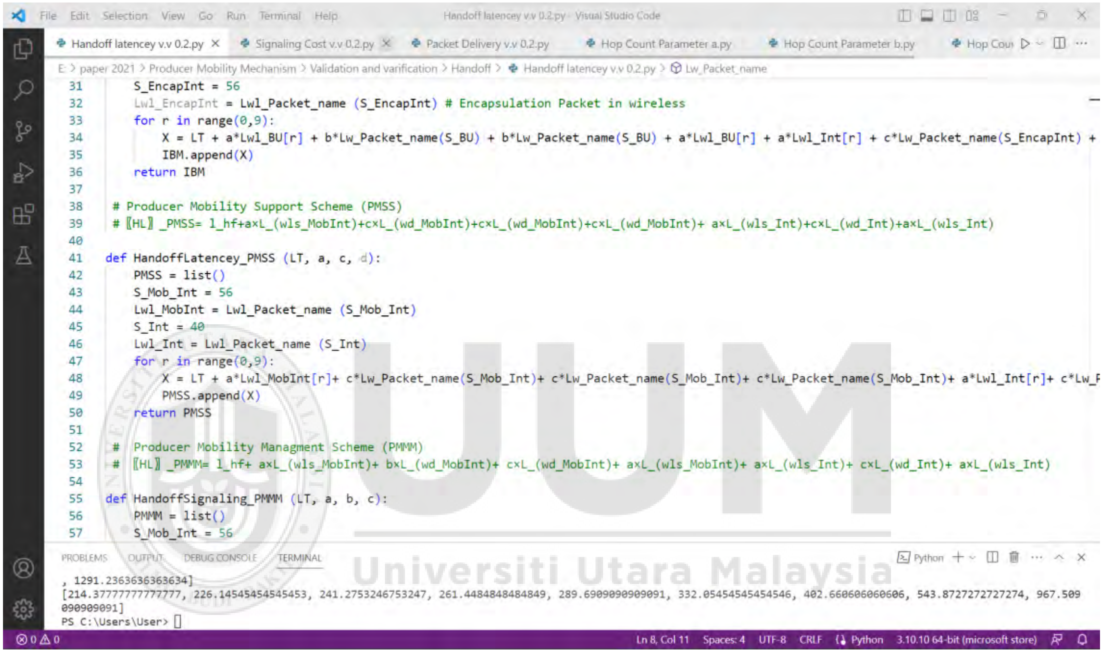


*Figure 4.8.* Model Verification Code Sample

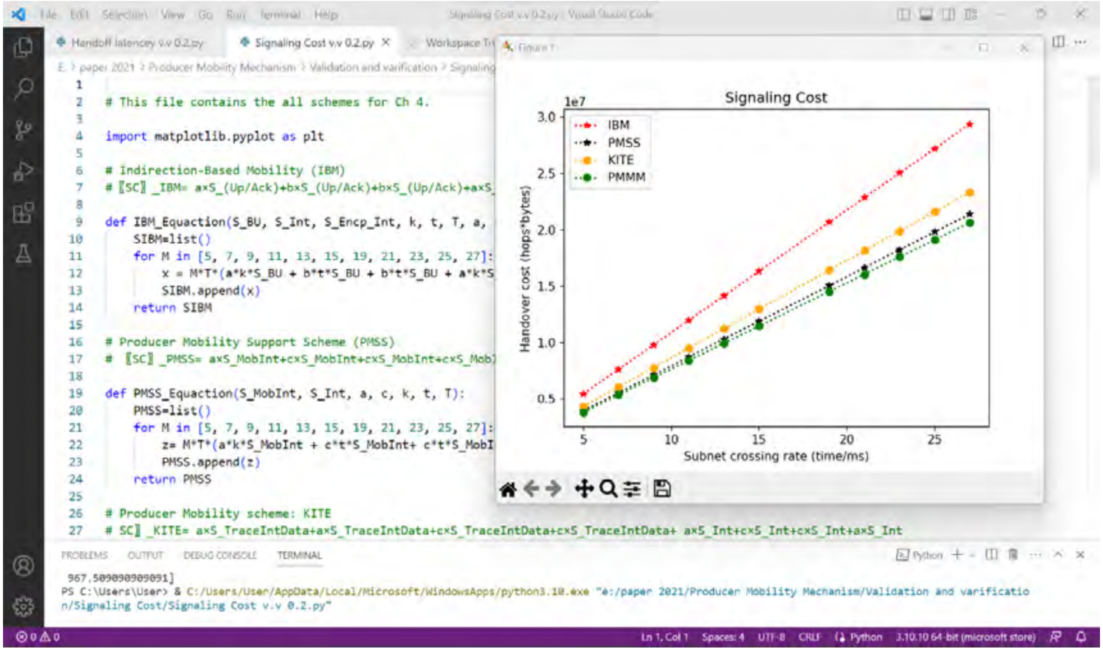



*Figure 4.9.* Proof of Successful Model Verification Code

### 4.4.3 Model Validation and Performance Evaluation



Handoff latency is a time frame which completes the signalling process along with the time to receive the first Interest packet from the next content router [27]. The handoff latency is the overall time it takes a mobile producer to disconnect, reconnect, and wait for the first Interest packet to arrive through a new content router [23]. The handoff latency is the one of the reliable indicators to measure the performance of a model or scheme when the latency covered is smaller than others, the handoff latency is seen as good and implies higher performance of the model or scheme. By referring to Figures 4.10, 4.11, and 4.12 that shows the varying hop count impact on parameter $a, b$, and $c$ respectively. The Figure 4.10 shows the impact of hop count parameter $a$ of transmission latency between the consumer or producer and CR. The Figure 4.11 shows the impact of hop count parameter $b$ which measure the transmission latency between the Old-CR and New-CR. The Figure 4.12 shows the impact of parameter $c$ that measure the transmission latency between the

CRs. The presented figures show the comparison between the IBM, PMSS, KITE, and PMMM.

By referring to Figure 4.10, the latency of KITE and IBM are showing the increasing trend of latencies. The transmission delay between consumer or producer to router is different because of different way of transmission approach. The parameter $a$ reflects the better latency result in PMMM. In a result, the PMMM showing the lowest latency as compared to PMSS.

In Figure 4.11, the transmission delay between the Old-CR and the New-CR is changed, which causes the latency of KITE and IBMA to considerably increase while remaining constant for PMMM and PMSS $b$. The result of PMMM and PMSS solutions remains unchanged since the parameter $b$ has no transmission impact. In the cases of IBM and KITE, the results get worse when the value of $b$ rises because of the latency associated to the handoff messages that went through Old-CR (home router or indirection point). Even though changing $b$ caused PMSS results to differ from IBM, doing so had the same impact on Figure 4.12 transmission delay between routers $c$.

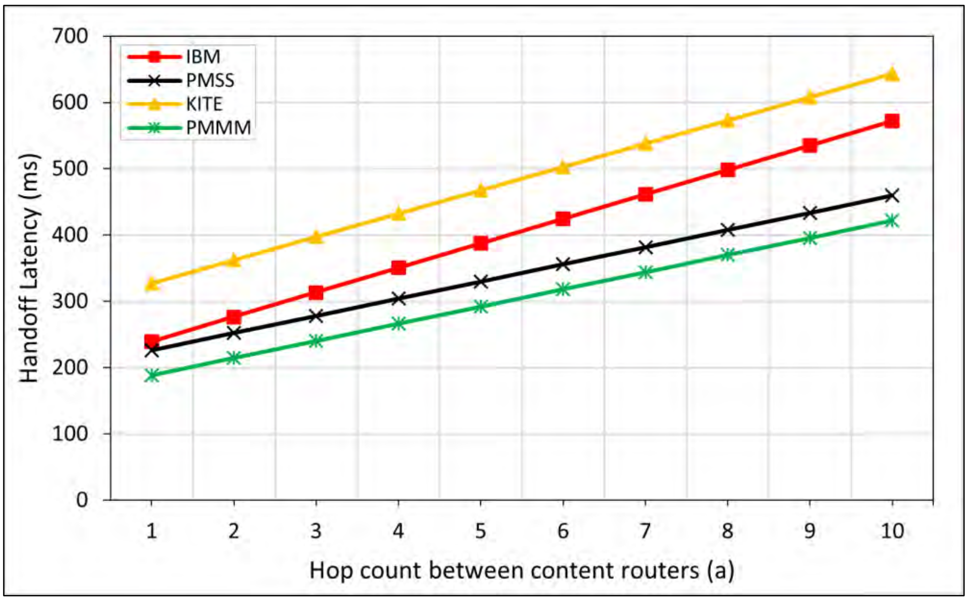



*Figure 4.10.* Handoff Latency Impact on *a*

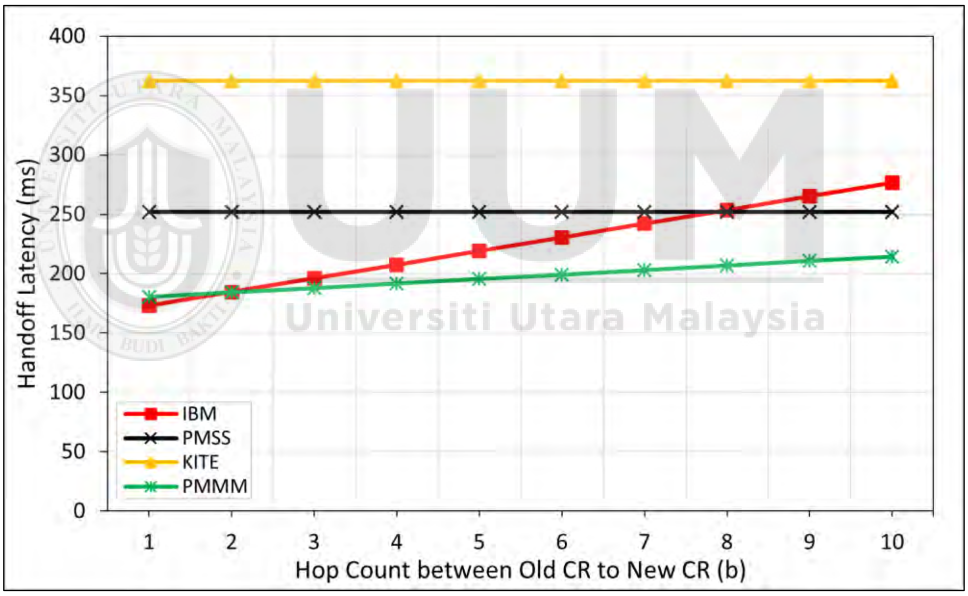



*Figure 4.11.* Handoff Latency Impact on *b*

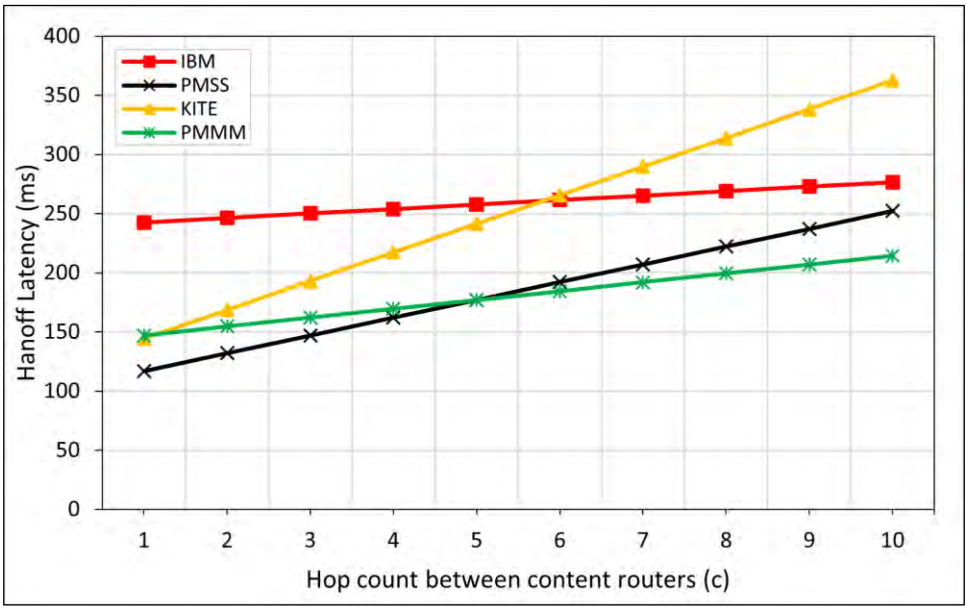



*Figure 4.12.* Handoff Latency Impact on *c*

The PMMM solution shows the better performance in term of handoff latency as compared to IBM, PMSS, and KITE solutions with lowest latency 180ms. While IBM, PMSS and KITE have an average latency 173ms, 252ms, and 362ms respectively, as shown in Figure 4.11. Moreover, the performance of PMMM is gradually improved by intersecting the PMSS and constantly improves the performance as shown in Figure 4.12. Hence, the performance of PMMM is improved as compared to IBM, PMSS, and KITE. The long handoff latency causes in the failure of network connectivity.

The cost of handoff signalling counts the number of messages transmitted across the network from the producer to the consumer node for the continuation of communication after the handoff. When the cost is lower than others, the handoff signalling cost is considered positive and shows higher performance of the model or scheme. The handoff signalling cost expressed numerically in Figures 4.13, 4.14, and 4.15 represents the costs associated with the IBM, PMSS, KITE, and PMMM solutions. Figure 4.14 shows how changing the transmission cost hops/packets between the Old-CR and New-CR ($b$) affects the handoff signalling cost performance. The KITE and PMSS shows the higher level of signalling cost due to each message pass by the anchor router according to their design. Therefore, the distance increased towards the New-CR due to additional network node which increases in the hop count. Further, the message goes through the extra node that effects the KITE and PMSS solution. While the PMMM and IBM showing the better performance and gradually the PMMM intersects the IBM and shows the lowest signalling cost as shown in Figure 4.14. Moreover, the handoff signalling cost performance by varying transmission cost hop/packet between access router $c$ is depicted in Figure 4.15.

The results shows that due the general effect of parameter $c$, whereas each signalling message must pass through the CR. The numerical values for the handoff signalling cost of the existing and proposed solution are dramatically rising. While the PMMM trend line reflects the downwards trend in the long term as compared to PMSS and KITE. Thus, the overall numerical results indicates that PMMM has the improved pattern as compared to IBM, PMSS, and KITE as illustrated in Figures 4.13, 4.14, and 4.15. Consequently, it validates the PMMM concept performance.

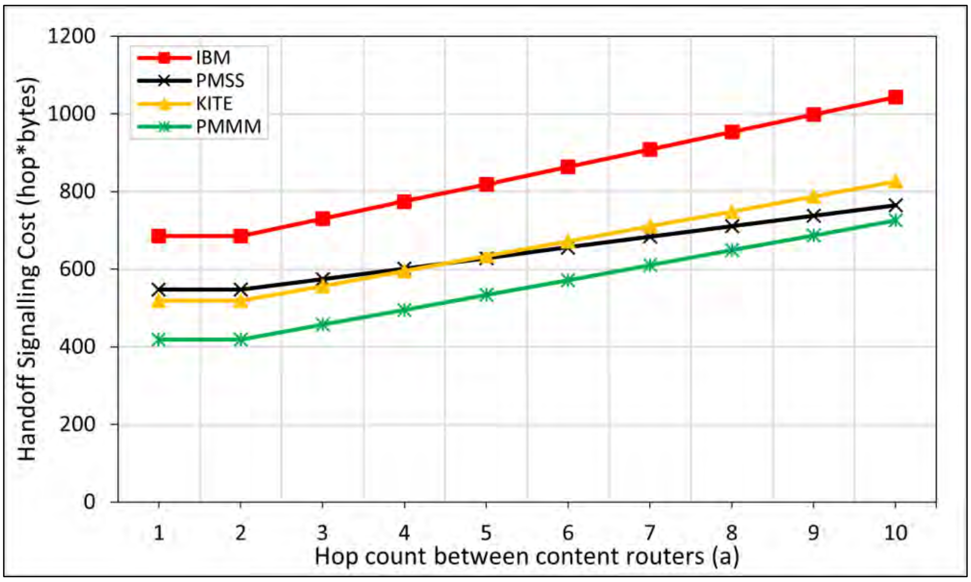



*Figure 4.13.* Signalling Cost Impact on $a$

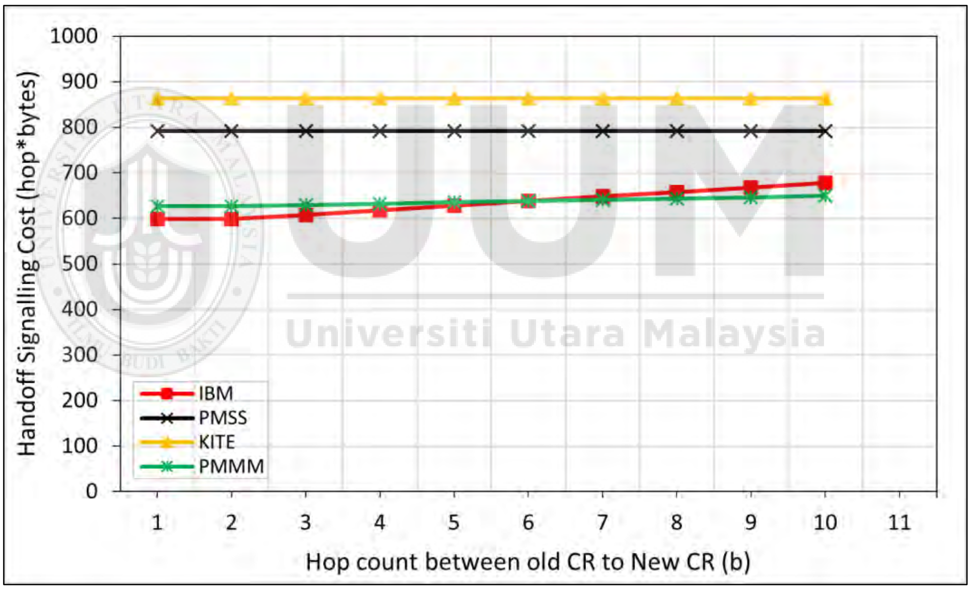



*Figure 4.14.* Signalling Cost Impact on $b$

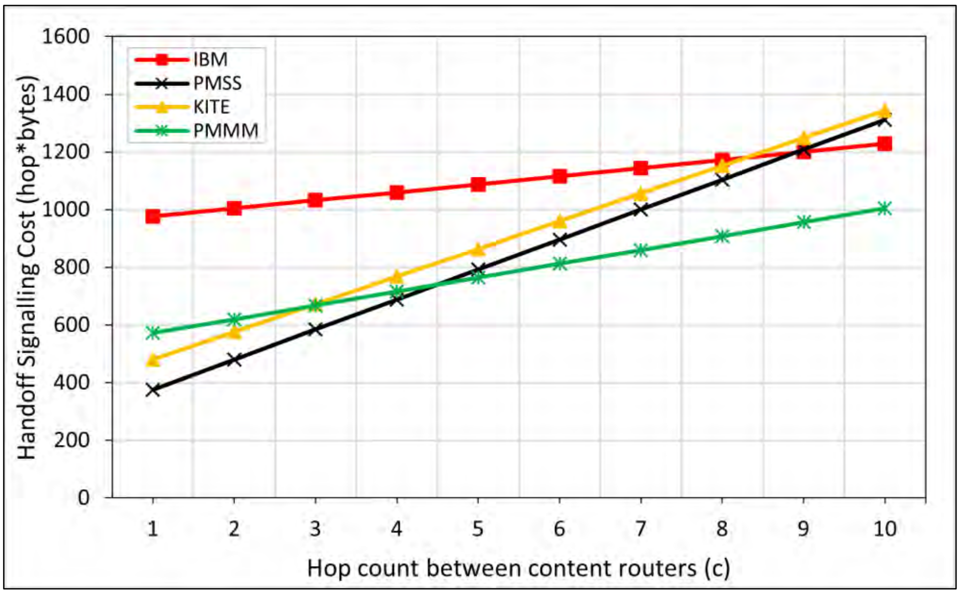



*Figure 4.15.* Signalling Cost Impact on $c$

By referring to Figure 4.14 indicates the variation in parameter $b$, the trend line begins with the increasing trend but at certain point it intersects the IBM trend line and changes its trend downwards. Meanwhile, the IBM trend line shows the upwards trend. While the PMSS and KITE trend shows downward trend with the constant rate. The results in Figure 4.15 shows the increasing trend of KITE and PMSS in long term meanwhile the PMMM trend line shows the less variation as compared to other solutions for parameter $c$. The PMSS uses the single packet to setup the route, unlike in KITE uses the two packets to manages the route.

The packet delivery cost is determined by the effectiveness of data path optimization or the minimizing the path stretch ratio. The results of the packet delivery cost analysis are shown in Figures 4.16, 4.17 and 4.18, respectively, for the variable transmission cost hop per packet parameters $a, b,$ and $c$. Given that PMSS offers data path optimisation after handoff, as was previously mentioned in the literature, both numbers demonstrate that the proposed PMMM and PMSS have similar packet delivery cost performance. As a result, Figures 4.16, 4.17 and 4.18's findings showed that the proposed PMMM provides data path optimisation following the handoff and is also validated by comparison with the PMSS solution. The packet delivery cost of PMSS is trend changes with the increase of parameter $a$ and the PMMM follow the same pattern of movement which overlaps the trendline with each other. while KITE showing the higher level of data packet delivery as compared to PMMM and PMSS due to usage of additional hops. The KITE trend line moves upwards with the increase of $b$ parameter due to data goes through the immobile anchor. While the IBM trend lines also follow the KITE trend line due to usage of additional CR for packets delivery management. This is caused by the fact that IBM solution, which is represented by parameter $b$, is required to transport Interest and data packets over Old-CR and New-CR links, yet all are impacted when parameter $c$ is changed. Therefore, the KITE and IBM trendlines overlaps each other due same rate of packet delivery.

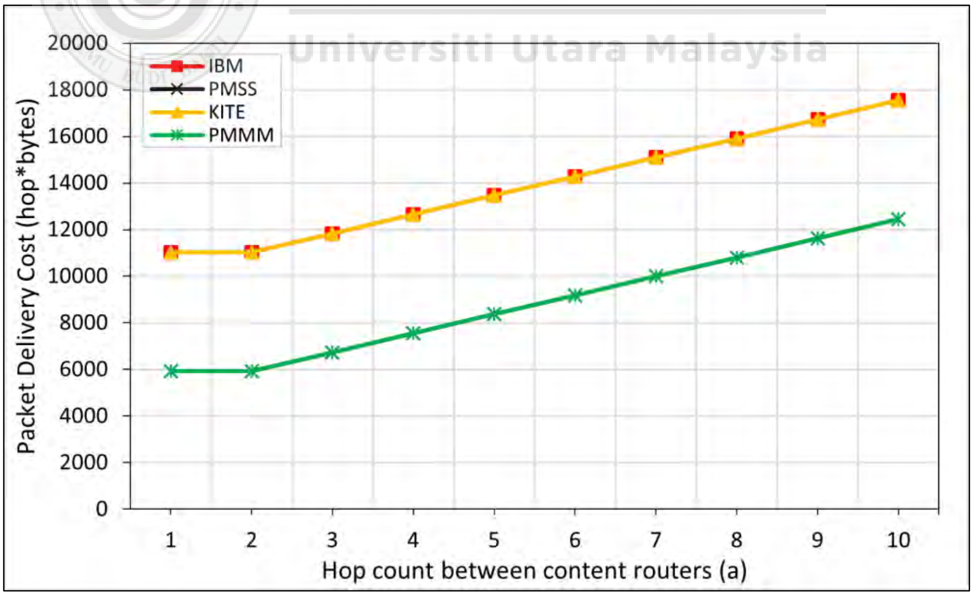



*Figure 4.16.* Data Packet Delivery Impact on $a$

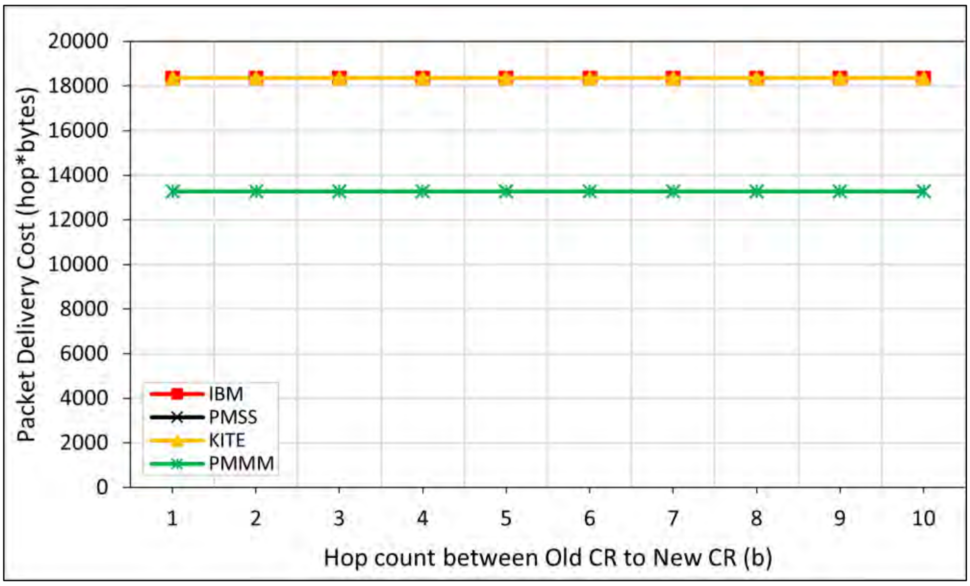



*Figure 4.17.* Data Packet Delivery Impact on *b*

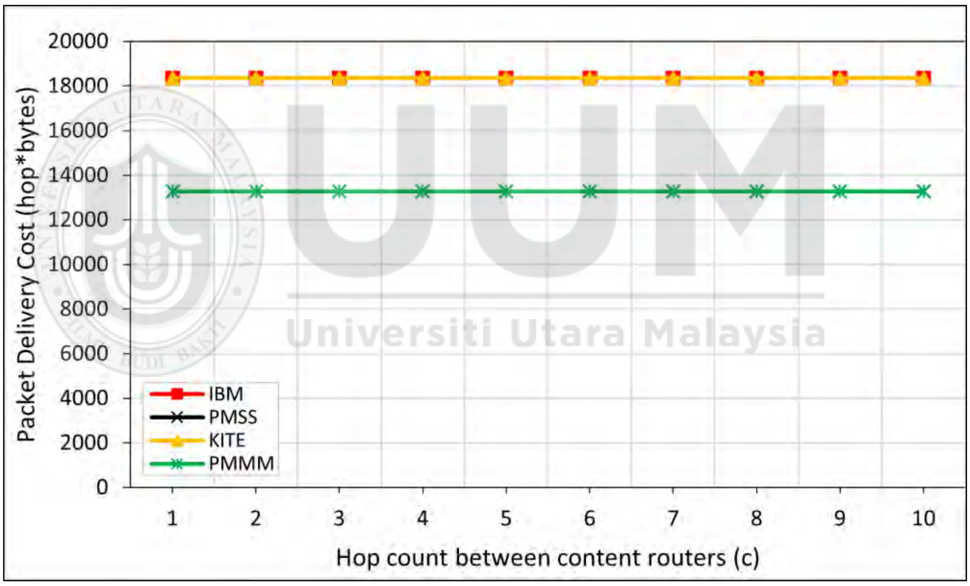



*Figure 4.18.* Data Packet Delivery Impact on *c*

The analytical model developed has several limitations, particularly concerning scalability and the assumptions made during its creation. One significant limitation is the reliance on a simplified network topology, featuring only a single producer and consumer. While this setup facilitates efficient analysis, it may not accurately reflect the complexities of larger, more dynamic networks, potentially limiting the model's applicability in real-world scenarios. Additionally, the inclusion of only three types of routers, varying in position and operational mechanisms, restricts the exploration of diverse routing strategies. This limited router configuration may overlook important interactions and performance metrics that could arise in more complex networks with varying router types and placements.

To improve and extend the model for future research, several strategies can be employed. First, expanding the topology to include multiple producers and consumers would provide a more realistic representation of network dynamics and interactions. Second, incorporating a broader variety of router types and configurations could yield insights into how different routing mechanisms impact performance in complex environments. Furthermore, implementing simulation techniques alongside the analytical model could enhance its scalability and provide a means to validate results across a wider range of scenarios. By addressing these limitations, the model can be refined to better capture the intricacies of real-world networking environments and improve the generalizability of its findings.

### 4.5 Summary

This chapter expresses the analytical model of proposed PMMM to reduce the associated issues such as long handoff latency, signalling cost, and packet delivery cost. The graphical reference and impact models are examined based on the important factors that contribute to or have an impact on the issues with producer mobility support and the solutions. Using the hop count approach, the impact model, which represents the proposed solution for the producer mobility in NDN, is created. Analytical investigation method is then used to verify, validate, and investigation the impact model. The network analysis model has traditionally been used to develop and verify alternative designs for concepts proposed in mobile networking. Additionally, the network analysis model is used to formulate the hop count handoff latency, signalling cost, and packet delivery of the existing solutions and the proposed PMMM. Additionally, the existing and proposed solutions are verified and validated using Python code developed in the Visual Studio Codes.



Three different algorithms are developed to analytical investigation of proposed PMMM, IBM, PMSS, and KITE. The algorithms include the handoff latency analysis, signalling cost and packet cost analysis. The overall results of PMMM in parameter $a, b,$ and $c$ shows the better performance as compared to IBM, PMSS, and KITE.

# CHAPTER FIVE

# PRODUCER MOBILITY MANAGEMENT MODEL DESIGN AND IMPLEMENTATION

This chapter transitions from the theoretical framework established in the previous chapter to the practical design and implementation of the PMMM. Building upon the analytical model and mathematical proofs discussed in Chapter 4, this chapter delves into the detailed design and actual implementation of PMMM. The analytical model provided a foundational understanding of the key metrics—handoff latency, signalling cost, and data packet delivery path—within the context of existing solutions like IBM, PMSS, and KITE. Here, we translate these theoretical insights into a concrete, operational mechanism.

The primary objective of this chapter is to present the detailed design of PMMM, highlighting the specific methods and techniques employed to realize the conceptual model in a real-world setting. This includes an in-depth examination of the packet formats, data structures, and transmission pipelines necessary for effective producer mobility management. It also includes a comprehensive explanation and design justification for the choices made. By thoroughly detailing the design principles and considerations, this chapter ensures a clear understanding of how the PMMM addresses the issues identified analytically.

This understanding is crucial for the subsequent chapters, where we will implement and evaluate PMMM in a simulated environment. The insights provided here serve as a guide for researchers and practitioners to effectively deploy and assess the proposed model's performance. Overall, this chapter bridges the gap between theory and practice, laying the groundwork for a robust evaluation of PMMM's efficacy.

## 5.1 Introduction

This chapter focuses on addressing the issue of producer mobility in NDN by designing and implementing a producer mobility support model. This model, known as the PMMM, aims to control and support producer mobility in NDN to overcome the associated issues. PMMM introduces two schemes that work together to manage producer mobility and enhance network performance:

1. **Mobility Notification Packet (MNP):** A scheme that informs the network about the producer's movement, allowing for timely updates to the FIB's.
2. **Mobility Update Packet (MUP):** A scheme that updates the network routers with the new location of the producer, ensuring efficient routing of Interest packets to the producer's new location.

These schemes collectively help reduce packet losses, decrease handoff latency, lower signalling costs, and increase throughput. Additionally, PMMM modifies the normal forwarding scheme to support these new design schemes.

The schemes are supported by mobility management packets. Thus, the packet format and data structure play a very important role in designing an effective producer mobility management model. Mobility management packets are crucial in informing the system about producer mobility within the network, serving as notifications when a producer associates or disassociates with different access points in the network system. To facilitate the utilization of these packets, modifications or upgrades are made to the forwarding data structure. Specifically, additional functions are incorporated into the forwarding data structure to support the handling of mobility management packets. This development enables the triggering of mobility management packets under specific conditions, enhancing the efficiency and effectiveness of producer mobility management within the network system. In order to understand the PMMM development, it is necessary to understand the high-level overview of NDN, which comprises several modules.

## 5.2 High-Level Overview

The Named Data Networking Forwarding Daemon (NFD) and NDN-CXX modules are the core components of NDN. The content dissemination is controlled by these modules which manages the internal functional structure of NDN. These core modules work as a backbone of the NDN in Interest and data transmission. These both modules function together to makes possible the content dissemination through different pipelines. The NFD and NDN-CXX modules are modified by additional method in order to content dissemination and to support the mobility management packets in PMMM.

### 5.2.1 NDN Forwarding Daemon



In NDN architecture, NFD serves as the reference implementation of the forwarding plane. Within an NDN network, packets containing Interest and data are sent and maintain by NFD. The fundamental functionality for receiving, processing, and forwarding NDN packets is provided by NFD, which operates on network devices like routers or networked devices with NDN functional capabilities. It implements the NDN forwarding technique, which uses the network's forwarding policies and the available routing information to decide the next hop or hops for an Interest packet and provides the efficient packet track and trace mechanism.

Additionally, NFD supports a number of NDN features and methods, including Interest aggregation, CS, PIT, name-based forwarding, and FIBs for routing decisions. It is a crucial part of an NDN network since it dynamically forwards Interest packets and caches data packets, allowing for the effective and scalable delivery of NDN content. Because it controls packet forwarding and routing based on content names rather than host addresses, it is essential to the functionality and performance of an NDN network.

Understanding the NFD module is crucial for implementing mobility management packets. The NFD handles fundamental packet forwarding through two key sub-modules: forwarding pipelines and forwarding strategies.

The forwarding pipeline contains the number of steps that each packet goes through. By referring to Figure 5.1, the incoming data packet is analysed by the IncomingData function in the pipeline. The pipeline performs further operation in order to authenticate the data integrity. The incoming data pipeline also checks the corresponding PIT of data packet. If it did not find the corresponding PIT, it drops the data packet.

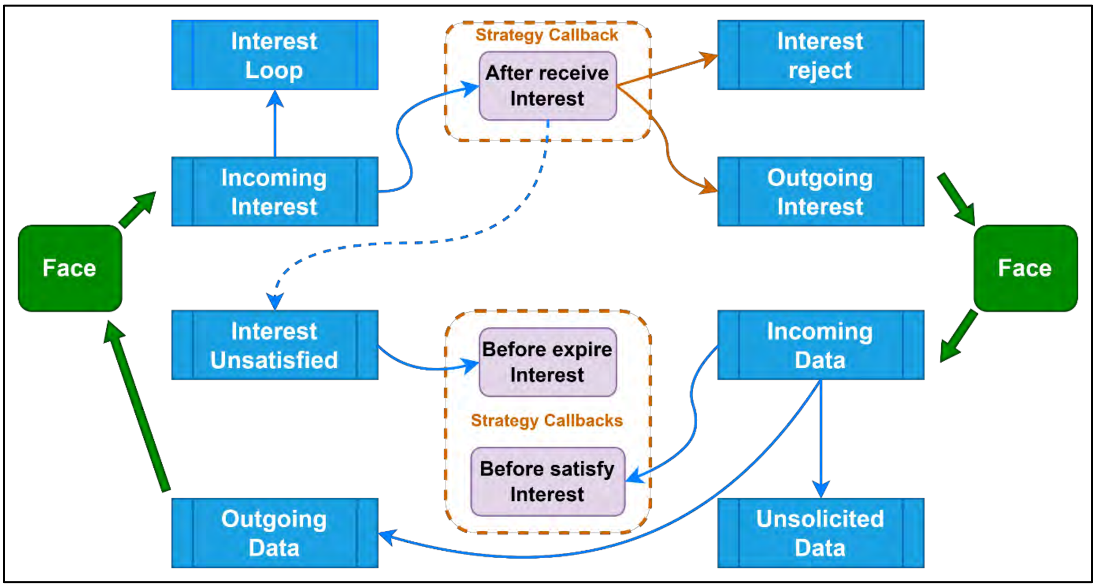



*Figure 5.1.* A Shape of NDN Forwarding Daemon Pipelines

The algorithms for mobility management packets are implemented in the forwarding module of the NFD. By default, the unsolicited data pipeline is activated after the incoming data pipeline. The unsolicited data pipeline handles data packets that do not have a corresponding PIT entry, essentially dealing with data that was not specifically requested. The incoming data pipeline receives the data packets and analyses their state. When the unsolicited data pipeline receives these data packets, it examines them and applies unsolicited data policies. Typically, if no PIT entry is found for the received data packets, they are declined by the unsolicited data stream. However, by changing the policy, the data can be cached in the routers.

#### 5.2.1.1 Unsolicited Data Stream

In NFD, the incoming data packet pipeline initially processes all incoming Data packets. If a Data packet is unsolicited—meaning, there is no corresponding entry in the PIT—it is then handled by the unsolicited data stream within the pipeline. In NDN, stack helpers are installed in each node to detect any changes in the application layer, forwarding layer, and routing layer. Consequently, any changes in the forwarding layer are propagated among the connected routers, ensuring consistency.

Each node in the network has an NDN data structure that includes the CS, FIB, and PIT. The CS on each node adheres to specific caching policies for incoming data packets. By default, the unsolicited data policy drops all unsolicited data packets. However, other policies, such as AdmitLocalUnsolicitedData and AdmitNetworkUnsolicitedData, can be configured to cache these unsolicited data packets. AdmitLocalUnsolicitedData accepts all unsolicited data packets from the localhost prefix, allowing communication between the NFD instance and local applications. AdmitNetworkUnsolicitedData accepts all data packets coming from network interfaces, allowing the caching of unsolicited data in the Content Store by altering the default caching policy [93]. The Table 5.1 shows the algorithm to alter the unsolicited data stream that able to caches the data in CS. When an unsolicited data packet is received, first it retrieves the incoming interface (inface) and the actual data content (data) carried by the packet. The function OnDataUnsolicitedData is then called to process the unsolicited data. The core of the algorithm lies in the decision-making process, where the UnsolicitedDataPolicy module is invoked to determine how to handle the packet. If the decision is to cache the data, it proceeds to insert the received data into the CS, which is the local cache of the NDN node.

Table 5.1

*Unsolicited Data Stream*

| **Algorithm 5.1: Unsolicited Data Stream** |
|---|
| **Get:** $inface, data$ |
| **Output:** Cache data |
| **Function OnDataUnsolicitedData** $(inface, data)$ |
| **Initiate** $decision\ = UnsolicitedDataPolicy \rightarrow decide(infcae, data)$; |
| **if** $decision ==\ UnsolicitedDataDecision\ .Cache$ **then** |
|     Content Store. Insert data; |
| **End** |

In the PMMM design, the NFD forwarder incorporates specific mechanisms to handle the mobility management packets. These packets are categorized into two types, each of which is processed by a separate pipeline based on the nature of the packet. The first type is the Mobility Notification Packet (MNP). This packet is a modified version of a data packet and is handled by the incoming data packet pipeline and further process by the on-mobility notification packet pipeline as shown in Figure 5.2. When an MNP is received, it undergoes processing within this pipeline, which includes operations such as caching the packet into the CS and retrieving the necessary FIBs for determining the next hops. The second type is the Mobility Update Packet (MUP). This packet is a modified version of an Interest packet and is received by the incoming interest pipeline and further processed by on-mobility update packet pipeline as shown in Figure 5.2. Both pipelines are defined in the forwarding pipeline as an additional sub function and as a trigger which is underlying in Incoming Interest and data pipelines.

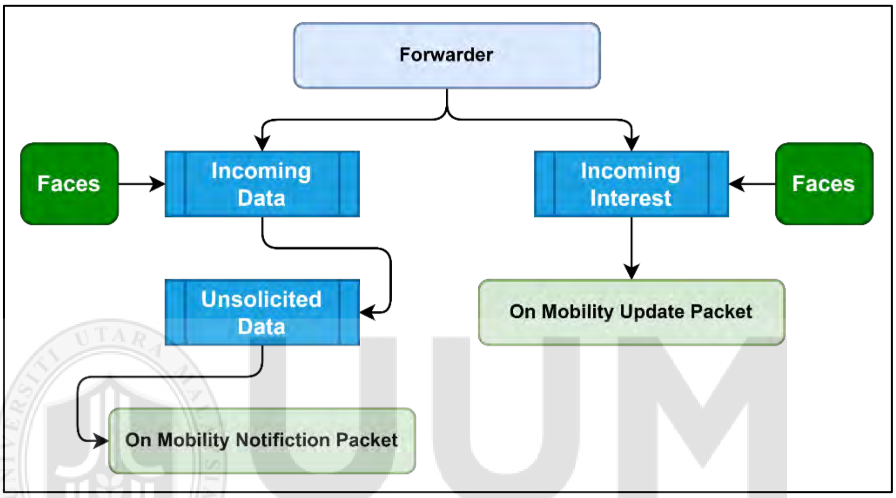



*Figure 5.2.* PMMM-based Forwarding Pipelines



When an MUP packet is encountered, it follows the operations defined within this pipeline. This typically involves broadcasting the MUP packet to the relevant next hop lists, ensuring that the update reaches all relevant nodes in the network. In the design of PMMM, the handling of mobility management packets is closely tied to the NDN-CXX module. NDN-CXX is a module within the NDN paradigm that is responsible for managing the Interest and data packets and their related operations. Modifications to the existing Interest and data packets, as well as the creation of new packet types for mobility management purposes, are typically handled by the NDN-CXX module. This module provides the necessary functionality and interfaces to modify the packet structures, define new packet types, and incorporate custom fields or extensions as required by the PMMM design. By leveraging the capabilities of the

NDN-CXX module, the PMMM design can introduce the necessary modifications to the structure and behaviour of Interest and data packets. This allows for the implementation of mobility-specific functionalities such as mobility MNP and MUP, which are integral to the PMMM.

### 5.2.2 NDN-CXX

NDN-CXX is a C++ library that provides an implementation of the NDN protocol. NDN-CXX offers functionalities for various components of an NDN system, including handling Interests and data packets, managing content stores, performing name-based routing, and managing network face communications. The library enables to create NDN applications in C++ and interact with the NDN network infrastructure. Moreover, the NFD used NDN-CXX for the implementation of Type-Length-Value (TLV) format, encoding, decoding, Interest packet, data packets, and face abstraction.



The data packets contain different fields in the packet such as name, meta info, content, and signature. In order to add additional fields in the packet, it needs to modify the TLV and assign an additional number to each field to encode and decode purposes. The data packets are the collection of different TLVs that identifies the type of packet. Where the T refers to the type of block i.e. name block or signature block, L refers to the length of the value block in bytes, and V shows the value of the TLV block. To design the mobility management packets, it needs to modify the TLV block by adding additional functional fields. Moreover, the data packets need to modify by adding new fields, such as mobility status, packet value, and content. Furthermore, technical challenges included ensuring backward compatibility with existing protocols, managing increased signalling traffic during mobility events, and maintaining low latency despite the added complexity of handling mobility updates. These modifications carefully optimized to prevent disruptions in data flow and to ensure a smooth user experience.

### 5.3 Detailed Design of MNP and MUP

The first type is the Mobility Notification Packet (MNP). This packet is a modified version of a data packet and is handled by the incoming data packet pipeline and further processed by the on-mobility notification packet pipeline, as shown in Figure 5.2. When an MNP is received, it undergoes processing within this pipeline, which includes operations such as caching the packet into the CS (Content Store) and retrieving the necessary FIBs for determining the next hops. The second type is the Mobility Update Packet (MUP). This packet is a modified version of an Interest packet and is received by the incoming interest pipeline and further processed by the on-mobility update packet pipeline, as shown in Figure 5.2. When an MUP packet is encountered, it follows the operations defined within this pipeline. This typically involves broadcasting the MUP packet to the relevant next hop lists, ensuring that the update reaches all relevant nodes in the network. As discuss in the previous section which explain the NDN-CXX, by following that we added two new packet design.

#### 5.3.1 Mobility Notification Packet

The newly added MNP in the proposed model follows a specific format, as depicted in Figure 5.3. The MNP includes several fields, such as name, content, nonce, and guider. The definitions of nonce and guider are consistent with those found in normal data packets, as previously explained in the NDN architecture packet format specification. However, in PMMM, the MNP is repurposed to serve as a means to notify the network about producer mobility events. To accommodate this functionality, modifications and additional fields are introduced in the MNP by leveraging the capabilities of the NDN-CXX module.

One of the added fields in the MNP is the "status" field. This field is used to differentiate between different types of mobility management packets. Specifically, the status field can have a value of either 0 or 1. A status value of 0 indicates that the MNP is notifying the forwarding pipeline about the detachment or unavailability of a producer in the network. This information is crucial for the network to adjust its routing and forwarding behaviour accordingly. When the forwarding pipeline receives an MNP with a status value of 0, it triggers the MNP forwarding function to proceed with forwarding the MNP until it reaches the consumer or consumers. Additionally, the MNP includes a "packet type" field, which indicates the type of packet it is. In this case, the packet type is set to indicate that it is an MNP. This field helps in identifying and processing the MNP correctly within the network.

### 5.3.2 Mobility Update Packet

The MUP in PMMM follows a specific format, which is illustrated in Figure 5.3. Several fields in the MUP, such as content, nonce, and guider, are identical to those found in data packets, as defined in the NDN packet format specification. The MUP shares a similar structure to the MNP, with the key difference lying in the values of the "status" and "packet type" fields. The MUP is triggered when it receives a status value of 1. This status value indicates that the producer has connected or become reachable within the network. Upon receiving a status value of 1, the forwarding pipeline triggers specific functions that assist the MUP in reaching the next router or, ultimately, the consumer.

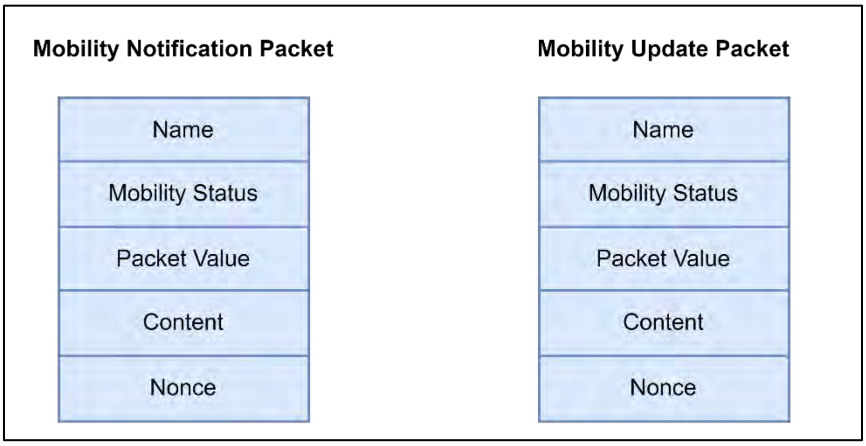



*Figure 5.3.* Mobility Management Packets Structure

Similar to the MNP, the MUP also includes the "packet type" field. In the case of the MUP, the packet type is set to "active." This value serves to notify the consumer about the reachability or attachment of the producer to a new router within the network. The "active" packet type field ensures that the consumer is informed of the producer's availability and can initiate Interest packets to retrieve the desired content from the producer. The integration of the PMMM into the NDN data structure supports smooth communication between consumers and producers. As shown in Figure 5.4, the NDN data structure analyses incoming packets to determine their type. The PMMM structure then processes the packets based on their mobility and packet values. Normal Interest and data packets follow the standard NDN forwarding path. However, MUPs and MNPs are processed by an additional forwarding structure.

Together, the MNP and MUP significantly lower signalling costs by minimizing unnecessary requests and ensuring timely updates about producer availability. This efficiency is crucial in dynamic environments where mobility can lead to frequent changes in network topology. By quickly notifying consumers of a producer's relocation and availability, both packets contribute to reduced handoff latency.

Consumers can access content more rapidly, leading to a smoother experience and higher content retrieval rates. In summary, the specific design of the MNP and MUP is justified by their roles in efficient communication, resource management, and user experience enhancement. Their formats are tailored to address the challenges of mobility, ensuring that network performance remains optimized even as producers relocate.

For sudden disconnections, the model employs the MNP to promptly inform consumers of the producer's temporary unavailability, preventing unnecessary requests and reducing network congestion. Additionally, fallback mechanisms allow consumers to switch to alternative content sources or cached data, ensuring continuity of service. In the case of prolonged handoffs, the PMMM incorporates graceful handoff protocols that maintain connections during transitions, coupled with buffering strategies that store incoming requests until the producer is available.

The transmission pipeline for mobility management packets, specifically the MNP and MUP, is designed to integrate seamlessly with existing NDN forwarding mechanisms, significantly reducing latency in dynamic networks. When a producer relocates, it first generates an MNP to notify specific consumers of its temporary unavailability, followed by a MUP to announce its new location. These packets are routed through NDN's content-based forwarding mechanisms, which direct them based on content names rather than specific locations. The MNP targets only interested consumers, preventing unnecessary traffic, while the MUP is broadcast across the network to inform all nodes of the producer's new location. This approach allows routers to update their forwarding tables and caches swiftly, ensuring that subsequent Interest packets can be directed to the new producer’s location without additional delays. By anticipating changes in producer availability, the MNP and

MUP effectively reduce handoff latency and minimize retransmissions, leading to a more responsive and efficient content retrieval process. When the producer initiates mobility and moves from CR3 to CR4, it sends an MNP from CR3 as shown in Figure 5.4. This MNP is recognized by each subsequent router along the path to the consumer. When the producer connects to CR4, it sends an MUP, which is recognized by the extended forwarding data structure on each router. As a result, the Interest and data paths before and after the handoff maintain an optimal communication path between the consumer and the producer, despite the producer's mobility.

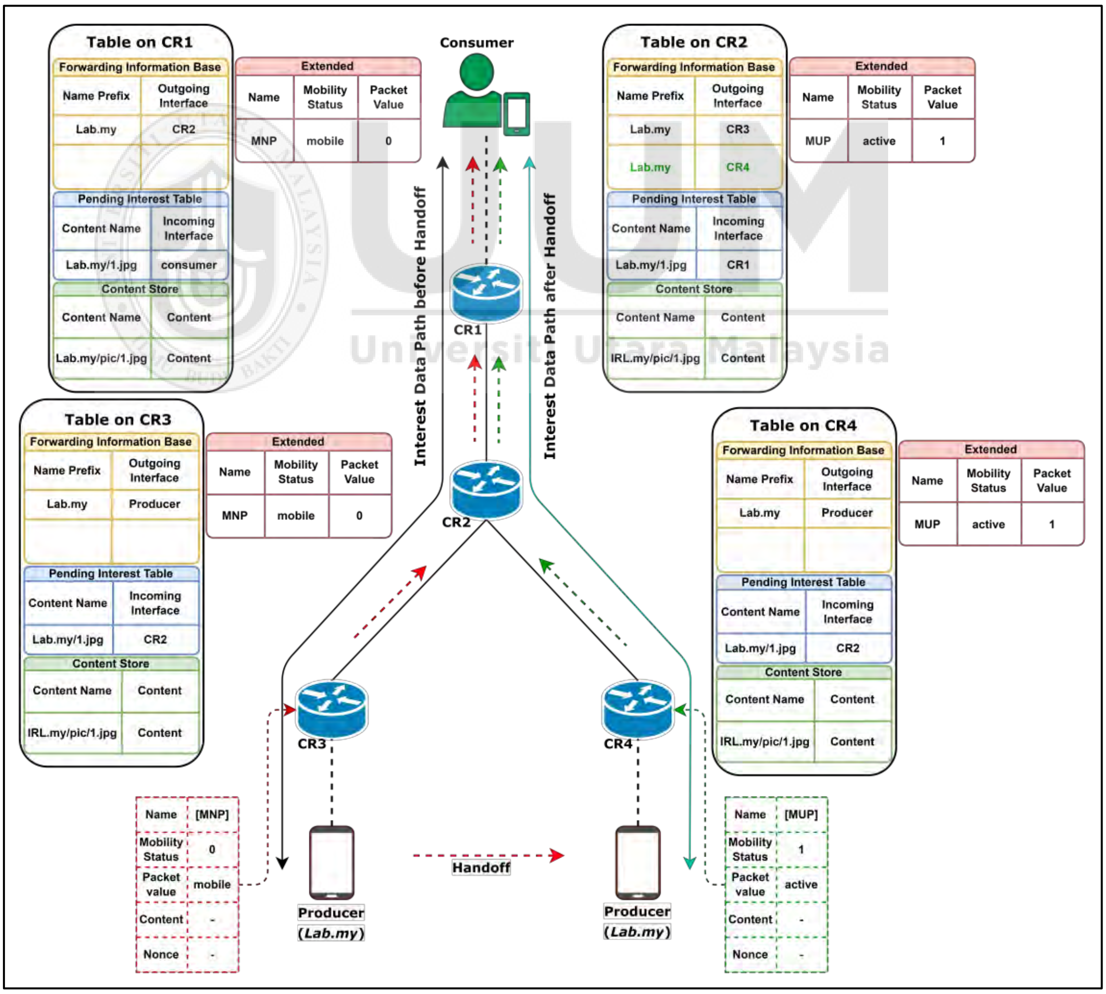




*Figure 5.4.* The Integration of PMMM in NDN Data Structure

The proposed model for communication between the consumer and producer is depicted in illustrated Figure 5.5. To effectively achieve the objectives, it is assumed that the consumer and producer engage in communication. The detailed description of the communication flow is as follow:

1. The consumer, located at CR1, initiates the communication by sending an Interest packet (*/ndn.mp4*), which is situated at (*IrLab.com*) attached to the CR3. This Interest packet expresses the consumer request for data.

2. The producer responds to the consumer request by supplying the data in succession of versions and segments, each corresponding to the Interest packets. These packets are recognized as (*IrLab.com/ndn.mp4/v1/sn).* Where '*n*' represents a sequential number (e.g., $n = 1, 2, 3,$ and so on).

3. At a particular point, when producer initiate to change its location, it notifies its mobility by sending MNP from CR3 until the CR1. This packet aware the consumer relating the producer mobility.

4. Upon receiving the MNP, the consumer pauses the Interest scheduling event for the specific producer prefix which is extracted by the MNP.

5. The producer completes the handoff process by relocation from CR3 to CR4. From CR4, it sends MUP to update its location towards the network and consumer.

6. The consumer generates an Interest packet (*/ndn.mp4*) to gets the remaining contents (*IrLab.com/ndn.mp4*).

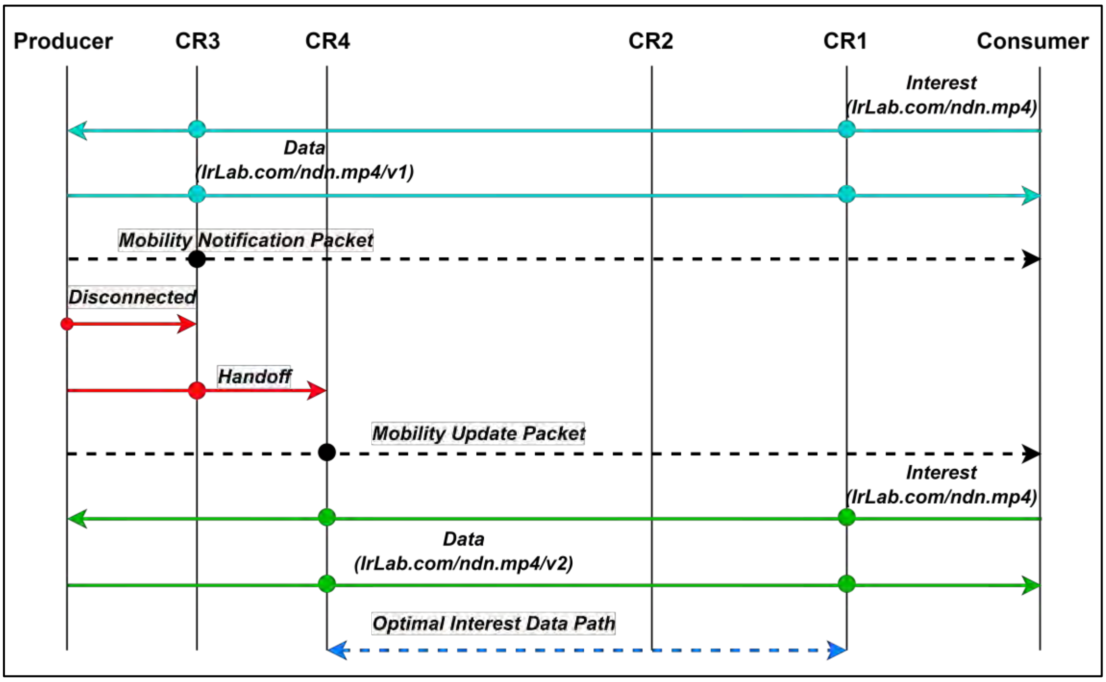



*Figure 5.5.* Message Flow in Proposed PMMM

## 5.4 Application

In NDN, the application refers to a service that used NDN paradigm to perform several tasks such as content distribution, content retrieval and real time communication. To use these services the NDN architecture introduced two types of application that helps to create network communication environment. The producer application and consumer application. Both applications build with several functions in order to communicate between them.

The consumer responsible for sending Interest packet and producer responsible to forwards the appropriate data packet by following the Interest packet traces. In order to implement the proposed mobility management packets, it is a need to modify the normal consumer and producer application.

### 5.4.1 Producer Application

The producer application is composed of several functions, but the most fundamental function of the producer is to receive and send packets. In order to support the proposed PMMM model, additional functions have been introduced and existing functions have been modified. Whenever the producer initiates a move or is about to disconnect, it informs the network about its detachment. To inform the network, the producer triggers the mobility management packet through the attached router.

In Figure 5.6, the producer analyses a weak signal using PoA (Point of Attachment). This analysis triggers the dissociation function, which in turn activates other functions. The producer prepares the MNP packet by including the mobility status and the packet value. The mobility status is utilized by the NDN protocol to perform additional operations, as described in Section 5.5. On the other hand, the packet value is used by the consumer to understand the current state of the producer. Once the MNP packet is ready, the producer schedules its transmission at a frequency of one. If it is the first time the packet is being sent, it proceeds normally as built. However, if the packet has been sent before, the frequency is reset to one again to avoid excessive signalling. After the scheduling, the packet is forwarded to the NDN forwarding protocol, which further processes the packet based on its assigned values. Overall, this process ensures that the producer's weak signal is effectively analysed and the resulting MNP packet is transmitted and processed in a controlled and efficient manner.

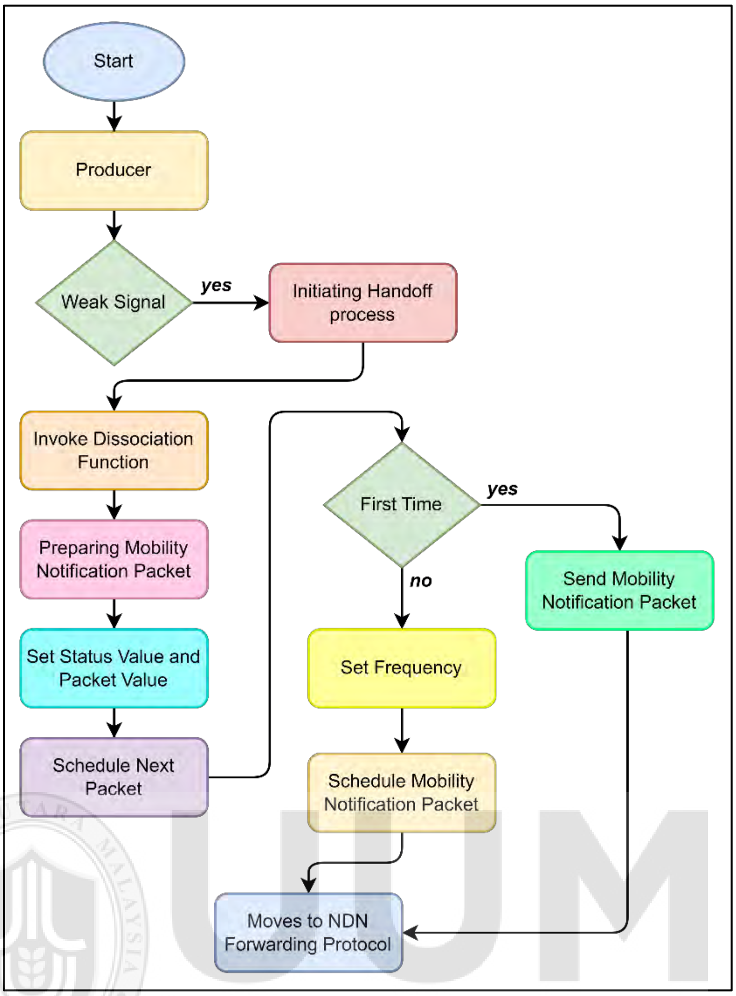



*Figure 5.6.* Producer Dissociation Function Flow Control

Based on the PMMM concepts, Table 5.2 shows the algorithm of producer dissociation function. Lines 1 and 2 of the algorithm express the occurrence of possible events and frequency as an input. Lines 5 to 10 represent the start of case *sp*, where the application begins by gathering network interfaces, adding producer prefix, and scheduling the next packet. Case *oa* from lines 11 to 15 triggers the dissociation function that invokes the MNP function. The activation of the dissociation function is connected to the router's main function, which notifies any changes in the router node list. The case *snmp* is described in lines from 16 to 42, where the MNP packet is built, and the status value is set to 1 and packet value to 'mobile'. It also sets the packet name, signature for security purposes, freshness period, and call the schedule function to forward the packet. The case *snp* is articulated in lines from 43 to 46, where the packet is scheduled by triggering events. If it is being sent for the first time, it will move normally; otherwise, it will be sent by adding frequency.

Table 5.2

*Algorithm on Dissociation of Producer in PMMM*

**Algorithm 5.2: Producer Dissociation Function**

1. **Possible Events:** start of application *sp*, schedule next packet *snp,* on dissociation *oa,* send mobility notification packet *smnp*
2. **Input:** Set m_frequency to 1.0
3. Set m_firstTime to true
4. **Switch** *Event* **do**
5. **Case** *sp* **do**
6. **Function** StartApplication()
7. Get network interface
8. Start adding prefix with interface and cost in FIB
9. Call ScheduleNextPacket
10. **End**
11. **Case** *oa* **do**
12. **Function** OnDissociation()
13. Get Dissociation notification
14. Call SendMNP
15. **End**
16. **Case** *smnp* **do**
17. **Function** SendMNP(dataName, pushMNP) **is**
18. **If** m_active is false **then**
19. Return
20. **End if**
21. Create a shared pointer to a data object and set it to data
22. Set data's name
23. Set data's freshness period to m_freshness milliseconds
24. Set data's content to a buffer of size m_virtualPayloadSize
25. **If** pushMNP is true **then**
26. Set data's status to 1
27. Set packet type to "mobile"
28. **End if**
29. Create a signature object and a signature info object with type value 255
30. **If** m_keyLocator has a positive size **then**
31. Set signature info's key locator to m_keyLocator
32. **End if**
33. Set signature's info
34. Set signature's value
35. Set data's signature
36. Call wireEncode on data
37. Call m_transmittedDatas with data, this, and m_face

```
  Call onReceiveData on m_appLink with data
 If pushMNP is true then
  Call ScheduleNextPacket
End if
End
Case snp do
Function ScheduleNextPacket
  If m_firstTime is true then
    Set m_sendEvent to Schedule(SendMNP, this, true)
    Set m_firstTime to false
Else if  m_sendEvent.IsRunning() is false then
Set m_sendEvent to Schedule(m_frequency, SendMNP, this, true)
 End
End
```

By referring to Figure 5.7, during producer mobility, it searches for the strong signal to the nearest PoA or CR. When producer found the strong signal and get attached to the new CR. This attachment triggers the association function, which in turn activates the other functions. The producer starts preparing the MUP packet by setting up the mobility status value and the packet value. The mobility status value is identified by the NDN forwarding protocol to perform additional operations, as stated in Section 5.5. On the other hand, the packet value is utilised by consumer to estimates the current state of the producer. On setting up the values, the producer schedules its transmission at a frequency of one. If it is the first time the packet is being sent, it proceeds normally as built. However, if the packet has been sent before, the frequency is reset to one again to avoid excessive signalling. After the scheduling, the packet is forwarded to the NDN forwarding protocol, which further processes the packet based on its assigned values. Overall, this process ensures that the producer strongly attached to the network and the resulting MUP packet is transmitted and processed in a controlled and effective manner.

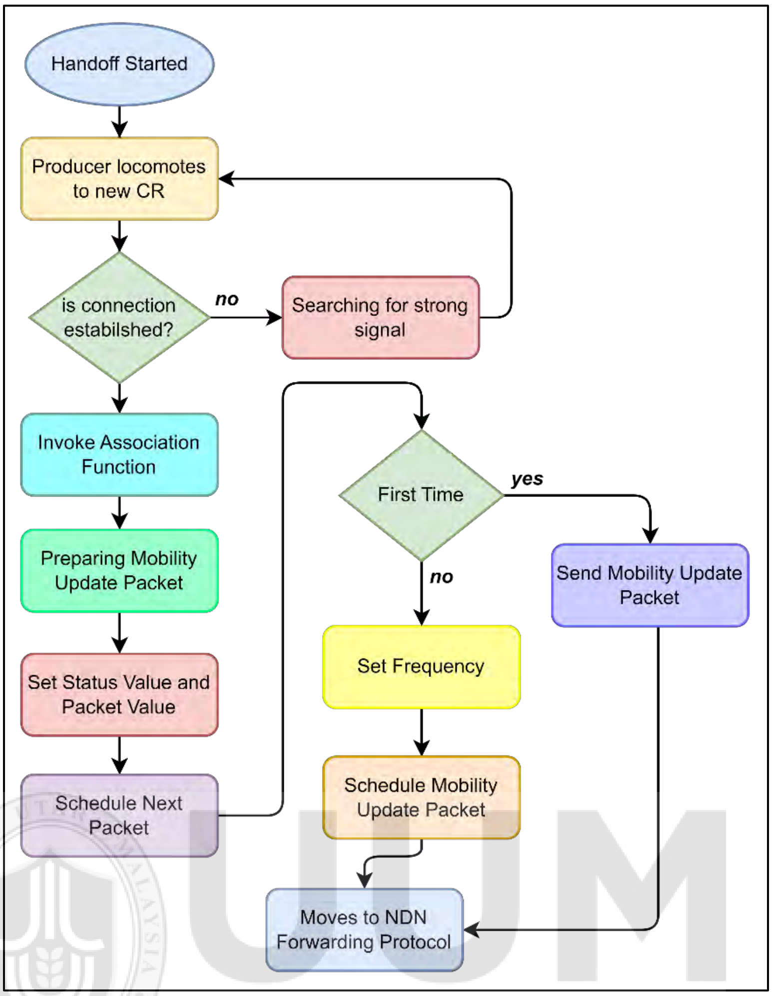



*Figure 5.7.* Producer Association Function Flow Control

Based on the PMMM concepts the Table 5.3 shows the algorithm of producer association function. Lines 1 and 2 of algorithm express the occurrence of possible events and frequency as an input. The lines 5 to 10 which represents the start of case *sp* that start of the application by gathering network interface and adding producer prefix and schedule the next packet. Case *oa* from lines 11 to 15 triggers the association function that invokes the MUP function. The activation of association function is connected to the router main function that notifies the any change in the router node list. The case *snmp* expressed in lines from 16 to 42 that build MUP packet and setting up the status value by 0 and packet value by "active". While it sets the packet name, signature for security purposes, freshness period and call the schedule function to forward the packet. The case *snp* articulated in lines from 43 to 46 that schedule the packet by triggering the events.

Table 5.3

*Algorithm on Association of Producer in PMMM*

**Algorithm 5.3: Producer Association Function**

1. **Possible Events:** start of application *sp*, on association *oa,* send mobility update packet *smup,* schedule next packet *snp.*
2. **Input:** Set m_frequency to 1.0
3. Set m_firstTime to true
4. **Switch** *Event* **do**
5. **Case** *sp* **do**
6. **Function** StartApplication()
7. Get Network Interface
8. Start adding prefix with interface and cost in FIB
9. Call ScheduleNextPacket
10. **End**
11. **Case** *oa* **do**
12. **Function** OnAssociation()
13. Get Assocication notification
14. Call SendMUP
15. **End**
16. **Case** *smup* **do**
17. **Function** SendMUP(dataName, pushMUP) **is**
18. **If** m_active is false **then**
19. Return
20. **End if**
21. Create a shared pointer to a data object and set it to data
22. Set data's name
23. Set data's freshness period to m_freshness milliseconds
24. Set data's content to a buffer of size m_virtualPayloadSize
25. **If** pushMUP is true **then**
26. Set data's status to 0
27. Set packet type to "active"
28. **End if**
29. Create a signature object and a signature info object with type value 255
30. **If** m_keyLocator has a positive size **then**
31. Set signature info's key locator to m_keyLocator
32. **End if**
33. Set signature's info
34. Set signature's value
35. Set data's signature
36. Call wireEncode on data
37. Call m_transmittedDatas with data, this, and m_face
38. Call onReceiveData on m_appLink with data
39. **If** pushMNP is true **then**
40. Call ScheduleNextPacket

```
End if
End
Case snp do
Function ScheduleNextPacket
  If m_firstTime is true then
    Set m_sendEvent to Schedule(SendMUP, this, true)
    Set m_firstTime to false
Else if m_sendEvent.IsRunning() is false then
    Set m_sendEvent to Schedule(m_frequency, SendMUP, this, true)
End
```

The NDN application comprises both a producer and a consumer application. Any changes made to the producer and forwarding protocol directly affect the efficiency of the consumer application. The PMMM design modifies the forwarding protocol and producer applications. As a result, the consumer application needs to be modified or developed in accordance with the changes introduced in the protocol and producer application. This ensures that the consumer application can effectively understand and interact with the communication process. By maintaining synchronization between the producer, forwarding protocol, and consumer application, a seamless and efficient communication flow can be achieved in the NDN application.

### 5.4.2 Consumer Application

The consumer application contains several functions, but the main function of consumer is sending Interest packet to get contents from producer or content routers. In order to send Interest packet, the consumer uses the schedule the packet's function. To support PMMM model vision, the additional function has been added and modifies the consumer application function.

According to PMMM, the producer sends multiple packets to effectively manage mobility in an ongoing communication network. These packets play a crucial role in assisting the management of consumer Interest packet transmission control during the producer handoff process. The producer mobility management packets, as depicted in Figure 5.8, are received by the consumer during communication. Upon receiving a packet with a specific packet type value (as specified in Section MNP and MUP), the consumer is able to identify and recognize the packet.

Once the consumer recognizes the packet, it analyses the value contained within it. If the value is "active," the consumer proceeds with scheduling the packets accordingly. However, if the packet value indicates "mobile," it signifies a change in the producer's mobility status. In response to the "mobile" packet value, the consumer takes appropriate action and pauses the scheduling of new Interest packets. This allows for the necessary adjustments to be made due to the mobility of the producer. By implementing this process in accordance with PMMM, the producer and consumer are able to manage mobility effectively within the ongoing communication network, ensuring efficient packet transmission and maintaining synchronization between the two entities.

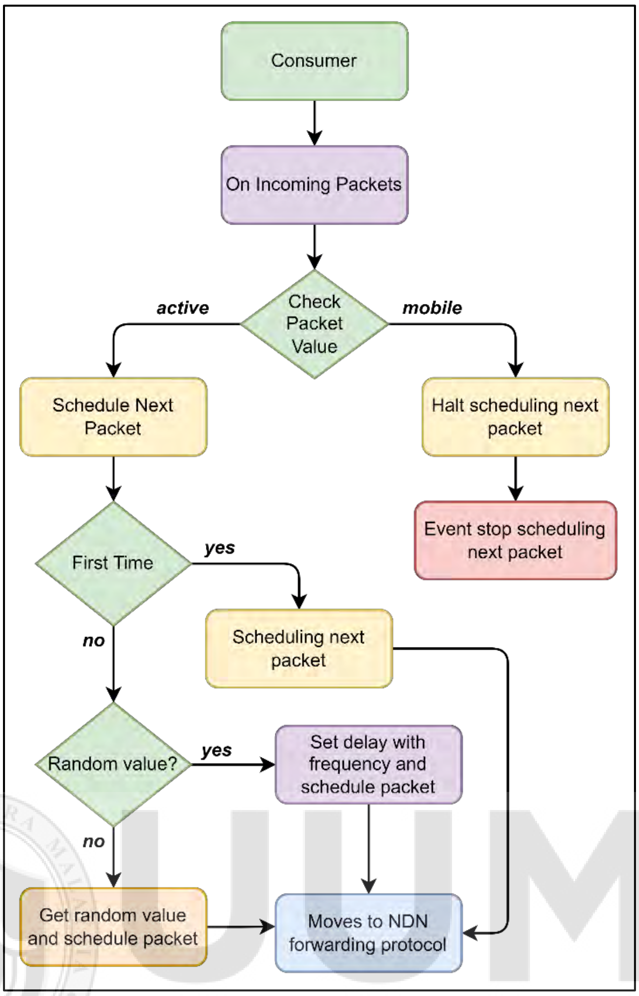



*Figure 5.8.* Consumer Flow Control Operation



Based on the PMMM concepts the Table 5.4 shows the algorithm of consumer that shows the modification and addition of function. Line 1 express the occurrence of possible events in the consumer application. Lines 2 to 11 represent the start of the case *od*, where it calls the base function whenever the data received by the consumer from producer. Whenever a data received by the consume, it is monitor by the consumer, if it gets the packet value, it is divided into two possible outcomes. If the packet value gets the value “mobile” as in line 6, it triggers the next line function that pause the packet scheduling process. While if the packet value gets the “active” entry, it triggers the next packet as in lines 9 and 10. Case *snp* is articulated in lines from 15 to 23 that schedule the Interest packet by triggering the events.

Table 5.4

*Algorithm for Consumer in PMMM*

**Algorithm 5.4: Consumer Function**

```
Possible Events: on incoming data packets od, schedule next packet snp.
Case od do
Function OnData(data)
    // Call the base class's OnData method
    App::OnData(data)
    If data.getPacketValue("mobile") is true then
        call ScheduleNextPacketHalt()
        m_sendEvent Schedule::Stop()
    else If data.getPacketValue("active") is true then
        call ScheduleNextPacket()
    end if
End Function
Case snp do
Function to process the packets towards producer
Function ScheduleNextPacket()
    If m_firstTime is true then
        m_sendEvent = Schedule(Seconds(0.0), SendPacket, this)
        m_firstTime = false
    else if m_sendEvent is not running then
        interval = (m_random == 0) ? Seconds(1.0 / m_frequency) : Seconds(m_random->GetValue())
        m_sendEvent to Schedule(interval, SendPacket, this)
    end if
End Function
```



### 5.5 Mobility Management Packets Transmission Pipeline Design

The forwarding process is a crucial component of the NFD that encompasses various methods and functions responsible for controlling the flow of Interest and data packets. In the design of PMMM, the conventional forwarding function is modified to incorporate additional functions for handling mobility management packets. The additional functions establish the forwarding paths to handle the mobility management packets received by the forwarder, enabling the smooth management of mobility. By referring to Figure 5.9, when a packet enters the forwarder in the PMMM architecture, it undergoes analysis. If the packet's status value is determined to be 0, it is identified as an MNP packet. The status value is typically set by the application, as explained in Section 5.3.1. The forwarder then stores the MNP packet as data in the CS and retrieves the FIBs associated with the next hops. Next, the forwarder iterates through the FIBs to identify similar Interest packets based on the prefixes of the MNP packet. If a matching Interest name is found, the forwarder forwards the MNP packet along the same path as the incoming Interest packet. However, if no matching Interest is found, indicating a lack of pending Interests for the corresponding content, the forwarder declines further processing of the MNP packet. This decision helps avoid unnecessary signalling cost.

On the other hand, if the forwarder encounters a packet with a status value of 1, it identifies it as an MUP packet. Similar to the MNP packet, the status value for MUP packets is set by the application, as explained in Section 5.3.2. When the forwarder identifies an MUP packet, it broadcasts the packet to the next hop lists, ensuring that all relevant nodes in the network receive the update. During this process, the forwarder extracts the incoming packet's prefix and interface information. Subsequently, it creates an extended FIB and updates it with the new interface path. This update ensures that the extended FIB reflects the latest network topology and availability of resources.

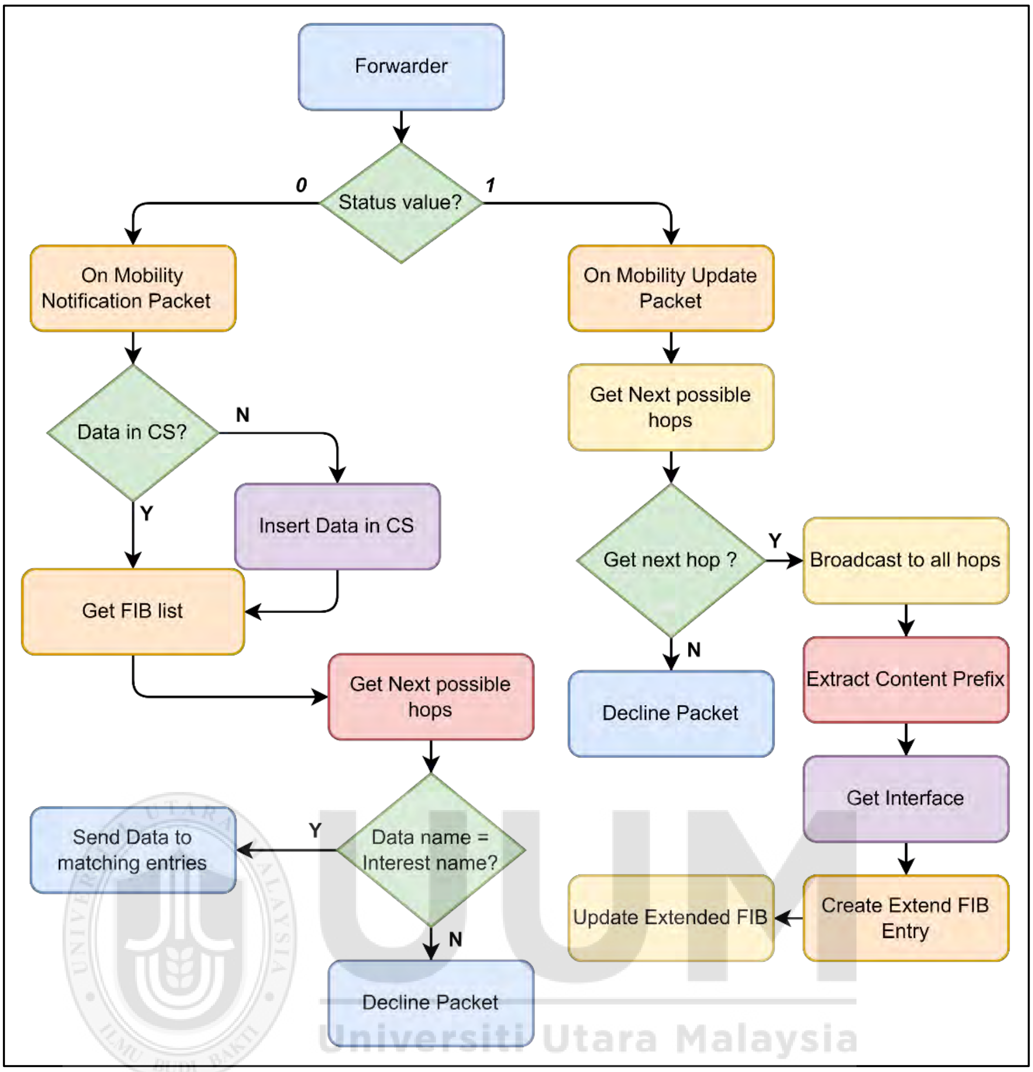



*Figure 5.9.* Forwarding Pipelines Function Flow Control in PMMM

The table represents the PMMM-based forwarding algorithm, which introduces a new forwarding pipeline to support mobility management packets. The first line describes the possible events that can occur in the forwarding pipeline. The first case *pf* that start from lines 2 to 14 explains the packet forwarding function that differentiate among the incoming packets based on status value. If the status value is 0 at line 7, the packet is identified as an MNP packet and is redirected to the next function stated in line 17. On the other hand, If the status value contains 1 at line 11, the packet is identified as a MUP packet and further lead by the specific function starting from line 43.

The case *omnp* describes the handling of incoming MNP packet. The MNP is recognised as unsolicited data packet and cached into the CS by changing the caching policy, as explained in section 5.2.1.1. Additionally, the FIBs collect the next hop list and search for the matching Interest packets to forward the MNP packet. If a matching MNP prefix is found same as an Interest name, the forwarder extracts the incoming face from PIT in record and forward the MNP along the same path. However, if no matching name found, the packet is dropped immediately to prevent excessive and unnecessary signalling.

The case *omup* at line 43 describes the operations involved in handling MUP packet. When an MUP packet is identified, the forwarder initiates the process by creating a PIT to keep track of pending Interests for this packet. Next, the forwarder searches the FIB to determine the next hop or hops for the MUP packet. If a matching entry is found in the FIB, indicating the presence of reachable destinations, the forwarder proceeds to broadcast the MUP packet to the entire network. Broadcasting the packet ensures that all relevant nodes in the network receive the update. During the process, the forwarder extracts the name prefix and incoming interface from the MUP packet. The name prefix provides information about the specific content or resource being updated, while the incoming interface indicates the interface through which the packet arrived. Additionally, the forwarder updates the extended FIB by broadcasting the packet information that corresponds to the name prefix. This update ensures that other nodes in the network are informed about the changes in the network topology or availability of resources. However, if no suitable next hop or related FIB entry is found upon the arrival of the MUP packet, the forwarder decides to decline further processing of the packet. This decision helps prevent unnecessary signalling or communication attempts when there are no appropriate destinations or routes available.

Table 5.5

*Algorithm for Consumer in PMMM*

**Algorithm 5.5: Packet Forwarding pipelines**

```
Possible Events: forwards the incoming packets pf, On incoming mobility notification packet
omnp, On incoming mobility update packet omup
Case pf do
Mobile Producer connected/disconnected to point of attachment.
Input: a face object inFace and a data packet object data
Function: PacketFowarder(inFace, data, interest):
//If the data packet has a status of 0, it is a mobility notification packet
If data←getStatus() == 0: then
// Call the function to handle the mobility notification packet and forward it to the next hops
This←onMobilityNotificationPacket(inFace, data)
//If the data packet has a status of 1, it is a mobility update packet
If interest←getStatus() == 1: then
//Call the function to handle the mobility update packet and forward it to the next hops
This←onMobilityUpdatePacket(inFace, interest)
End Function
Case omnp do
//Function call On Mobility Notification Packet
Funciton: onMobilityNotificationPacket(inFace, data)
//Caches the incoming data packet
If !(data in CS) then
Insert Data in CS
//Using the FIBs to get next hops for matching data name
Const fib.FIBEntry = fibEntry← findLongestPrefixMatch (data.getName)
Const fib.NextHopList = fibEntry← getNextHops
For next hops do
If hops.Cost < min.Cost then
      minCost ← hops.Cost;
    end
end
for Possible next hops do
  if hop.costs == mincosts then
//Extract the matching packets with data name
Find in record do
if data.getName == interest.getName
  send data to the matching nexthops
else
// To avoid excessive signalling
data.decline
  end
end
End Function
Case omup do
//Function call On Mobility Update Packet
Funciton onMobilityUpdatePacket(inFace, interest)
If (interest) then
      Find next hop
Get possible next hops from FIB Interface
For next hop do
```

```
If hop.cost < min.cost then
      minCost ← hop.Cost;
    end
end
For Possible next hops do
  If hop.cost == mincost then
for create PIT do
if interest.getName
  send to the nexthops
  Call L44
else
// To avoid excessive signalling
interest.decline
end
//Update the FIBs
If get ← producer face & Nexthops then
Extract content prefix
Get interface
Update ExtendedFIB.entry ← MUP
broadcast.prcocess (MUP to available faces)
else
//To avoid high signalling packets
interest.decline
  end
end
End Function
```

## 5.6 Numerical Performance Evaluation



The performance evaluation refers to assessing and measuring the effectiveness of a network model in solving a specific concern. The numerical and simulation performance evaluations are the two different ways to measure the performance of the proposed model [85, 94]. Therefore, the design of the PMMM is evaluated numerically with the benchmarking studies before the simulation implementation to further validate and verify the model in the network. The performance measurement includes several performance metrics such as handoff latency, signalling cost, and the path optimization. The network analysis model is shown in Figure (4.3) that contains the consumer, producer, and several content routers. The total wireless and wired link delay between two consecutive nodes is defined in Chapter Four, Equations 4.1 and 4.2. Further, the network analysis model parameters values are shown in Table 4.5. The wired and wireless transmission latency between the consumer, producer, content routers are expressed as in Equations 5.1 and 5.2.

$$TLat_w = \ b \times L_{wd\_Up\_Ack/wd\_MobInt/wd\_TraceIntData} \tag{5.1}$$

$$TLat_{wl} = \ a \times L_{wls\_Up/wls\_MobInt/wls\_TraceIntData} \tag{5.2}$$

Where the $L_{wd\_Up\_Ack/wd\_MobInt/wd\_TraceIntData}$ shows the certain type of data packet used in wired link in each solution such as IBM, PMSS, KITE, and PMMM. Similarly, the $L_{wls\_Up/wls\_MobInt/wls\_TraceIntData}$ shows the certain type of Interest packet in wireless link in order to create a link. By employing the hop formulation, it is straightforward to assess the comprehensive performance of the network. This includes evaluating factors such as handoff latency, signalling cost, and path optimization.

### 5.6.1 Handoff Latency

The handoff latency is total time that a producer disconnects, reconnect, and arriving of first Interest packet on new connection. To measure the handoff latency, we use the hop count method. It measures the distance between two consecutive nodes. Each content router associated with link delay, queuing delay, and bandwidth for both wired and wireless connection as in 4.1 and 4.2.

By referring to Figure 5.10 shows the handoff latency impact with respect to wireless link failure probability variation. The results show the PMMM has the lowest latency as compared to IBM, PMSS and KITE. While, the IBM and KITE has the highest latency caused by the signalling process. KITE uses two types of packets to setup the connectivity and IBM also uses two types of packets to manage connectivity. Additionally, both solutions use the immobile anchor as a centralize controller between consumer and producer that creates non-optimal path between consumer and producer communication. The PMSS uses a MI packet along with immobile anchor to manage and continue the network connectivity. Further, the PMSS solution creates the sub optimal path between consumer and producer that shows the lower in latency as compared to IBM and KITE.

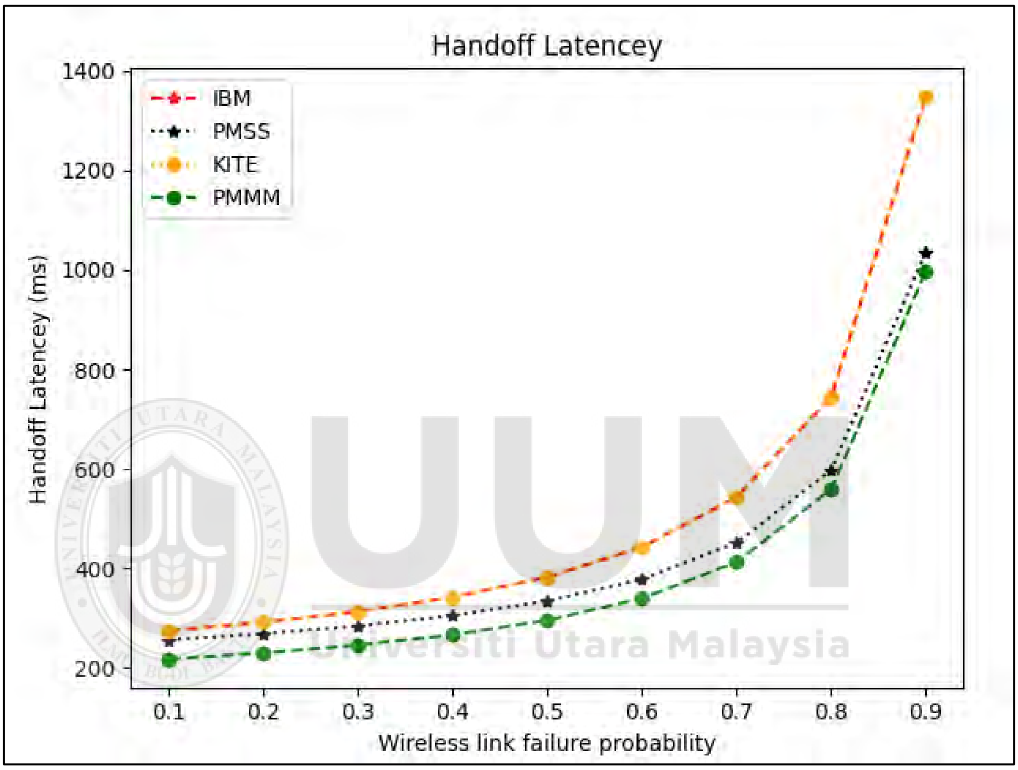



*Figure 5.10.* Handoff Latency Variation with Link Failure Probability

Whereas PMMM uses MUP to continue its network connectivity in short period of time and uses the optimal path without involving of any static node or centralize controller or immobile anchor node. Hence, the results reflect that the PMMM outperforms IBM, PMSS, and KITE in comparison. This outcome attributed to the fact that a signalling process MNP was initiated prior to the handover taking place. Further, the Table 5.6 shows the difference between each solution. Where, the PMMM shows the lowest level of handoff latency during 0.9 probability as compared to IBM, PMSS and KITE.

Table 5.6

*Numerical Results on Handoff Latency with Link Failure Probability*

| Probability | IBM | PMSS | KITE | PMMM |
|---|---|---|---|---|
| 0.1 | 274.9778 | 256.3556 | 274.9778 | 217.7556 |
| 0.2 | 291.7455 | 268.5273 | 291.7455 | 229.9273 |
| 0.3 | 313.3039 | 284.1766 | 313.3039 | 245.5766 |
| 0.4 | 342.0485 | 305.0424 | 342.0485 | 266.4424 |
| 0.5 | 382.2909 | 334.2545 | 382.2909 | 295.6545 |
| 0.6 | 442.6545 | 378.0727 | 442.6545 | 339.4727 |
| 0.7 | 543.2606 | 451.103 | 543.2606 | 412.503 |
| 0.8 | 744.4727 | 597.1636 | 744.4727 | 558.5636 |
| 0.9 | 1348.109 | 1035.345 | 1348.109 | 996.7455 |



### 5.6.2 Signalling Cost

The handoff signalling cost denotes the quantity of data packets or messages exchanged between the initial sender and final recipient, encompassing all successive hops, during the handoff phase. For the formulation of our handoff signalling cost analysis, we employed a similar hop count methodology as previously applied in our handoff delay investigations. By referring to Figure 5.11, shows the correlation between the handoff signalling cost and subnet crossing rate among the IBM, PMSS, KITE, and PMMM. The subnet crossing rate refers to transitions of mobile device from subnet to another within large network. A higher subnet crossing rate means the device frequently switches between different networks, while a lower rate indicates it stays on the same network for longer periods.

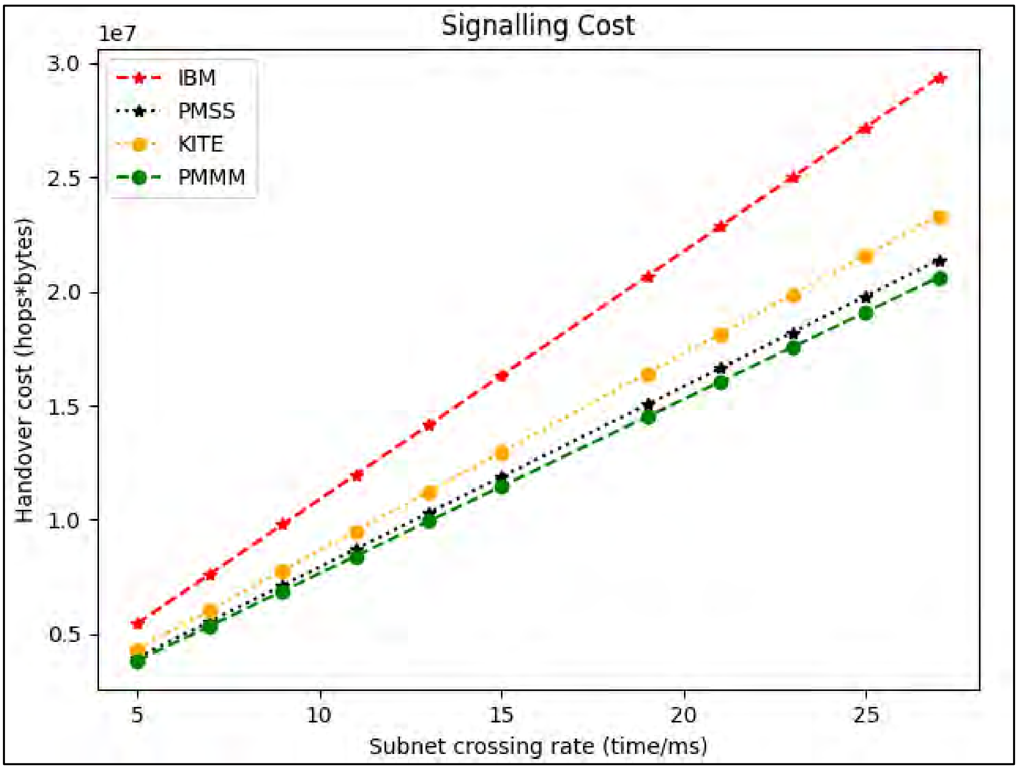



*Figure 5.11.* Signalling Cost Variation with Subnet Crossing Rate

The IBM shows the higher level of signalling cost produced by the binding update and binding acknowledgement signalling messages. Additionally, the signalling messages increases the stretch ratio due higher hop count and triangular routing to setup the path. Similarly, the KITE uses the two packets and an immobile anchor to maintain the communication, but it shows the less in signalling cost as compared to KITE due to the strategical placement of the immobile anchor or less in path stretch ratio. The PMSS shows the lowest signalling cost as compared to IBM and KITE due to use of one type of signalling packet and an immobile anchor to continue the interrupted communication. While the PMMM shows the lowest level of signalling cost among all the solutions which reflets the better performance of solution. The PMMM creates the optimal path without involving any immobile anchor or centralize controller that improves its signalling costs.

### 5.6.3 Path Optimization

The path optimization is measured after the completion of producer handoff process, and the packets between consumer and producer moves through the new shortest route of communication. Further, it includes the consumer Interest packet that's moves to producer and in response the data. The Figure 5.12 represents the data packet delivery cost of all solutions that includes IBM, PMSS, KITE, and PMMM.

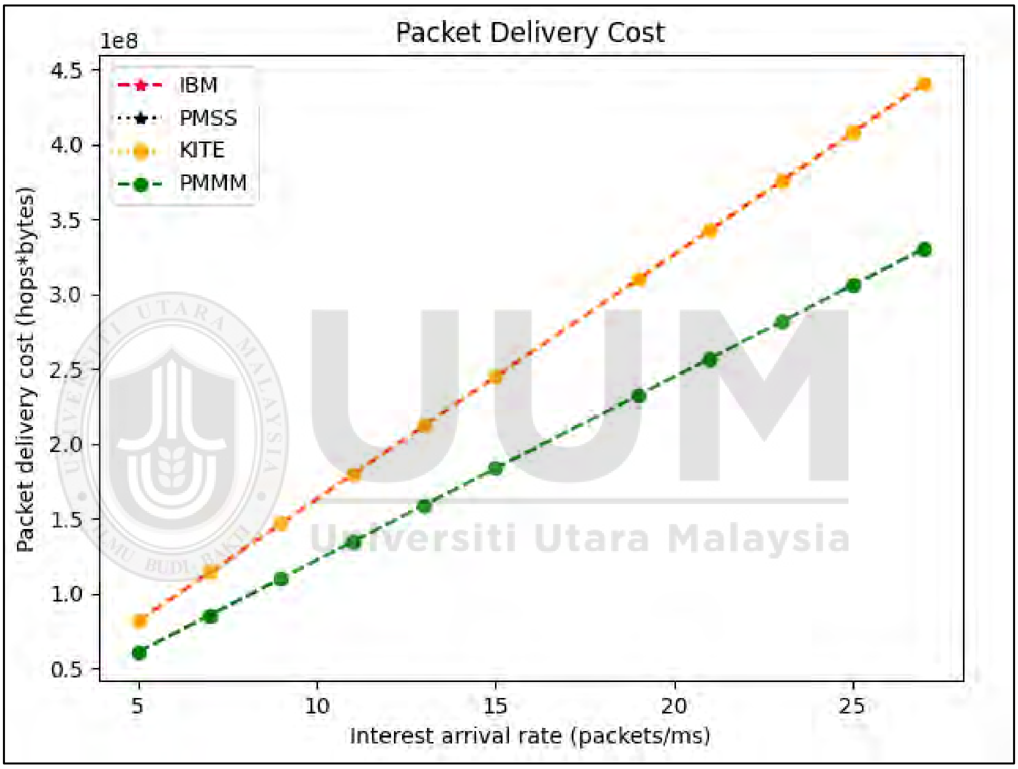



*Figure 5.12.* Packet Optimization Cost with Interest Arrival Rate

The results show the overall packet delivery of PMMM is lowest and the PMSS delivery ratio overlaps the PMMM trendline due to same delivery ratio. Both solutions optimise path for the Interest and data packet delivery while eliminating the reliance centralized or immobile anchor node. However, the IBM and KITE solutions exhibits a higher level of packet delivery cost caused by the additional hops such as immobile anchor. This immobile anchor introduces a path stretch ratio, which impacts the efficiency and cost-effectiveness of the delivery process. Therefore, the KITE and IBM solutions trendline overlaps caused by the similar delivery cost.

Through the numerical performance evaluation comparing the proposed PMMM with benchmarking studies such as IBM, PMSS, and KITE, it has been consistently observed that PMMM outperforms in all performance metrics. The superior performance of PMMM can be attributed to its optimal routing approach towards the consumer and its innovative anchorless methodology. Unlike the benchmarking studies, which rely on anchor points to manage mobility in the network, PMMM eliminates the need for such anchor points, thereby reducing the overhead and minimizing additional hops in the network. These findings highlight the potential of PMMM as a promising solution for efficient and reliable communication in mobile networks.

## 5.7 Summary

This research proposes a solution called PMMM, which aims to provide seamless support for producer mobility in NDN. PMMM incorporates mobility management packets specifically designed to facilitate producer mobility. The mobility management packets consist of two types: mobility notification packets and mobility update packets. These packets play a crucial role in managing the mobility of producers within the NDN architecture. To handle the mobility management packets, the normal forwarding mechanism is updated to accommodate the specific requirements of PMMM. This ensures that the packets are correctly processed and forwarded within the network. Additionally, both the consumer and producer applications are designed and modified to align with the working of PMMM. These modifications enable the consumer and producer applications to effectively interact with the mobility management packets and adapt to the changing mobility status of producers. By implementing PMMM and incorporating the mobility management packets, seamless producer mobility is achieved within the NDN framework. The modified forwarding mechanism and synchronized consumer and producer applications ensure efficient communication and support for mobility management in the network.

# CHAPTER SIX

# PRODUCER MOBILITY MANAGEMENT MODEL SIMULATION IMPLEMENTATION AND EVALUATION

This chapter provides the implementation and evaluation of the PMMM. The previous chapter elaborate in-depth the PMMM, including the design of mobility management packets and the supportive forwarding strategy. Moreover, the overall performance of PMMM is validated and evaluated, demonstrating its high level of performance and robustness. This chapter further elaborates on the PMMM and implements it in a simulation environment. For a better understanding and validation of PMMM, its performance is compared with KITE and PMSS. The chapter involves several sections which starts with the setting up of the suitable environment for the PMMM implementation and simulation. Additionally, it provides the simulation parameters, topologies, and scenarios. Sections 6.3 and 6.4 delve into designing tools for the accurate implementation of PMMM and measuring the accuracy of PMMM, respectively. The last section highlights the envisioned results from the various execution of the simulation with the benchmarking studies.

## 6.1 Implementation and Simulation Environment

The PMMM is effectively implemented in the NDN-based simulator, known as ndnSIM. To measure the performance of PMMM, it is analysed and simulated under a control environment in ndnSIM. The ndnSIM is built upon the open-source Network Simulator 3 (NS-3). It provides high accuracy and dependable simulation results that make it ideal and a first choice among the NDN developers and researchers. Additionally, it provides real-world scenarios in simulation experiments that ensures the high practical applicability of applications. The ndnSIM is developed with a modular approach which is based on several C++ classes, libraries, methods, and functions to model the performance of NDN entities. These entities include the Faces that assist the application and network nodes to communicate with each other. In addition, it contains CS for caching contents, FIB for routing decisions, and the PIT for monitoring the Interest status. The ndnSIM outperform in its capability to assist the flexible modification and change of a particular component without impacting on the other parts of the system or components.

The design of ndnSIM developed by the incorporation of NDN protocol stack (ndn::L3 Protocol) as a core component. Additionally, the ndn-cxx library and the NFD as a forwarding component uses different strategies to process packets. All these well-structured modulars enables to customize and simulates the various namespaces, strategies, modifications, and scenarios within the NDN environment. However, implementing extensive modifications in NDN protocol stack and its supporting libraries experience several significant challenges. These include high technical complexity, potential malfunctions or unresponsive behaviour from the modified components, an overall reduction in efficiency compared to more streamlined models, unusual behaviour of network nodes, and less stable forwarding update. Furthermore, the potential for introducing bugs or regressions during the integration process can compromise the stability and reliability of the NDN network, which is a critical concern for many real-world deployments. These challenges underscore the importance of careful planning, thorough testing, and robust change management processes when making extensive updates to the NDN protocol stack and its supporting libraries. Therefore, to address these issues, the core NDN components are carefully customized and enhanced within a controlled test environment. This approach allows for targeted improvements while maintaining stability and performance, rather than making broad, potentially disruptive modifications to the entire protocol stack.

Regardless of network-layer protocol model, it effortlessly incorporates with different link-layer protocol such as LTE (Long Term Evolution), CSMA (carrier sense multiple access), wireless and so on. Moreover, it offers the comprehensive collection of interfaces that improve the functionality. The interface involves applications face abstraction and network device face. The interface utilized by the consumer, producer, and network router to link and establish network communication model. To analysing the performance of several model, it provides the various helpers module that generates the simulation traces. The helpers such as NDN stack helper, global routing, strategy choice, and link control provides the detailed tracing about the network traffic behaviour and performance of each component in NDN.

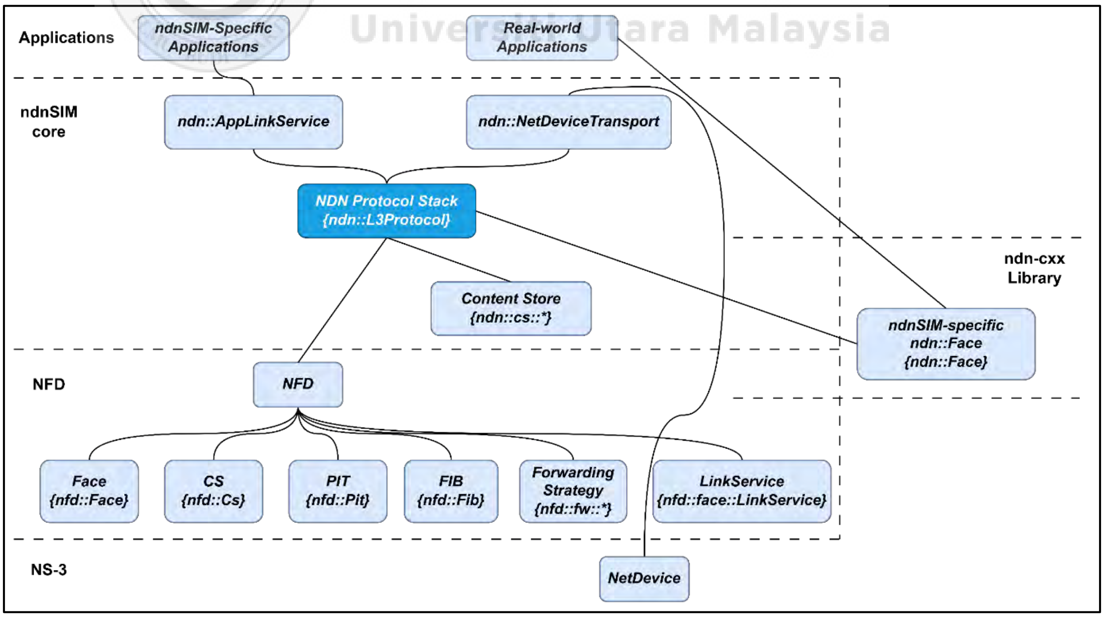



*Figure 6.1.* The Core Structure of ndnSIM

The several basic features, components and the structural design principles of components are illustrated in Figure 6.1. The Linux distribution 20.04 LTS operating system is used as the platform for the PMMM simulation implementation, which is one of the required platforms for the installation of the NS-3 network simulation tool. In order to analysing the different network layers, the NS-3 as a discrete-event simulator primarily focuses on the layers 2,3 and 4 of the network stack. The NS-3 is broadly uses for the Internet system modelling and different network communication modelling. While, for the successful simulation implementation of PMMM, NS-3 is integrated with the ndnSIM 2.6 that configured with the Linux distribution 20.04 LTS operating system.

### 6.1.1 Algorithm's Implementation

The implementation of the PMMM simulation model follows the comprehensive proposed algorithm, as outlined in Table 6.1. The algorithm provides the several steps and settings to run the simulation code. It involves the creation and placement of network node, the network topology plugin, wired and wireless node links configuration, selection of mobility model and configuration of mobility model, and configuration of content store. Additionally, it includes the installation of NDN helper stack, configuration of forwarding strategy according to the intended PMMM design and mobility management packets. Furthermore, it contains helper classes to monitor the packet flow and creates the trace file to evaluate the performance metrics.

The lines 1 to 4 declare the input variables and constant values. It sets mobileNodeSize to 3, indicating that three mobile nodes will be managed in the simulation. The speed variable is assigned a value of 50, likely representing the movement speed of these nodes in specified units. Lastly, StopTime is initialized to 100. The lines 5 to 7 create the default configuration and links between the nodes and channel. It establishes a PointToPointNetDevice with a data rate of 1 Mbps and a PointToPointChannel featuring a 20 ms delay, simulating realistic data transmission conditions. Additionally, a DropTailQueue is set with a maximum capacity of 10 packets to mimic network congestion. The lines 8 to 10 describe the topology selection through topology plugin. The code then defines a Node Container for network nodes and uses a TopologyReader to select between a Grid or Abilene Topology. Finally, it reads and instantiates the nodes based on the chosen topology, laying the groundwork for the simulation.

The lines 11 to 18 explains the selection and configuration of the wireless module that involves the PHY layer, MAC layer, and Wi-Fi model. It begins by creating a WifiHelper instance and sets the Wi-Fi standard to 802.11b. A YansWifiPhyHelper is initialized to define the physical layer, including channel settings and transmission power parameters. The WifiMacHelper is set up for an ad-hoc Wi-Fi MAC type and installed on the specified nodes. The lines 19 to 25 delineates the mobility model and configuration of the mobility model connected to the nodes and devices. A MobilityHelper is created, and a NodeContainer named MobileNodes is populated with the previously defined number of mobile nodes. The mobility model is configured to allocate positions and install a constant position model. Finally, it sets a RandomWalk2dMobilityModel, defining bounds, distance, and speed for the mobile nodes, enabling dynamic movement within the simulation.

The lines 26 to 29 explains the configuration and installation of the NDN stack that enables the NDN data structure and features on each node. It begins by initializing an ndnHelper instance, configuring an LRU content store with a maximum size of 1000, and enabling default routing before installing the stack across all nodes. The lines 30 to 41 comprehensively explains the PMMM configuration that involves the mobility management packets and PMMM forwarding strategy along with the consumer and mobile producer. A prefix is defined as "/prefix," and faces are installed for the mobile nodes. The code then establishes a default strategy (either MNP or MUP) for the specified prefix and installs the forwarding strategy. Following this, a consumer application (ConsumerCbr) is created and configured with the prefix, then installed on the consumer nodes. Similarly, a producer application (MobileProducer) is set up with the same prefix and installed on the mobile producer nodes. Finally, the global routing helper registers the origins for both the producer and mobile nodes under the defined prefix, facilitating data retrieval and distribution in the NDN framework.

The lines 42 to 50 elaborates the KITE solution configuration that based on service anchor/rendezvous sever along with the PIT forwarding strategy and mobile nodes. It begins by setting a default rendezvous prefix (rvPrefix) as "/prefix" and installs a forwarding strategy for the PIT. An RVHelper application is initialized to manage rendezvous anchors, with attributes set for the rendezvous prefix, and is installed on all nodes. Next, a server application (rpHelper) is set up for a Facebook server and installed on the designated server node. Finally, the code initializes a general application helper for the mobile nodes, installing the application on them. This setup facilitates the integration of rendezvous-based data retrieval in the simulation.

The lines 51 to 62 explains the PMSS solution configuration that contains MI packet with broadcast strategy, consumer, and mobile producer. It starts by setting a prefix as "MI/prefix" and installs the NDN stack on the mobile nodes. The default prefix for MI is defined as "/prefix," and a broadcasting strategy is installed for handling data transmission. Following this, a consumer application (ConsumerCbr) is created and configured with the prefix, then installed on the consumer nodes. Similarly, a producer application (MobileProducer) is set up with the same prefix and installed on the mobile producer nodes. Finally, the global routing helper registers the origins for both the producer and mobile nodes under the specified prefix, enabling effective data sharing and retrieval in the PMSS framework.

The lines 63 to 67 describe the simulation stop time, helper class to generates the trace file. The code snippet initiates the simulation for the PMMM, KITE, and PMSS solutions. It sets the simulator to stop after the defined StopTime. To facilitate performance analysis, it installs trace file generators: L2RateTracer for link layer drop rates, saving results to "Drop-rate.txt," and L3RateTracer for layer 3 rate tracking on the mobile nodes, outputting data to "Rate-trace.txt." After setting up the tracing, the simulator is executed with the Run command, and once the simulation concludes, it cleans up resources with the Destroy command, ensuring proper termination of the simulation environment.



Table 6.1

*The PMMM Solution Implementation Algorithm*

**Algorithm 6.1: Scenario File**

1. **Initialize** variables
2. **int** mobileNodeSize = 3
3. **int** speed = 50
4. **int** StopTime = 100

   ***//The default configuration of point-to-point links and channels parameters***
5. **Set** Default PointToPointNetDevice, DataRate = 1Mbps
6. **Set** Default PointToPointChannel, Delay = 20ms
7. **Set** Default DropTailQueue, MaxPackets =10

   ***//Adding the Grid and Abilene Topology Plugin and set P2P link***
8. Node Container nodes
9. TopologyReader.Set (Grid Topology or Abilene Topology)
10. Nodes = TopologyReader.Read

    ***//Adding wireless module configuration***
11. WifiHelper wifi
12. wifi.SetStandard(WIFI_PHY_STANDARD_80211b)
13. YansWifiPhyHelper wifiPhy = YansWifiPhyHelper
14. wifiPhy.SetChannel(wifiChannel)
15. wifiPhy.Set(“TxPowerStart”, “TxPowerEnd”, “TxPowerLevels”, “TxGain”)

16. WifiMacHelper wifiMac
17. wifiMac.SetType(AdhocWifiMac)
18. wifi.Install(wifiPhy, wifiMac, nodes);
    ***//Adding Mobility module and configuration***
19. MobilityHelper mobility
20. NodeContainer MobileNodes
21. MobileNodes.Create (mobileNodeSize)
22. Mobility.SetPositionAllocator (posAllocate)
23. Mobility.SetMobilityModel(ConstantPositionMobilityModel)
24. Mobility.Install (MobileNodes)
25. mobility.SetMobilityModel (RandomWalk2dMobilityModel = Bounds (area), Distance, Speed)
    ***//Installation of NDN stack helper***
26. StackHelper ndnHelper
27. ndnHelper.SetOldContentStore (CS = LRU, MaxSize = 1000)
28. ndnHelper.SetDefaultRoutes (true)
29. ndnHelper.InstallAll()
    ***//PMMM solution Selection***
30. Set Prefix = "/prefix"
31. FaceContainer → faces = ndnHelper.Install (MobileNodes)
    ***//PMMM Solution Selection***
32. SetDefault (MNP or MUP.Prefix = /prefix)
33. StrategyChoiceHelper.InstallAll (PMMMFowarding.Strategy)
    ***//Install Consumer and Producer***
34. AppHelper consumer (ConsumerCbr)
35. consumer.SetPrefix (prefix)
36. consumer.Install (consumer Nodes)
37. AppHelper producer (MobileProducer)
38. Producer.SetPrefix (prefix)
39. Producer.Install (MobileProducer)
40. ndnGlobalRoutingHelper.Add Origins (prefix, MobileProducer)
41. ndnGlobalRoutingHelper.Add Origins (prefix, MobileNodes)
    ***//KITE solution Selection***
42. SetDefault (rvPrefix= /prefix)
43. StrategyChoiceHelper.InstallAll (PITFowarding.Strategy)
44. AppHelper RVHelper (RV) (Service/rendezvous Anchor)
45. RVHelper.SetAttributes("RVPrefix", String Value (rvPrefix))
46. RVHelper.Install (nodes.Get())
47. AppHelper rpHelper (Server) (Facebook Server)
48. ApplicationContainer serverApp = rpHelper.Install (serverNode)
49. AppHelper appHelper (MobileNodes)
50. ApplicationConatiner App = appHelper.Install (MobileNodes)
    ***//PMSS Solution Selection***
51. Set Prefix = "MI/prefix"
52. FaceContainer → faces = ndnHelper.Install (MobileNodes)
    ***//PMSS Solution Selection***
53. SetDefault (MI.Prefix = /prefix)
54. StrategyChoiceHelper.InstallAll (MI.Broadcast.Strategy)
    ***//Install Consumer and Producer Application***
55. AppHelper consumer (ConsumerCbr)
56. consumer.SetPrefix (/prefix)
57. consumer.Install (consumer Nodes)

```
AppHelper producer (MobileProducer)
Producer.SetPrefix (/prefix)
Producer.Install (MobileProducer)
ndnGlobalRoutingHelper.Add Origins (prefix, MobileProducer)
ndnGlobalRoutingHelper.Add Origins (prefix, MobileNodes)
//Start Simulation for PMMM, KITE, and PMSS.
Simulator → Stop (StopTime)
//Trace File Generator as an Output
L2RateTracer.InstallALL ("Drop-rate.txt")
L3RateTracer.Install (mobileNodes, "Rate-trace.txt")
Simulator → Run
Simulator → Destroy
```

### 6.1.2 Simulation Parameters

The simulation parameters refer to the configuration, settings, and variables needed to control the simulation environment. These parameters determine the behaviour and the outcomes of the simulation. The type of design being simulated, and the simulation's objectives determines the precise the parameters involved. The working mechanisms of these networking parameters closely mirror the real-world communication processes that govern actual network interactions. By reflecting the fundamental principles and constraints of physical network infrastructure, these parameters accurately simulate the transmission, routing, and exchange of data as it would occur in a live, operational environment. This tight coupling between the virtual and physical realms allows for realistic testing, modelling, and analysis of network behaviour, ensuring the fidelity of conclusions and insights derived from these simulated environments. Ultimately, the seamless integration of real-world networking dynamics into the parameter structures is what enables these virtual networks to serve as faithful representations of their real-world counterparts. Therefore, this research contains several simulation parameters such as mobility model, topologies, consumers, producer, and NDN set-up. Two different network topologies, Abilene and the 4x4 grid, are used for two distinct scenarios in the simulation environment. The speed of the mobile producer varies between 0 m/s and 100 m/s, depending on the specific setup of each scenario. A summary of the simulation parameters are their respective values is presented in Table 6.2.

Table 6.2

*Simulation Parameters Configuration and Associated Values*

| **Category** | **Parameters Names** | **Parameters values** |
|---|---|---|
| Mobility | Mobility Model | Random Waypoint Mobility |
| | Mobility Speed | 1 – 100 m/s |
| | Mobile Nodes | 1 – 5 m/s |
| | Network | 802.11n |
| NDN Configuration | Forwarding Strategy | Best Route |
| | Caching Replacement Strategy | LRU, 100 items each node |
| | Cache Size | 1000 Objects |
| | Interest Rate | 10/sec |
| | Data Packet Size | 1024 bytes |
| | Application | Consumer and Producer |
| Topology | Grid 4x4 | 1Gbps Link |
| | Abilene | 1Gbps Link |
| | Link Delay | 10ms |

### 6.1.3 Simulation Topologies



In network simulation environment, the simulation topology refers to the arrangement and the connectivity of network components. It determines how nodes, routers, or other network components are interconnected. Several research uses the several topologies in different scenarios. Owing to the previous research works, this research used the 16-nodes-based-grid (4x4) topology and Abilene topology. In essence, the grid and Abilene topologies represent different levels of abstraction and realism, each serving a specific purpose in network simulations. The grid topology provides a foundational, scalable framework for studying general network properties, while the Abilene topology offers a realistic testbed for investigating the performance and behaviour of a specific, historically significant network infrastructure. Additionally, it includes the mobile producer and consumers ranging from 1 to 3.

The topologies are generated by the simulation framework using separate files, which are subsequently read by the ndnSIM annotated topology reader module when the simulation is running. The Point-to-Point connections with a data rate of 1Gbps, channel delay of 10ms, and a maximum transmission queue size of 10 packets per link in both directions are used to connect the routers and consumers. During the simulation run, the application includes the given topology file for each scenario. Figure 6.2(a) shows the 4x4 grid topology and node placement, and Figure 6.2(b) shows the Abilene topology. These topologies have been selected out especially and used in the PMSS and KITE benchmark solution.

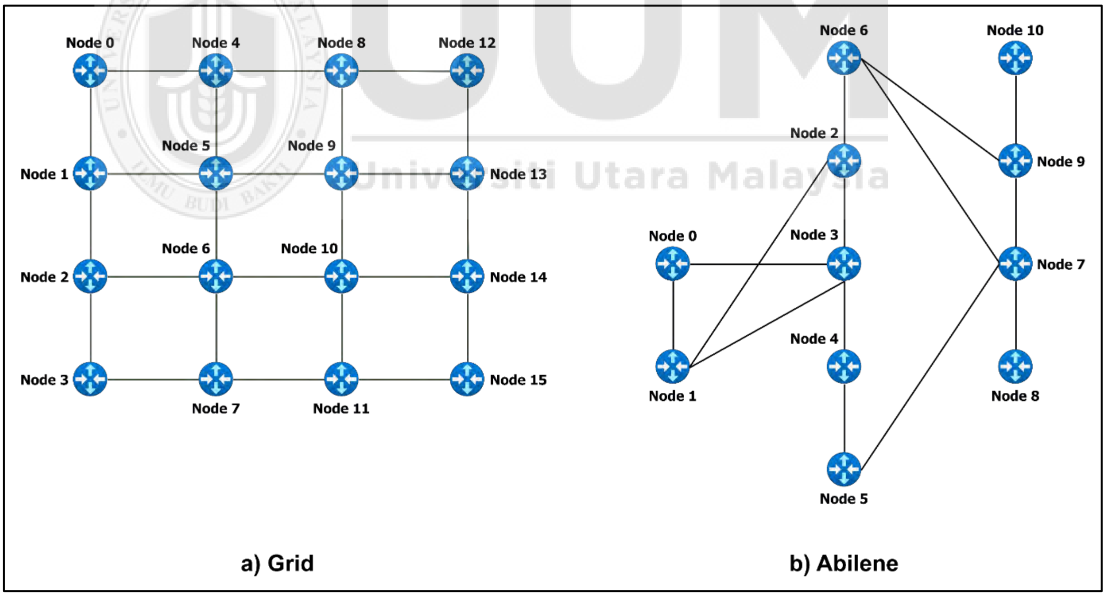



*Figure 6.2.* The Structure of Grid and Abilene Network Topologies in ndnSIM

### 6.1.4 Simulation Scenarios Design

The two scenarios, known as the Grid-based Scenario (GS) and the Abilene-based Scenario (AS), are built upon the 4x4 grid and Abilene topologies, respectively. These topologies are visually represented in Figure 6.2(a) and Figure 6.2(b). In GS, the simulation is performed by using the 4x4 topology, where the network nodes are placed in a grid-like arrangement. In AS, the simulation is implemented by organising the network node in Abilene topology, that shows the real-world network infrastructure known as Abilene network.

#### 6.1.4.1 Grid-based Scenario

The Grid-based Scenario (GS) network configuration consists of 4x4 grid topology that contains total 16 network nodes. These network nodes are placed 100 meters distance from each other in a grid topology. In addition, a mobile producer is placed in the scenario that can be change over time based on simulation parameters. The simulation runs interval is 100 seconds for each scenario. By default, GS contains the three consumers and one mobile producer in the grid. In each simulation scenario the number of mobile producers is adjustable. The mobile producer in GS moves randomly among the different Access Points (APs), where each AP covers the 400x400 square meters of area. The mobility speed of mobile producer is constant that ranging from 10 to 100 m/s. This mobility scenario allows the mobile producer to cover the wide area and navigate between the different APs during the simulation. In GS, the network nodes in the grid serves as router and AP that enables to communication between consumer nodes and mobile producer nodes. The proposed PMMM is implemented and evaluated with the benchmarking studies such as PMSS and KITE in this simulation scenario.

#### 6.1.4.2 Abilene-based Scenario

In contrast to the GS, the Abilene-based Scenario (AS) is configured with the Abilene network topology that consists of 12 to 13 nodes. In AS, the simulation is runs for 100 seconds and it contains number of mobile producer's range from 1 to 3.

The mobile producer in AS moves randomly among different APs with varies speed from 10 to 100 m/s. The proposed PMMM is implemented and evaluated with the benchmarking studies such as PMSS and KITE in this simulation scenario. To access the throughput and several other metrices the simulation time is varied from 0 to 100 seconds. These different scenarios able to measures the change int the throughput over the time in the PMMM and the benchmarking studies.

## 6.4 Designing Tools

To comprehensively evaluate the performance of the proposed PMMM, this research used an adequate operating system and simulation tools that are specifically used by the research communities in the ICN and NDN domain. These operating system and simulation tools are commonly recognized and widely used in NDN research community to access, analyse, and evaluates the performance of the NDN-based networking mechanisms.



***Ubuntu:*** This research used an Ubuntu 20.04 LTS version known as "Focal Fossa" which is a free and open-source operation system. The Ubuntu 20.04 provides the long-term support until the year of 2025 that ensures the accuracy and stability for the several data analysing tools and networking simulators. The networking research community freely benefit from the Ubuntu 20.04 ecosystem and executes the several scenarios under their respective simulator.

***NS-3:*** Network Simulator 3 (NS-3) is a freely open-source Discrete Event Simulation (DES) tool for modelling and analysing the network communications architecture and the Internet paradigm for the research and educational purpose. The NS-3 is allowing to integrate on several operating systems including Ubuntu. In this research, the NS-3 is installed on Ubuntu 20.04 LTS that provides the scalability to different network layers for research purposes. Additionally, it provides the integration of ndnSIM and several other modules for simulation experiment in NDN.

***ndnSIM:*** The ndnSIM is a freely open-source simulator that based on NS-3. The ndnSIM is uses to modelling and analysing several NDN communication models in NDN paradigm. It facilitates to implement several networks designs components and features in NDN. In this research, ndnSIM version 2.6 is managed to install on NS-3 as new network and transport layer. The ndnSIM is freely available under the terms of General Public Licences (GPL).

***Visual Studio:*** Microsoft developed Visual Studio Code (VS Code), a free and open-source coding editor. It is aimed at offering quick, lightweight, cross-platform environment for writing and debugging C++ based programming codes. Programmers, developers, and researcher easily debug C++ code right inside the editor owing to the robust built-in debugger, troubleshoot errors, and check variables. This research uses the VS code as a tool for writing codes and debugging codes.

***R-Studio:*** R-Studio is an open-source Integrated Development Environment (IDE) for R language that used for statistical computing and graphics. It provides the user-friendly interface and several libraries to analysis the large size data sets. This research uses the R-Studio to analyse the large size simulation trace files which are obtained by executing scenarios in ndnSIM. The obtained trace files are handled by the R language in R-Studio and plots the results in graphical representation. This software tool capable to handles the large data size trace files and its freely available under the Affero GPL.

### 6.5 Verification and Validation

The presented algorithms in section 6.1.1 are implemented in the ndnSIM using C++ programming environment for the purpose of verification and validation of PMMM. Additionally, the PMMM is evaluated with the benchmarking studies. The programming code are developed and intergraded within the ndnSIM modules that support the specifications outlined in this study. By referring to Figure 6.3 that shows the screenshot of the programming codes. To ensure the accuracy of the different scenarios, the several required C++ headers is included in the scenarios file. Additionally, it is validated in ndnSIM by compiling and linking these headers in the scenarios file. While the verification of the codes is identified by the running of the scenarios without any error. The configuration command is used to execute the code, on the successful execution it displayed the message build finished successfully as shown in Figure 6.4.

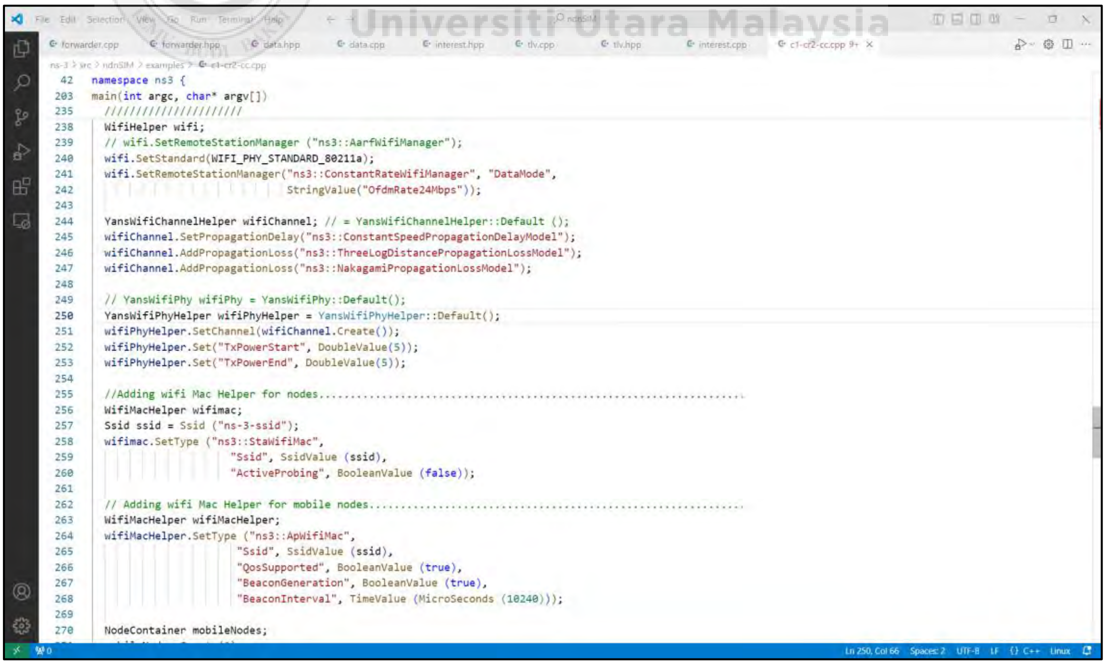


*Figure 6.3.* Showcase of Scenario File Programming Code

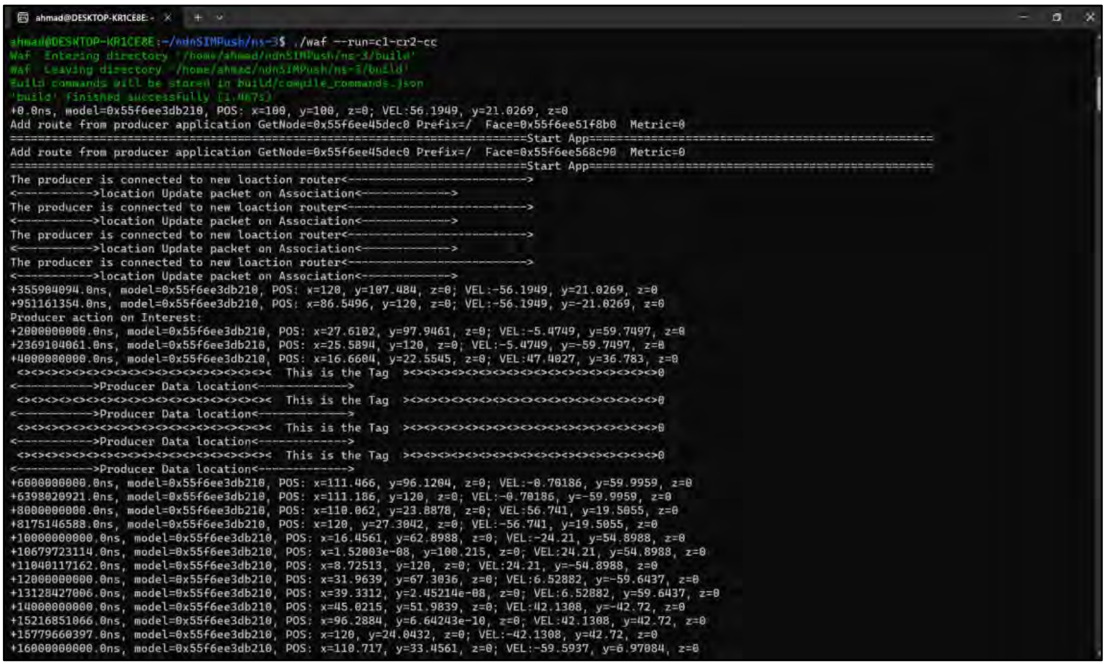



*Figure 6.4.* The Successful Execution and Build of Scenario File with Output

The on-screen simulation results are shown in Figure 6.4, which can also be saved in form of trace file in ndnSIM. The simulation results also be represented by the gettering the more than one trace files because the tracing helpers allows to read each node communication. By analysing and reading the trace files, it provides the efficiency of several performance metrics such as throughput, packets delivery, handoff signalling cost, packet delay, Interest losses, and hop count. The trace results are measured and stored in bytes which are known rate. This rate determines the packets received and forwarded by the network node during simulation in NDN environment. The trace file monitors and measures the Interest packet, the measurements are represented in the trace file such as In-Interest, Out -Interest, In-Satisfied-Interest, and Out-Satisfied-Interest. Similarly, the trace file also monitors, measures and represents the data packets measurement in the trace file. The output trace file is saved in text file format, while the information and values are organised in rows with tab separated. Additionally, the trace helpers class collects and aggregates the statistical information. The screenshots are presented in Figures 6.5 and 6.6 that signifies the trace files of application-delay and rate respectively.

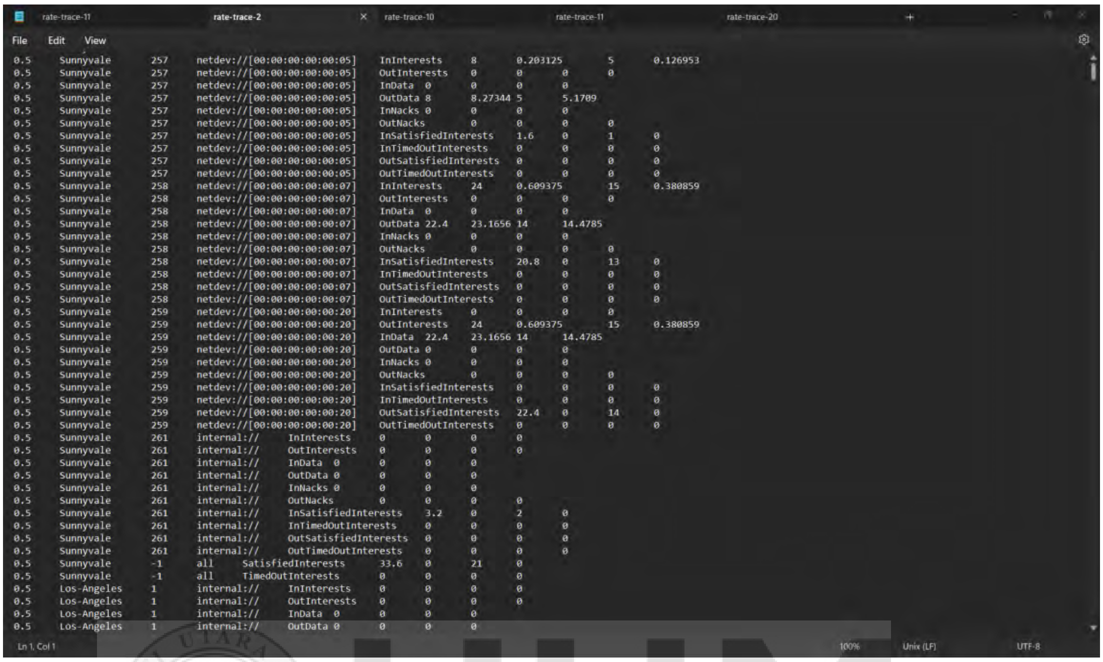


*Figure 6.5.* The Data Rate Trace File Output



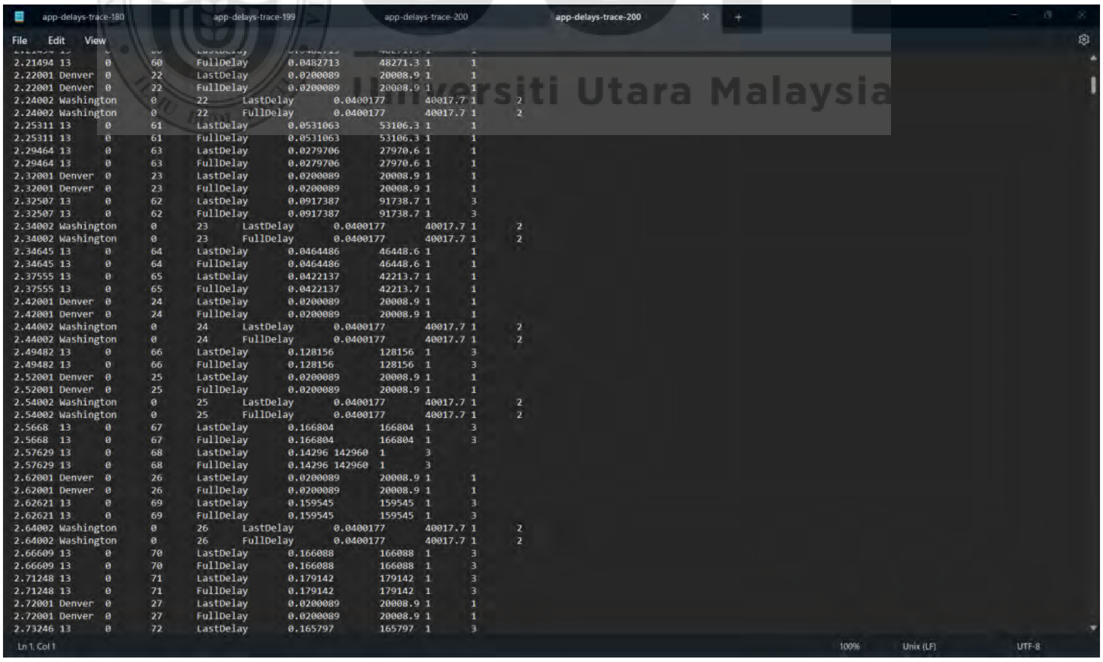


*Figure 6.6.* The Delay Rate Trace File Output

These trace files potentially used for the validation process of the PMMM. Moreover, it also helps to determines the performance of the systems by applying different metrics. The validation process of PMMM is successfully completed as shown in Figure 6.4 that shows the detailed output results in on-screen. Additionally, the Figures 6.5 and 6.6 are the trace files that are produced during the simulation time to monitor and analyse the simulation output. For the validation process, the particular field such as receiving Interest labelled as InInterest and the sent data labelled as OutData have acquire the attention that generates the detailed metrics results from trace file. Further, the PMMM is executed with the KITE and PMSS solution in both scenarios. Moreover, the simulation output is plotted on the graph, the simulation time is plotted on the x-axis while the InInterest and OutData is plotted on the y-axis.

The analysis shown in Figure 6.7 combines the source code, data fetched from the trace file, and a visualization of the results in a graph, providing a valid and comprehensive approach by using R-Studio. The results of GS and AS are plotted and illustrated in Figure 6.8 respectively that shows the overall performance of the PMMM, KITE, and PMSS. The Figure 6.8(a) shows the behaviour of the PMMM solution in the GS that is probably similar to the PMSS related to the InInterest and OutData as shown in Figure 6.8 (c) due to optimal path, while the Figure 6.8 (b) shows the KITE results that is bit difference as compared to the PMMM and PMSS due to non-optimal path behaviour in Interest and data transmission. However, the output of PMMM is notable different in term of OutData that is more stable as compared to the other solutions. This improved performance is due the optimal path communication that decreases the path stretch ratio and reduces the Interest packets loss, as demonstrated in Figures 6.8 and 6.9.

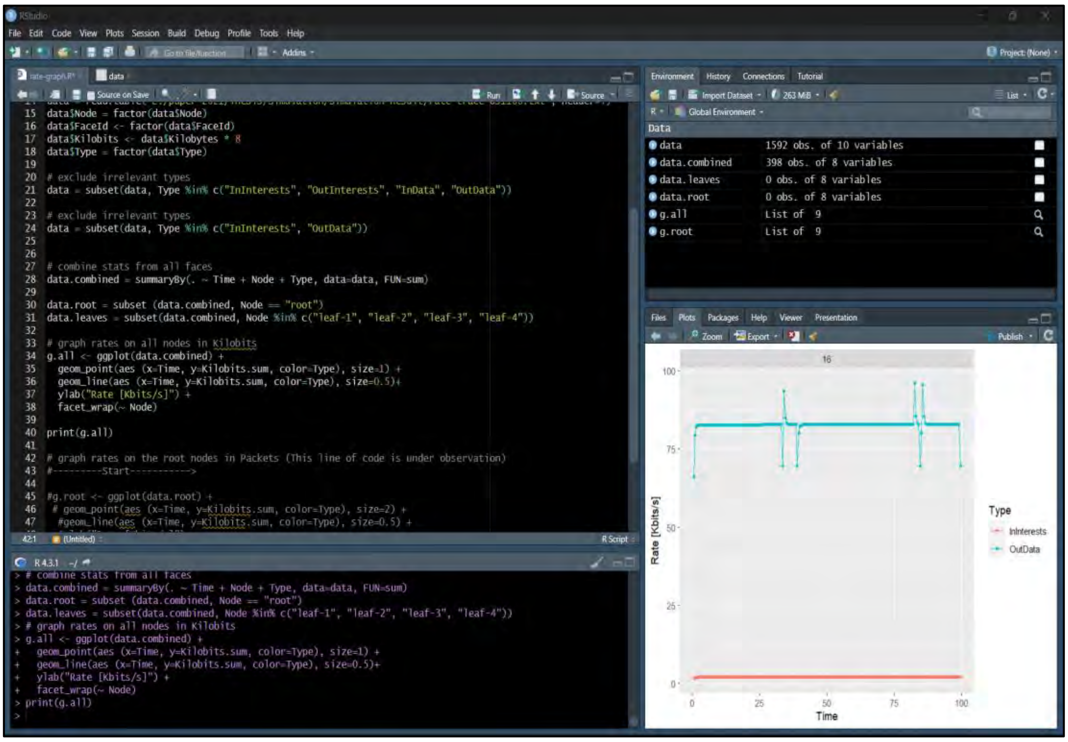
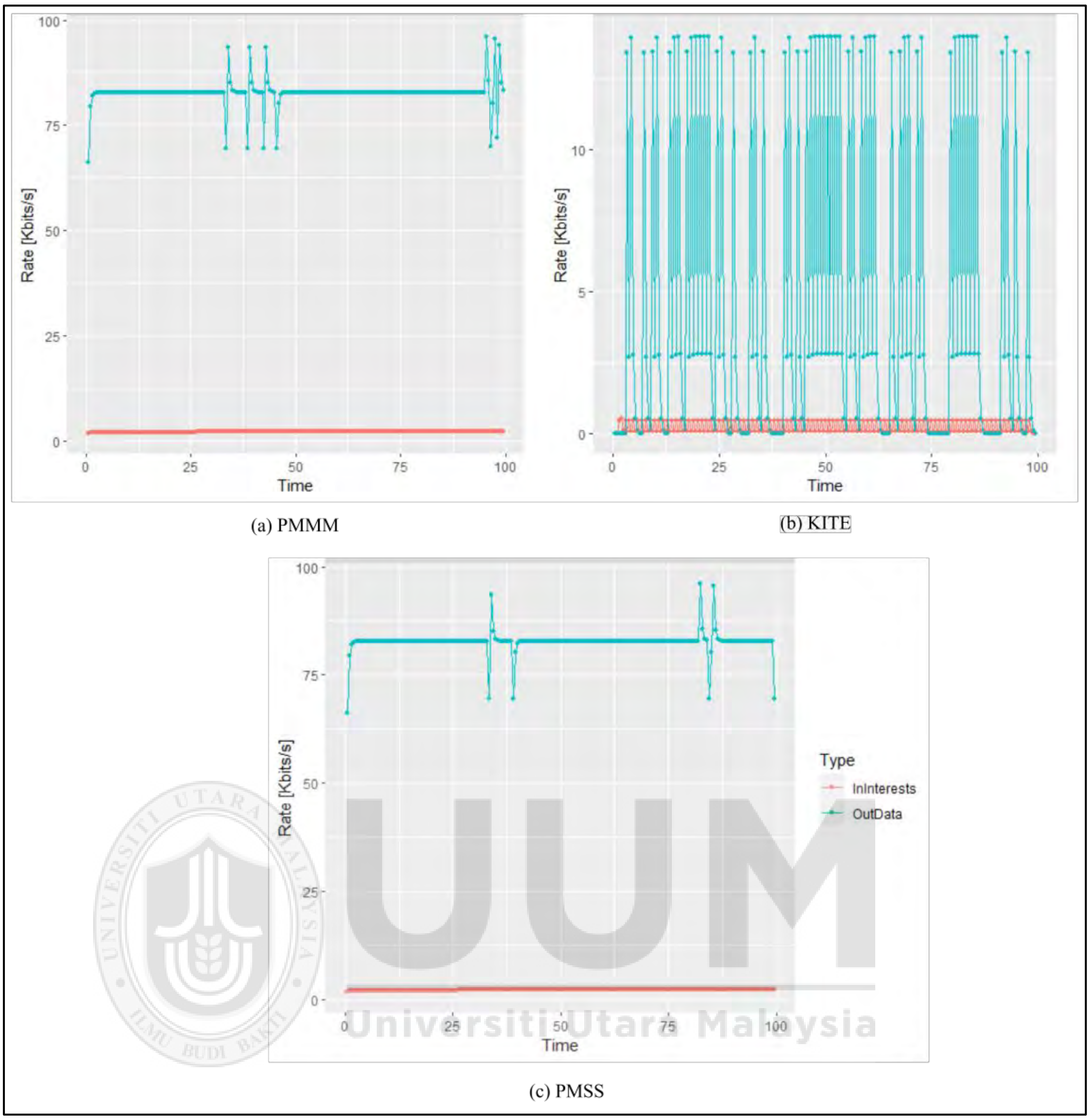



*Figure 6.7.* Uncovering Performance Bottlenecks Through Trace File Investigation in RStudio

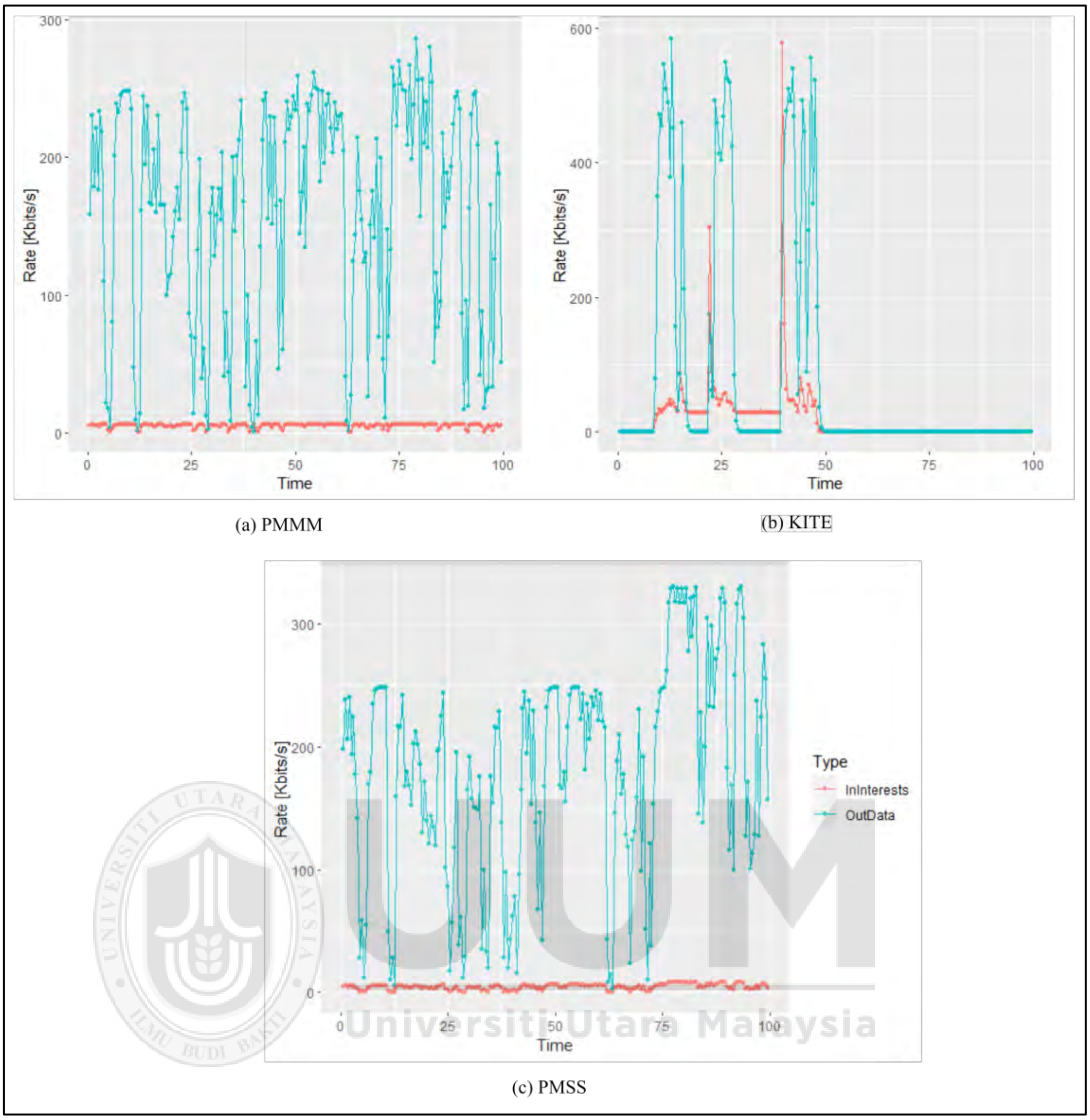



(a) PMMM

(b) KITE

(c) PMSS

*Figure 6.8.* The Interest Data Rate Validation of PMMM, KITE, and PMSS in GS




(a) PMMM (b) KITE (c) PMSS



*Figure 6.9.* The Interest Data Rate Validation of PMMM, KITE, and PMSS in AS

## 6.6 Simulation Results Analysis

The performance evaluation of the KITE and PMSS solution accomplished by using the two different methods such as analytical and simulation method. Whereas the IBM approach evaluated by using the analytical method only. In this study, the performance evaluation of the proposed PMMM evaluated through analytical modelling and through simulation. While the IBM approach evaluated through analytically only which is defined as approach in previous chapters. Therefore, the KITE and PMSS solutions are simulated and used for benchmarking with the proposed PMMM. Moreover, the KITE solution values are combined by using the average values of KITE both pull and upload pattern.

The network simulation of PMSS, KITE, and PMMM are conducted that runs the simulation over 100 seconds. The simulation environment involves the two different infrastructural topologies. While in simulation setup uses the mobile producer which moves within the simulation scenario by using the random walk mobility model. The mobile producer precisely moves within the defined boundaries of mobility model. According to the PMSS, it uses the anchor points strategically, the nodes 5, 6, 9, and 10 are considered as anchor points. In simulation setup, the consumer node is connected to the node 15 in GS. On the order hand, it is connected to node 3 and 7 in the AS. The topology visual infrastructure and node numbers for both GS and AS is represented in Figure 6.2. The consumer in KITE and PMMM is connected to the node 0 in GS and linked with node 15 in the AS. Further, the mobile producer speed varies during simulation in order to evaluate the performance of the system. Additionally, the time also varied in different scenarios to get the different performance metrics values. These values involve to accessed and evaluates the handoff latency, signalling cost, packet delivery, and throughput of different solutions, therefore the PMMM results are evaluated and benchmarked with KITE and PMSS.

These metrics are essential for accurately simulating real-world network conditions and ensuring relevant results. Handoff latency, the time to transfer an active connection between access points, varies with technology, user speed, and signal strength, directly impacting user experience. Packet loss, the percentage of lost packets, affects application performance differently, influenced by real-world factors like interference and obstacles, making its simulation crucial for assessing network reliability. Signalling cost, the overhead of establishing and maintaining communication, reflects operational efficiency and resource usage, vital for balancing performance and expenses. Together, these parameters enhance network optimization, user experience, and planning strategies, as supported by existing studies and benchmarks.

Using ndnSIM to test the PMMM model has several limitations that can affect result generalizability. One key issue is the reliance on simplified network topologies, which may not capture the complexities of real-world networks, particularly regarding varying user densities and mobility patterns. Additionally, ndnSIM's performance is sensitive to parameters like buffer sizes and caching strategies; inadequate calibration can skew results. The available mobility models also struggle with high-speed scenarios, limiting assessments of PMMM in dynamic environments. Scalability constraints can hinder simulations of large networks, narrowing experimental scope. Finally, default settings may not align with specific study conditions, leading to biased results. To enhance reliability, researchers should supplement ndnSIM findings with empirical data or alternative methods, accounting for real-world network complexities.



### 6.6.1 Handoff Latency and Path Optimization

Handoff latency refers to the time interval between when a mobile producer receives a last Interest packet from the previous router and received a new Interest packet from the new router after the handoff. The latency is determined by the path stretch ratio, as increase in the path stretch the increase in the latency due to the increase in the distance that includes several intermediate nodes between the consumer and producer communication path. Consequently, the handoff latency and data path stretch potentially evaluated by analysing the hop count between the consumer to the producer. The hop count refers to total number of intermediate content routers through which an Interest and data packet must pass between the consumer and producer.

In this research, the average hop count is measured by running the simulation experiment in GS and AS with the different speed of mobile producer. After, the completion of simulation process, the results are obtained in form of trace file which contains the monitoring of the packets in different hops with respect to the varies speed of mobile producer in both scenarios. Further, the results are monitored and plotted in graphical representation in order to understand the efficiency of the proposed model and the benchmarking studies in both scenarios. In plotted graph the x-axis represents the mobile producer speed, and the y-axis describes the average hop count in both scenarios as show is Figures 6.10 and 6.11. The Figures reflets the clear path stretching average between the proposed PMMM and the benchmarking studies KITE and PMSS.

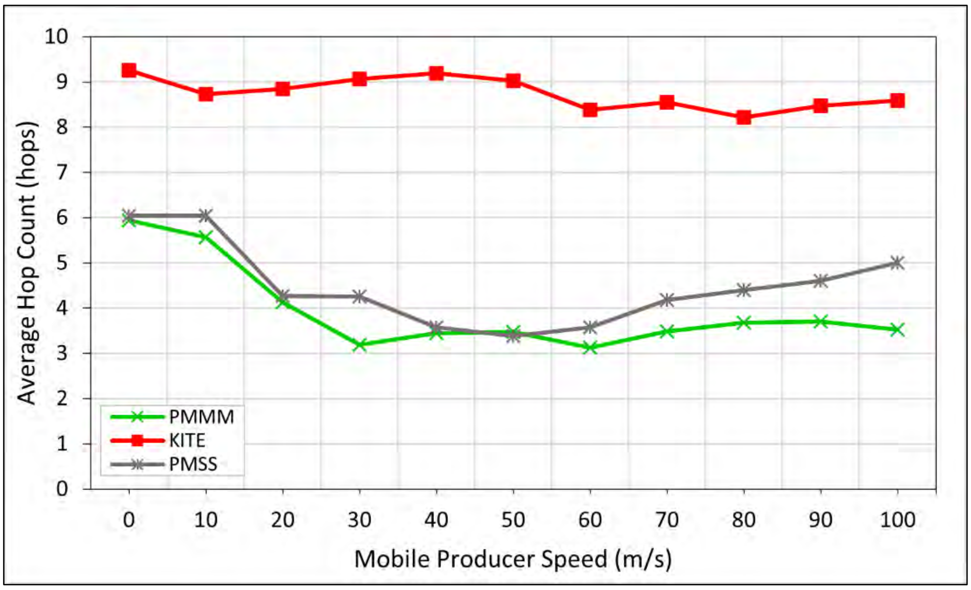



*Figure 6.10.* Data Rate of PMMM vs KITE and PMSS in GS

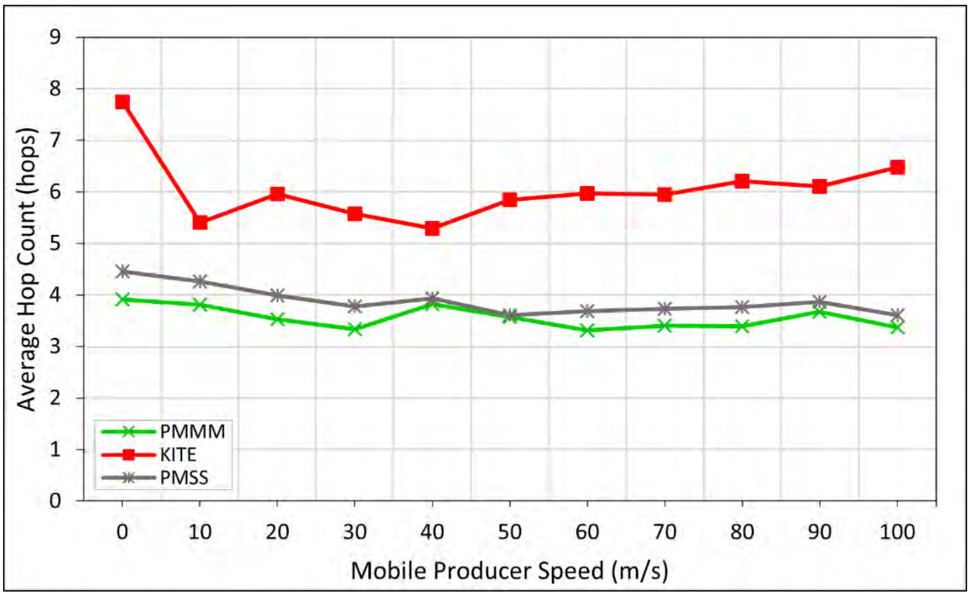



*Figure 6.11.* Data Rate of PMMM vs KITE and PMSS in AS

The GS shows the decreasing trend of average hop count in PMMM with respect to mobile producer speed, while the KITE trend line shows the higher average hop count as compared to PMMM and PMSS. While the PMSS trend line shows the lesser in average hop count as compared to KITE due to the suboptimal routing path. Consequently, the PMMM trend line shows the lowest average hop count with respect to mobile producer speed, it is due to the optimal routing path during communication and anchorless approach. While the KITE fully uses the anchor router and the PMSS solution partially uses the anchor router to establish the path between consumer and producer by using MI packet broadcast. Therefore, the PMMM solution shows the lowest level of average hop count. The lowest in the average hop count improves the handoff latency, both KITE and PMSS show the high handoff latency as compared to PMMM in both scenarios as shown in Figures 6.10 and 6.11.

### 6.6.2 Handoff Signalling Cost

The handoff signalling cost denotes the quantity of data packets or messages exchanged between the initial sender and final recipient, encompassing all successive hops, during the handoff phase. This cost considers both directions of communication: from the source to the target, and reciprocally. For the formulation of handoff signalling cost analysis, we employed a simulation in both GS and AS as shown in Figures 6.12 and 6.13.

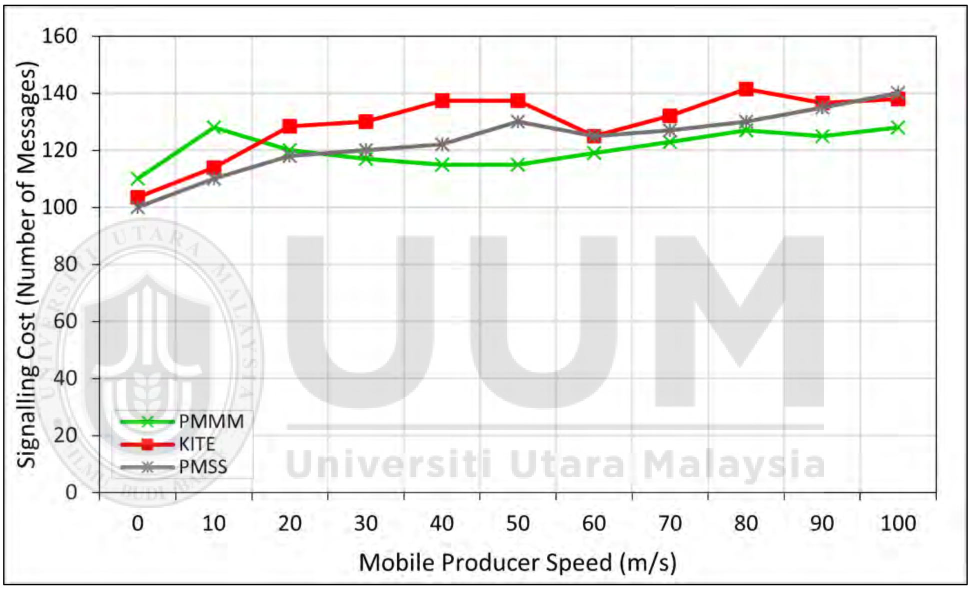



*Figure 6.12.* Handoff Signalling Cost between PMMM, KITE, and PMSS in GS

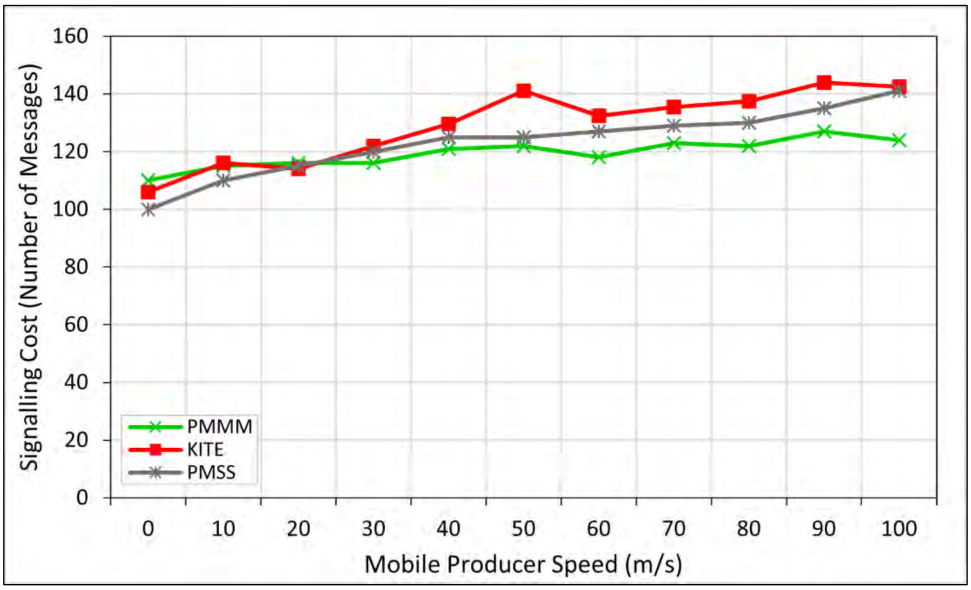



*Figure 6.13.* Handoff Signalling Cost between PMMM, KITE, and PMSS in AS

The average signalling cost of both scenarios are graphically plotted and presented in Figures 6.12 and 6.13, whereas the x-axis represents the mobile producer speed and y-axis represents the average signalling cost. The Figures 6.12 and 6.13 represents the average signalling cost of PMMM, KITE and PMSS in both scenarios. The PMMM trend line shows the promising result despite the use of two different packets in order to manage the producer mobility. While the KITE and PMSS average handoff signalling cost is almost same due to the use of anchor in the network topology. While the PMSS result shows the improved pattern due to the suboptimal path. Conversely, the PMMM trend line is better due to the anchorless approach that least use of nodes in order to create optimal path. However, the PMMM is performed better as compared to PMSS due to optimal path between the consumer and producer. The KITE shows the high in the average handoff signalling cost due to use of centralized node in order to manage the producer mobility.

### 6.6.3 Interest Packet Loss

To measure the performance of the network in NDN, the Interest packet loss is the one of the significant performance metrics that quantify the network system performance. The Interest packet loss associates with the sustainability of the producer mobility in NDN environment. When the frequency of the producer mobility high or its speed becomes increase, it impacts the performance of the system. The Figures 6.14 and 6.15 shows the plotted graphs of the mobile producer with the varying speed in GS and AS in the x-axis.

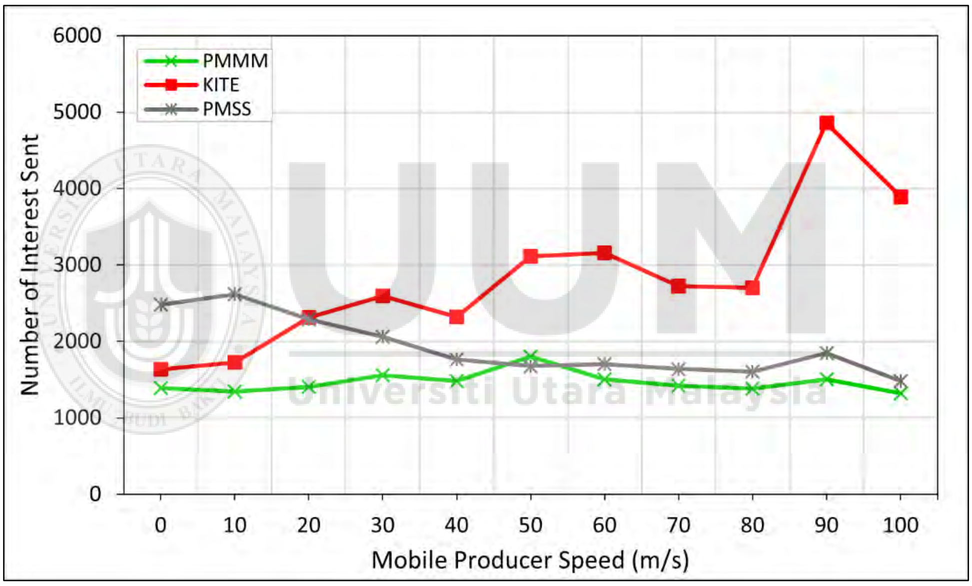



*Figure 6.14.* Interest Packet Loss in PMMM, KITE, and PMSS in GS

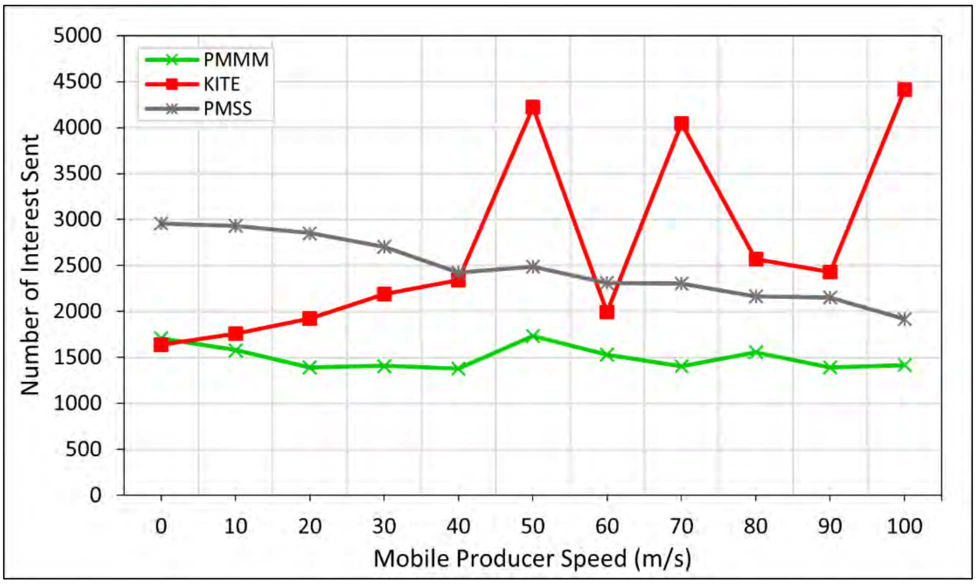



*Figure 6.15.* Interest Packet Loss in PMMM, KITE, and PMSS in AS

The Interest packet loss is quantified by analysing the number of Interest packets that unable to deliver the data packets in NDN network. The higher degree of Interest packet loss impacts the other performance metrics such as throughput and Interest retransmission. However, the PMMM shows the higher level of Interest packets satisfaction. In GS, the trend line shows the stable transmission of Interest data packets in the PMMM as shown in Figure 6.8. The PMMM solution uses the two different packets to control the Interest packet loss during the handoff process. While the KITE and PMSS solution less focused over the Interest packet loss during the producer handoff process. In PMMM, the long handoff latency impact lesser due to control transmission of Interest packets by using mobility management packets such as MNP and MUP packets. The AS also show the stable and high data delivery. However, the KITE results show the less stability in the Interest packet loss, while the PMSS shows the better performance as compared to the KITE solution. The PMSS solution uses the MI packet with the broadcast strategy that redirects the Interest packets towards the mobile producer after the handoff process. This solution performs better than KITE and provides the route for the incoming Interest packets.

### 6.6.4 Throughput

The throughput refers to the number of packets transmitted between nodes over a network. In NDN, the throughput refers to the amount of Interest packets able to deliver data packets successfully. The throughput signifies the performance of the network communication model, higher the throughput indicates the reliable and efficient network communication model. Further, the higher throughput also determines the network optimization level. The throughput is calculated through simulation results in both GS and AS. The calculated results are plotted graphically as illustrated in Figures 6.16 and 6.17.

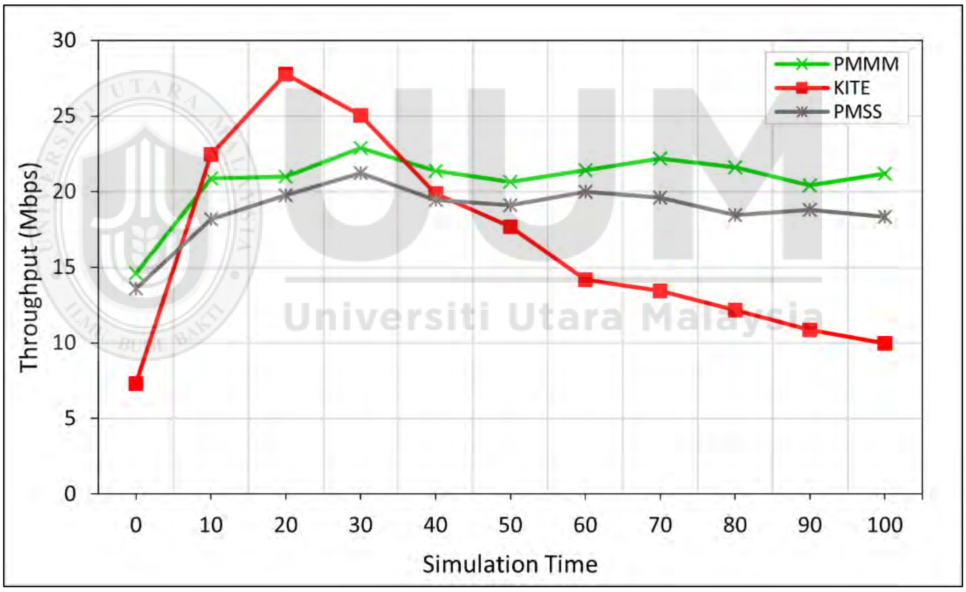



*Figure 6.16.* Throughput between PMMM, KITE, and PMSS in GS

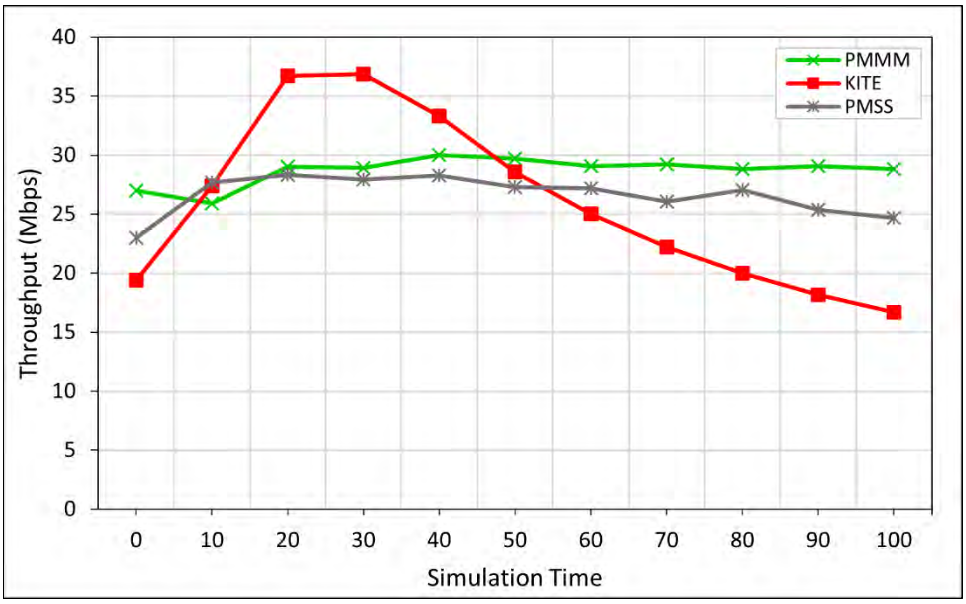



*Figure 6.17.* Throughput between PMMM, KITE, and PMSS in AS

In GS, the PMMM shows the best performance in comparison to KITE and PMSS as shown in Figure 6.16. The PMMM solution uses the two types of packets in order to manage the producer mobility and able to create the optimal path between the consumer and producer. After the producer handoff process the optimal path is created between the consumer and producer that continues the communication through optimal path. While during the handoff process the network overcomes the excessive Interest packet loss that maximizes the network performance and shows the higher throughput. However, the KITE and PMSS solutions use anchor points and are inefficient in of terms controlling the incoming packets during the handoff process. In AS, Figure 6.17 shows the PMMM trend lines reflects the better results in comparison to the KITE and PMSS due the aforementioned network communication model.

### 6.7 Summary

This research provides a solution known as PMMM, which is simulated to provide seamless support for mobile producers in NDN, mimicking real-world implementation as closely as possible. The previous chapter deeply explains the design of PMMM, while this chapter details the implementation of the PMMM design in a simulator known as ndnSIM. To efficiently implement the PMMM the ndnSIM is integrated with the NS-3. The scenarios are created and the MNP and MUP are implemented in ndnSIM. Furthermore, the application layer and network layer are modified according to the presented design in the previous chapter. The scenarios file merged all the intended changes during the simulation. The two different scenarios are created by using two different topologies in order to get the performance of the PMMM and benchmarking studies. The first scenario is based on Grid topology which is known as GS. While the second scenario is based on Abilene topology which is known as AS. The scenarios are simulated by setting up the different parameters and getting the results. All these scenarios and parameters are systemised as exercised in real world implementations to assess the accurate performance of the PMMM. The different performance metrics are used to measure the performance of the PMMM and the benchmarking solution which is known as evaluation phase. The evaluation involves the metrics such as handoff latency, handoff signalling cost, Interest packet loss and throughput. The PMMM, KITE and PMSS are evaluated among these metrics. Consequently, the performance evaluation results shows that the PMMM perform best among the KITE and PMSS solutions. Hence, the PMMM solution provides the better and seamless support for the producer mobility in NDN. Further, the PMMM solution is capable to proof itself and ideal support in the NDN based Internet of Things (NDN-IoTs).

# CHAPTER SEVEN

# CONCLUSION AND FUTURE WORK

## 7.1 Introduction

The NDN is an innovative and promising content distribution network paradigm that offers various benefits in the communication system such as content caching, scalability, efficiency, and reliability. These significant benefits inspire the various researchers to replace the traditional host-oriented content distribution with the content-centric nature distribution. The content-centric based communication influences various emerging trends and cutting-edge technologies such Internet of Things (IoT), Internet of Everything (IoE), and Internet of Medical Things (IoMT) in the digital society. Additionally, these cutting-edge technologies play a vital role in several industries and development sector such as e-health system, autonomous vehicle industry, e-commerce, and education. These emerging trend and cutting-edge technologies are widely used and incorporated in the mobilized environment that benefits in the scalable and seamless content distribution while moving in the network. Furthermore, these efficient and revolutionary innovations are capable of providing the significant and comprehensive solutions to improve the mobility concerns in the NDN. Therefore, these insightful interests encourage and fuel the current research to ensure that the NDN paradigm is equipped with the essential mobility management.

The PMMM solution aims to facilitate the seamless mobility support in NDN to integrate with the cutting-edge technologies to revolutionize the 6G, Wireless Sensor Network (WSN), and automatic network industry. The primary objective of the PMMM to provide the seamless content distribution and reduce the packet loss during the mobile producer transition towards the different location. Importantly, the PMMM design does not impact the fundamental architecture of NDN. Instead, it introduces a limited set of functionalities and updating the application layer, network layer and the routing layer to support the PMMM. The mobility management packets such as MNP and MUP are implemented in the application layer and in the network forwarding layer of NDN. These packets assist in creating the optimal path between the consumer to producer communication after the handoff process. The PMMM solution potentially improves the performance of the network in terms of various metrics such as handoff latency, signalling cost, throughput, packet loss, and packet delivery ratio. Additionally, it provides optimal path between consumer and producer without using static router or anchor or home agent router.

In this study, the problem is addressed related to the NDN mobility have been proposed and evaluated known as PMMM. The PMMM resolves the producer mobility issues during the handoff process. The rest of the chapter is organized as follows: Section 7.2 describes a brief overview of the overall research; Section 7.3 outlines the research contribution, Section 7.4 explains the research limitations and finally, Section 7.5 provides the future direction of the study.

### 7.2 Research Summary

Mobility management and seamless support are crucial for uninterrupted communication in NDN, which has significant potential for IoT, IoMT, WSN, and 6G networks. The research community has explored various approaches for managing producer mobility, including Indirection-based, DNS-based, Anchor-based, Mapping-based, and Rendezvous-based approaches, but these often struggle with complex infrastructures. The KITE solution simplifies this by using an immobile anchor but suffers from path stretching issues. The PMSS solution addresses these challenges but still faces high latency and packet loss during transitions. In response, the PMMM solution optimizes paths and minimizes packet loss without relying on immobile anchors, thus avoiding single points of failure. Evaluations through analytical and simulation methods show that PMMM outperforms previous solutions in handoff latency, signalling costs, and packet delivery, while achieving maximum path optimization.

Chapter One provides an overview of NDN, discussing its research background, motivations for being a preferred Internet architecture, and identifying challenges in producer mobility management that raise key research questions. It sets out research objectives and outlines the scope and significance of the study. Chapter Two emphasizes the importance of mobility management in NDN, categorizing it into consumer and producer mobility, and highlighting challenges despite the in-network caching feature. It presents a taxonomy of unsupported producer mobility, discusses various approaches and their accomplishments, and identifies unresolved issues for future research. A survey of past producer mobility management studies evaluates their performance based on metrics like handoff latency, packet loss, and signalling costs, concluding with critical analyses of the different approaches. Chapter Three introduces the DRM as a framework for achieving the research objectives, defining the conceptual model of PMMM and outlining the tools, methods, and performance metrics. Chapter Four elaborates on the PMMM design within NDN, using a rigorous analytical model to manage handoff latency, signalling costs, and packet delivery, while applying hop count techniques in conjunction with existing models like IBM, PMSS, and KITE. Chapter Five presents the conceptual foundation of PMMM, highlighting its design principles for effective implementation. Chapter Six evaluates PMMM's performance through simulations using ndnSIM and NS-3, comparing it to KITE and PMSS. The results indicate that PMMM outperforms previous models in handoff latency, signalling costs, packet delay, and throughput, confirming its reliability and the successful achievement of research objectives.

### 7.3 Research Contribution

A study of the current state of the art indicates that various producer mobility management models have been introduced. The solutions involve various strategical placement of different types of static router in order to support producer mobility. Additionally, the solutions use the different types of additional packets to manage the producer mobility. The first contribution of this research is to define a framework, where it compares some of the common state-of-the-art producer mobility solutions. The development of the framework based on various parameters which are selected by the previous literature analysis. The second contribution elaborates the comparison between the different producer mobility management solutions that analysed the most prominent metrics: handoff latency, signalling cost, throughput, Interest packet loss, and data packet delivery. The third and the core contributions of this research is to propose a producer mobility management model that able to overcome the limitations of the benchmarking studies such as KITE and PMSS. The following highlights some of the significant contributions of this research:

1. A comprehensive analysis of the producer mobility management approaches in NDN.

2. A comparative analysis between the producer mobility management approaches in NDN.

3. The formulation of the proposed PMMM network analytical model that improves the handoff latency to minimize signalling cost and ensures the path optimization.

4. The design of mobility management and forwarding strategy that manages the producer mobility to enhance the throughput and minimize the Interest packet loss during the handoff process.

5. The implementation of the PMMM by using NS-3-based ndnSIM and evaluation the performance with the KITE and PMSS in the NDN network simulation environment.

## 7.4 Research Limitation

This research is carried out under the careful and appropriate selection of the performance evaluation technique such as modelling and simulation methodology that contributes practically and theoretically. It thoroughly adheres to standard procedures in modelling and simulation, including the conceptual model development, designing and implementation of the simulation model. Additionally, the study diligently completes the verification, validation, and evaluation with the benchmarking study to attain the research main goal. It is noteworthy to mention that the research focused on the handoff mobility management within the limited topologies such as Grid and Abilene topology. It does not consider the la network topologies such as Rocket Fuel and Tree topologies. Therefore, the evaluation of the PMMM performs as a benchmarking study among the KITE and PMSS which is carried out on Grid and Abilene topologies. Furthermore, this research does not take into account of certain factors, such as consumer mobility, security, network caching and scalability. This research is limited to producer mobility within a certain scope of

NDN environment and presented parameters. To address these limitations, future research should expand the evaluation of PMMM to encompass larger and more complex network topologies that reflect real-world conditions. Incorporating diverse scenarios, including varying user densities and mobility patterns, will provide a more comprehensive understanding of PMMM's scalability. Additionally, integrating consumer mobility into the model will enhance its applicability in environments where both producers and consumers interact dynamically.

## 7.5 Future Direction

This research proposes a model to solve the associated problem in the producer mobility in NDN. The proposed solution, called PMMM, offers the seamless mobility management and creates the optimal path between consumer and producer communication. Furthermore, it solves the challenges associated with the handoff, ensures the seamless transition of producer among the different network areas. However, for further research advancements and practical implementation of PMMM, there are numerous significant aspects to be mindful concerning:

*Deploy Cutting-Edge Technologies*

The PMMM solution supports the producer mobility and improves the several performance metrics in the NDN. According to the future prospective, the PMMM solution has ability to improve the content dissemination in several cutting-edge technologies such as Internet of Things (IoT), Internet of Everything (IoE), and Internet of Medical Things (IoMT). Further, its efficient mobility management model aims to ensure the seamless communication among the mobile devices using the different networks such as Mobile Ad hoc Network (MANET), Vehicular Ad hoc Network (VANET), and six-generation (6G) mobile networks.

In IoT environments, for instance, mobile sensors in smart agriculture can use PMMM to optimize communication paths, enabling timely data transmission about crop health and soil conditions to farmers, which enhances decision-making and resource efficiency. In the context of 6G networks, PMMM can facilitate seamless data transmission for autonomous vehicles, ensuring real-time updates on traffic conditions and obstacles, thereby improving safety and operational efficiency.

In autonomous vehicles, PMMM can optimize real-time data communication between vehicles and infrastructure, enhancing navigation and safety by facilitating quick responses to dynamic traffic conditions. In e-health, the model could manage data transmission from mobile health monitoring devices, ensuring timely delivery of critical patient information to healthcare providers, which is vital for immediate medical responses. In smart cities, PMMM can optimize traffic management systems by enabling mobile traffic cameras and sensors to communicate effectively with central systems, allowing for rapid adjustments to traffic signals and reducing congestion. However, deploying additional different network modules and environments for simulation process requires specialized hardware, dedicated facilities, and a highly skilled technical team to implement and manage. Therefore, due to the constraints of limited time, high costs, and technical complexity, the PMMM approach is typically confined to simulations with a more focused set of parameters and environments.



*Real-Time Implication*

The performance of the producer mobility might yield different evaluation results during the delay in the real-time content communication. While, in this research, the specific content is not provided such as the audio and video, it is crucial to acknowledge the significant influence content and high proportion of real-time content communication. Further, research is necessary to deal and comprehensively evaluate the impact of the real-time application, particularly in light of increasing demand of cutting-edge technologies such as IoT, IoMT, IoE, and wireless sensor network. However, implementing the solution in a real-time environment requires several high-end equipment, specialized integrated modules, and expert personnel, which may take a significant amount of time to acquire and integrate. Moreover, the PMMM design able to optimize the real-time traffic by integrate the additional static router or server to handle the low delay audio and video streaming. Additionally, it encounters the potential bottlenecks, such as network congestion due to varying content demand and limited bandwidth, which degrades the quality of services and efficiency of the network.

Translating simulation results of the PMMM into real-world applications poses several challenges. One of the primary issues among all challenges is the simplified simulation scenario, which unable to express the dynamics and complexity of real-world networks, such as varying number of consumer and diverse mobility model. Additionally, simulation results may rely on idealized conditions that can lead to discrepancies when applied to practical scenarios, where factors like network congestion, interference, and security concerns come into play. To mitigate these challenges, it is essential to validate simulation findings through empirical studies in diverse, real-world environments, ensuring that the model can adapt to varying conditions. Incorporating feedback mechanisms that allow for continuous learning and adjustment in the model based on real-world performance data can also enhance its applicability.

*Consumer and Producer Mobility Management*

This research presents a solution aimed at addressing the several challenges in producer mobility, supported by existing literature that demonstrates the lack of producer mobility management in NDN. However, the study recognised that consumer and producer experience distinct challenges that can be addressed together, resulting in a robust network communication system with improved in the several network performance metrics. Notably, any freely moving node without any constrains in the network can function as a consumer and producer. Consequently, proposing a solution that ensures the support for consumer and producer mobility is a worthy of investigation. Future research could address this by employing more comprehensive mobility models that account for diverse consumer behaviours, such as varying speeds, patterns of interaction, and the impact of external factors like environmental conditions. By utilizing data-driven approaches, such as machine learning algorithms, researchers can analyse real-world mobility patterns and incorporate them into the network design. By exploring this approach, this research aims to thrives in the development of comprehensive solutions that achieve the mobility requirements for consumer and producer. Additionally, it ultimately enhances the overall performance of the real-time NDN-based network communication.

*Testbed Evaluation*

In this research, the performance evaluation of the PMMM is primarily conducted through analytical modelling and simulation analysis. While the use of a widely recognized NDN simulator allows for large-scale network experiments that closely mimic real-world conditions, the system still requires validation on a physical testbed to facilitate its commercialization. Constraints such as limited time and high costs have restricted the PMMM evaluation to analytical modelling and simulation. Despite these limitations, these methods represent significant advancements in NDN. However, integrating alternative approaches, such as empirical studies or real-world pilot projects, could yield different insights by capturing the complexities and variabilities of practical deployments. Conducting tests in a physical environment would provide valuable data on user behaviour and network dynamics, ultimately enhancing the understanding of PMMM's effectiveness and informing its optimization for real-world applications.

## REFERENCES


[1] B. Feng, H. Zhou, and Q. Xu, "Mobility support in named data networking: A survey," *EURASIP Journal on Wireless Communications and Networking,* vol. 2016, no. 1, p. 220, 2016.

[2] M. A. Naeem, R. Ali, M. Alazab, M. Yhui, and Y. B. Zikria, "Enabling the content dissemination through caching in the state-of-the-art sustainable information and communication technologies," *Sustainable Cities and Society,* p. 102291, 2020.

[3] M. A. Naeem, M. A. U. Rehman, R. Ullah, and B.-S. Kim, "A Comparative Performance Analysis of Popularity-Based Caching Strategies in Named Data Networking," *IEEE Access,* vol. 8, pp. 50057-50077, 2020.

[4] N. H. A. Zukri, A. S. C. M. Arif, M. AlSamman, and A. Abrar, "Enabling a Sustainable and Inclusive Digital Future with Proactive Producer Mobility Management Mechanism in Named Data Networking," in *International Conference on Computing and Informatics*, 2023, pp. 343-354: Springer.

[5] A. Abrar, A. S. C. M. Arif, K. M. Zaini, M. H. Omar, and Y. Meng, "Advancing producer mobility management in Named Data Networking: A comprehensive analytical model," *Journal of King Saud University-Computer and Information Sciences,* vol. 36, no. 4, p. 102045, 2024.

[6] A. Abrar, A. S. C. M. Arif, and K. M. Zaini, "Internet of things producer mobility management in named data networks: a survey, outlook, and open issues," *International Journal of Communication Networks and Distributed Systems,* vol. 29, no. 5, pp. 493-512, 2023.

[7] Cisco. (March 9, 2020). *Cisco Annual Internet Report (2018–2023) White Paper*. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

[8] A. Afanasyev, J. Burke, T. Refaei, L. Wang, B. Zhang, and L. Zhang, "A brief introduction to Named Data Networking," in *MILCOM 2018-2018 IEEE Military Communications Conference (MILCOM)*, 2018, pp. 1-6: IEEE.

[9] M. Hussaini, S. A. Nor, and A. Ahmad, "Producer mobility support for Information Centric Networking approaches: A review," *Int. J. Appl. Eng. Res,* vol. 13, no. 6, pp. 3272-3280, 2018.

[10] V. Jacobson, D. K. Smetters, J. D. Thornton, M. F. Plass, N. H. Briggs, and R. L. Braynard, "Networking named content," in *Proceedings of the 5th international conference on Emerging networking experiments and technologies*, 2009, pp. 1-12: ACM.

[11] K. Swaroopa, S. K. Magal, and T. Nedunchezhian, "A FAVE Cache Strategy for Producer Mobility in Content Centric Networks," 2020.

[12] A. Abrar, A. S. C. M. Arif, and K. M. Zaini, "Producer mobility support in information-centric networks: research background and open issues," *International Journal of Communication Networks and Distributed Systems,* vol. 28, no. 3, pp. 312-336, 2022.

[13] G. Xylomenos *et al.*, "A survey of information-centric networking research," *IEEE Communications Surveys & Tutorials,* vol. 16, no. 2, pp. 1024-1049, 2013.

[14] M. Aggarwal, K. Nilay, and K. Yadav, "Survey of named data networks: future of internet," *International Journal of Information Technology,* vol. 9, no. 2, pp. 197-207, 2017.

[15] A. Aboodi, T.-C. Wan, and G.-C. Sodhy, "Survey on the Incorporation of NDN/CCN in IoT," *IEEE Access,* vol. 7, pp. 71827-71858, 2019.

[16] C. Fang, F. R. Yu, T. Huang, J. Liu, and Y. Liu, "A survey of green information-centric networking: Research issues and challenges," *IEEE Communications Surveys & Tutorials,* vol. 17, no. 3, pp. 1455-1472, 2015.

[17] C. Fang, H. Yao, Z. Wang, W. Wu, X. Jin, and F. R. Yu, "A survey of mobile information-centric networking: Research issues and challenges," *IEEE Communications Surveys & Tutorials,* vol. 20, no. 3, pp. 2353-2371, 2018.

[18] D. Saxena, V. Raychoudhury, N. Suri, C. Becker, and J. Cao, "Named data networking: a survey," *Computer Science Review,* vol. 19, pp. 15-55, 2016.

[19] R. N. B. Rais and O. Khalid, "Study and analysis of mobility, security, and caching issues in CCN," *International Journal of Electrical & Computer Engineering (2088-8708),* vol. 10, 2020.

[20] M. Hussaini, M. A. Naeem, B.-S. Kim, and I. S. Maijama'a, "Efficient Producer Mobility Management Model in Information-Centric Networking," *IEEE Access,* vol. 7, pp. 42032-42051, 2019.

[21] M. Hussaini, S. A. Nor, and A. Ahmad, "Producer mobility support schemes for named data networking: A survey," *International Journal of Electrical and Computer Engineering,* vol. 8, no. 6, p. 5432, 2018.

[22] S. Fayyaz, M. A. U. Rehman, M. S. ud Din, M. I. Biswas, A. K. Bashir, and B.-S. Kim, "Information-centric mobile networks: a survey, discussion, and future research directions," *IEEE Access,* 2023.

[23] A. Abrar, A. S. M. Arif, and K. M. Zaini, "A systematic analysis and review on producer mobility management in named data networks: Research background and challenges," *Alexandria Engineering Journal,* vol. 69, pp. 785-808, 2023.

[24] L. Alkwai, A. Belghith, A. Gazdar, and S. Al-Ahmadi, "Comparative Analysis of Producer Mobility Management Approaches in Named Data Networking," *Applied Sciences,* vol. 12, no. 24, p. 12581, 2022.

[25] M. Meddeb, A. Dhraief, A. Belghith, T. Monteil, and K. Drira, "Producer mobility support in named data internet of things network," *Procedia Computer Science,* vol. 109, pp. 1067-1073, 2017.

[26] G. Tyson, N. Sastry, I. Rimac, R. Cuevas, and A. Mauthe, "A survey of mobility in information-centric networks: Challenges and research directions," in *Proceedings of the 1st ACM workshop on Emerging Name-Oriented Mobile Networking Design-Architecture, Algorithms, and Applications*, 2012, pp. 1-6: ACM.

[27] T.-X. Do and Y. Kim, "Optimal Provider Mobility in Large-Scale Named-Data Networking," *KSII Transactions on Internet & Information Systems,* vol. 9, no. 10, 2015.

[28] D. Kim and Y.-B. Ko, "On-demand anchor-based mobility support method for named data networking," in *2017 19th International Conference on Advanced Communication Technology (ICACT)*, 2017, pp. 19-23: IEEE.

[29] Y. Zhang, H. Zhang, and L. Zhang, "Kite: A mobility support scheme for ndn," in *Proceedings of the 1st ACM Conference on Information-centric Networking*, 2014, pp. 179-180: ACM.

[30] A. Abrar, K. Mohd Zaini, A. S. Che Mohamed Arif, and M. H. Omar, "Towards a Sustainable Digital Society: Supporting Producer Mobility in Named Data Networking Through Immobile Anchor-Based Mechanism," in *International Conference on Computing and Informatics*, 2023, pp. 330-342: Springer.

[31] J. Lee, S. Cho, and D. Kim, "Device mobility management in content-centric networking," *IEEE Communications Magazine,* vol. 50, no. 12, pp. 28-34, 2012.

[32] D. Han, M. Lee, K. Cho, T. Kwon, and Y. Choi, "Publisher mobility support in content centric networks," in *The International Conference on Information Networking 2014 (ICOIN2014)*, 2014, pp. 214-219: IEEE.

[33] F. Hermans, E. Ngai, and P. Gunningberg, "Mobile sources in an information-centric network with hierarchical names: An indirection approach," *7th SNCNW,* 2011.

[34] D. h. Kim, J. h. Kim, Y. s. Kim, H. s. Yoon, and I. Yeom, "End-to-end mobility support in content centric networks," *International Journal of Communication Systems,* vol. 28, no. 6, pp. 1151-1167, 2015.

[35] M. Hussaini, S. Nor, and A. Ahmad, "PMSS: Producer Mobility Support Scheme optimization with RWP Mobility Model in Named Data Networking," *International Journal of Communication Networks and Information Security,* vol. 10, no. 2, pp. 329-339, 2018.

[36] L. Liu, Z. Ye, and A. Ito, "CAMS: Coordinator assisted mobility support for seamless and bandwidth-efficient handover in ICN," in *2015 IEEE Globecom Workshops (GC Wkshps)*, 2015, pp. 1-7: IEEE.

[37] A. F. Khan and C. Rajalakshmi, "A multi-attribute based trusted routing for embedded devices in MANET-IoT," *Microprocessors and Microsystems,* vol. 89, p. 104446, 2022.

[38] A. Ferozkhan and G. Anandharaj, "The Embedded Framework for Securing the Internet of Things," *Journal of Engineering Research,* vol. 9, no. 2, 2021.

[39] H. Lim, A. Ni, D. Kim, Y.-B. Ko, S. Shannigrahi, and C. Papadopoulos, "NDN construction for big science: Lessons learned from establishing a testbed," *IEEE Network,* vol. 32, no. 6, pp. 124-136, 2018.

[40] M. N. Sadiku, A. E. Shadare, and S. M. Musa, "Named data networking," *International Journal of Engineering Research,* vol. 6, no. 7, pp. 371-372, 2017.

[41] A. Abrar, A. S. C. M. Arif, and K. M. Zaini, "A Mobility Mechanism to Manage Producer Mobility in Named Data Networking," in *2022 IEEE Region 10 Symposium (TENSYMP)*, 2022, pp. 1-6: IEEE.

[42] L. Zhang *et al.*, "Named data networking," *ACM SIGCOMM Computer Communication Review,* vol. 44, no. 3, pp. 66-73, 2014.

[43] M. A. Naeem, S. A. Nor, S. Hassan, and B.-S. Kim, "Performances of Probabilistic Caching Strategies in Content Centric Networking," *IEEE Access,* vol. 6, pp. 58807-58825, 2018.

[44] G. M. De Brito, P. B. Velloso, and I. M. Moraes, *Information-centric Networks: A New Paradigm for the Internet*. John Wiley & Sons, 2013.

[45] D. Mars, S. M. Gammar, A. Lahmadi, and L. A. Saidane, "Using Information Centric Networking in Internet of Things: A Survey," *Wireless Personal Communications,* pp. 1-17, 2019.

[46] A. V. Ventrella, G. Piro, and L. A. Grieco, "Publish-subscribe in mobile information centric networks: Modeling and performance evaluation," *Computer Networks,* vol. 127, pp. 317-339, 2017.

[47] L. Wang, O. Waltari, and J. Kangasharju, "Mobiccn: Mobility support with greedy routing in content-centric networks," in *2013 IEEE Global Communications Conference (GLOBECOM)*, 2013, pp. 2069-2075: IEEE.

[48] X. Jiang, J. Bi, Y. Wang, P. Lin, and Z. Li, "A content provider mobility solution of named data networking," in *2012 20th IEEE International Conference on Network Protocols (ICNP)*, 2012, pp. 1-2: IEEE.

[49] Y.-S. Chen, C.-S. Hsu, and D.-Y. Huang, "A pipe-assisted mobility management in named data networking networks," in *The 16th Asia-Pacific Network Operations and Management Symposium*, 2014, pp. 1-4: IEEE.

[50] J. Augé, G. Carofiglio, G. Grassi, L. Muscariello, G. Pau, and X. Zeng, "Anchor-less producer mobility in ICN," in *Proceedings of the 2nd ACM Conference on Information-Centric Networking*, 2015, pp. 189-190: ACM.

[51] Z. Zhu, A. Afanasyev, and L. Zhang, "A new perspective on mobility support," *Named-Data Networking Project, Tech. Rep,* 2013.

[52] Y. Rao, H. Luo, D. Gao, H. Zhou, and H. Zhang, "Lbma: A novel locator based mobility support approach in named data networking," *China Communications,* vol. 11, no. 4, pp. 111-120, 2014.

[53] Y.-C. Tseng, S.-Y. Ni, Y.-S. Chen, and J.-P. Sheu, "The broadcast storm problem in a mobile ad hoc network," *Wireless networks,* vol. 8, no. 2-3, pp. 153-167, 2002.

[54] F. Hermans, E. Ngai, and P. Gunningberg, "Global source mobility in the content-centric networking architecture," in *Proceedings of the 1st ACM workshop on Emerging Name-Oriented Mobile Networking Design-Architecture, Algorithms, and Applications*, 2012, pp. 13-18: ACM.

[55] L. Rui, S. Yang, and H. Huang, "A producer mobility support scheme for real-time multimedia delivery in named data networking," *Multimedia Tools and Applications,* vol. 77, no. 4, pp. 4811-4826, 2018.

[56] Z. Yan, Y.-J. Park, Y.-B. Leau, L. Ren-Ting, and R. Hassan, "Hybrid Network Mobility Support in Named Data Networking," in *2020 International Conference on Information Networking (ICOIN)*, 2020, pp. 16-19: IEEE.

[57] T. Woo, H. Park, S. Jung, and T. Kwon, "Proactive neighbor pushing for enhancing provider mobility support in content-centric networking," in *2014 Sixth International Conference on Ubiquitous and Future Networks (ICUFN)*, 2014, pp. 158-163: IEEE.

[58] M. B. Lehmann, M. P. Barcellos, and A. Mauthe, "Providing producer mobility support in NDN through proactive data replication," in *NOMS 2016-2016 IEEE/IFIP Network Operations and Management Symposium*, 2016, pp. 383-391: IEEE.

[59] H. Farahat and H. S. Hassanein, "Proactive caching for producer mobility management in named data networks," in *2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC)*, 2017, pp. 171-176: IEEE.

[60] S. Korla and S. Chilukuri, "T-Move: A Light-Weight Protocol for Improved QoS in Content-Centric Networks with Producer Mobility," *Future Internet,* vol. 11, no. 2, p. 28, 2019.

[61] X. Jiang, J. Bi, and Y. Wang, "What benefits does NDN have in supporting mobility," in *2014 IEEE Symposium on Computers and Communications (ISCC)*, 2014, pp. 1-6: IEEE.

[62] S. Gao and H. Zhang, "Scalable mobility management for content sources in Named Data Networking," in *2016 13th IEEE Annual Consumer Communications & Networking Conference (CCNC)*, 2016, pp. 79-84: IEEE.

[63] M. Gohar, N. Khan, A. Ahmad, M. Najam-Ul-Islam, S. Sarwar, and S.-J. Koh, "Cluster-based device mobility management in named data networking for vehicular networks," *Mobile Information Systems,* vol. 2018, 2018.

[64] W. M. H. Azamuddin, A. H. M. Aman, H. Sallehuddin, Z. S. Attarbashi, W. Zhang, and S. Hassan, "Performance Analysis for Producer Mobility in Named Data Networking," *Journal of Advanced Research in Applied Sciences and Engineering Technology,* pp. 252-261, 2024.

[65] J. Tang, H. Zhou, Y. Liu, H. Zhang, and D. Gao, "A source mobility management scheme in content-centric networking," in *2014 IEEE 11th Consumer Communications and Networking Conference (CCNC)*, 2014, pp. 176-181: IEEE.

[66] Z. Zhou, X. Tan, H. Li, Z. Zhao, and D. Ma, "MobiNDN: A mobility support architecture for NDN," in *Proceedings of the 33rd Chinese Control Conference*, 2014, pp. 5515-5520: IEEE.

[67] F. Ren, Y. Qin, H. Zhou, and Y. Xu, "Mobility management scheme based on software defined controller for content-centric networking," in *2016 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, 2016, pp. 193-198: IEEE.

[68] L. T. M. Blessing, Chakrabarti, Amaresh. (2009). *DRM, a Design Research Methodology*. Available: https://www.springer.com/us/book/9781848825864

[69] L. T. Blessing and A. Chakrabarti, *DRM: A design reseach methodology*. Springer, 2009.

[70] V. Goebel and T. Plagemann, "REsearch/Scientific Methods in Computer Science," *Departament of Iformatics, University of Oslo,* 2015.

[71] A. R. Mohsen Guizani, Bilal Khan, Ala Al-Fuqaha. (2010). *Network Modeling and Simulation: A Practical Perspective*. Available: https://www.wiley.com/en-sg/Network+Modeling+and+Simulation%3A+A+Practical+Perspective+-p-9780470035870

[72] D. Thomas, A. Joiner, W. Lin, M. Lowry, and T. Pressburger, "The unique aspects of simulation verification and validation," in *2010 IEEE Aerospace Conference*, 2010, pp. 1-7: IEEE.

[73] A. S. Toor and A. Jain, "A survey on wireless network simulators," *Bulletin of Electrical Engineering and Informatics,* vol. 6, no. 1, pp. 62-69, 2017.

[74] O. M. D. Al-Momani, "Dynamic Redundancy Forward Error Correction Mechanism for the Enhancement of Internet-Based Video Streaming," ph.d., School of computing, Universiti Utara Malaysia 2010.

[75] M. M. Kadhum, "Network Performance and NS2," ed: Universiti Utara Malaysia, 2010.

[76] B. L. Ong, "A hybrid mechanism for SIP over IPv6 macromobility and micromobility management protocols," Universiti Utara Malaysia, 2008.

[77] L. F. Perrone and Y. Yuan, "Modeling and simulation best practices for wireless ad hoc networks," in *Proceedings of the 2003 Winter Simulation Conference, 2003.*, 2003, vol. 1, pp. 685-693: IEEE.

[78] R. Jain, *The art of computer systems performance analysis: techniques for experimental design, measurement, simulation, and modeling*. John Wiley & Sons, 1990.

[79] L. Campanile, M. Gribaudo, M. Iacono, F. Marulli, and M. Mastroianni, "Computer network simulation with ns-3: A systematic literature review," *Electronics,* vol. 9, no. 2, p. 272, 2020.

[80] S. Sharma, A. N. Mahajan, and R. C. Poonia, "An Inclusive survey of Network Simulators," in *Proceedings of International Conference on Sustainable Computing in Science, Technology and Management (SUSCOM), Amity University Rajasthan, Jaipur-India*, 2019.

[81] S. Mastorakis, A. Afanasyev, and L. Zhang, "On the evolution of ndnSIM: An open-source simulator for NDN experimentation," *ACM SIGCOMM Computer Communication Review,* vol. 47, no. 3, pp. 19-33, 2017.

[82] M. Hassan and R. Jain, *High performance TCP/IP networking*. Prentice Hall Upper Saddle River, NJ, 2003.

[83] M. Hussaini, S. A. Nor, A. Ahmad, R. Mustapha, and A. F. Abdulateef, "A conceptual model of producer mobility support for named data networking using design research methodology," *IAENG International Journal of Computer Science,* vol. 46, no. 3, pp. 1-11, 2019.

[84] M. Hussaini, S. A. Nor, and A. Ahmad, "Analytical modelling solution of producer mobility support scheme for named data networking," *International Journal of Electrical and Computer Engineering,* vol. 9, no. 5, p. 3850, 2019.

[85] Y. Zhang, Z. Xia, S. Mastorakis, and L. Zhang, "Kite: Producer mobility support in named data networking," in *Proceedings of the 5th ACM Conference on Information-Centric Networking*, 2018, pp. 125-136.

[86] V. Sivaraman and B. Sikdar, "Hop-count based forwarding for seamless producer mobility in ndn," in *GLOBECOM 2017-2017 IEEE Global Communications Conference*, 2017, pp. 1-6: IEEE.

[87] I. Ali and H. Lim, "Anchor-less producer mobility management in named data networking for real-time multimedia," *Mobile Information Systems,* vol. 2019, 2019.

[88] P. Kar, R. Chen, and Y. Qian, "An efficient producer mobility management technique for real-time communication in NDN-based remote health monitoring systems," *Smart Health,* vol. 26, p. 100309, 2022.

[89] M. Hussaini, M. A. Naeem, B.-S. Kim, and I. S. Maijama'a, "Efficient Producer Mobility Management Model in Information-Centric Networking," *IEEE Access,* 2019.

[90] W. Rafique, A. S. Hafid, and S. Cherkaoui, "Complementing IoT Services Using Software Defined Information Centric Networks: A Comprehensive Survey," *IEEE Internet of Things Journal,* 2022.

[91] Y. Rao, D. Gao, and H. Luo, "NLBA: A novel provider mobility support approach in mobile NDN environment," in *2014 IEEE 11th Consumer Communications and Networking Conference (CCNC)*, 2014, pp. 188-193: IEEE.

[92] M. Meddeb, A. Dhraief, A. Belghith, T. Monteil, K. Drira, and S. Gannouni, "AFIRM: Adaptive forwarding based link recovery for mobility support in NDN/IoT networks," *Future Generation Computer Systems,* vol. 87, pp. 351-363, 2018.

[93] C. Lynch, "Named Data Networking in Vehicular Ad-Hoc Networks: The Support of Push-Based Traffic for Transient, Periodic Data," 2020.

[94] J. Augé, G. Carofiglio, G. Grassi, L. Muscariello, G. Pau, and X. Zeng, "Map-me: Managing anchor-less producer mobility in content-centric networks," *IEEE Transactions on Network and Service Management,* vol. 15, no. 2, pp. 596-610, 2018.