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AN ENHANCED MOBILE TRAFFIC OFFLOADING MECHANISM BASED ON MULTIPLE ATTRIBUTES OF USER PREFERENCES

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Abstrak

Kemajuan teknologi terkini telah meningkatkan permintaan terhadap Internet secara signifikan, sekali gus menyebabkan peningkatan beban pada rangkaian selular. Oleh itu, Pengendali Rangkaian Mudah Alih (MNO) perlu memindahkan sebahagian pengguna kepada rangkaian WiFi. Namun, pemindahan secara sembarangan tanpa mengambil kira keutamaan dan mobiliti pengguna boleh menjejaskan kepuasan serta meningkatkan kos yang tidak perlu. Teknik pemindahan sedia ada lazimnya menumpukan sama ada kepada kriteria berasaskan rangkaian atau pengguna, dan sering mengabaikan interaksi antara kedua-duanya. Kajian ini bertujuan untuk meminimumkan nisbah dan kos pemindahan, serta memaksimumkan kepuasan pengguna yang dipindahkan. Sehubungan itu, kajian ini membentangkan satu kerangka pemindahan baharu yang peka terhadap mobiliti, berasaskan Proses Keputusan Markov Ufuk Tak Terhingga dengan Diskaun (IHDMDP). Model ini menggabungkan lokasi, kelajuan pengguna, keadaan rangkaian, dan keutamaan pengguna bagi menjamin keputusan pemindahan yang rasional. Dengan menjadikan mobiliti sebagai teras strategi, pendekatan ini memastikan pengguna hanya dipindahkan apabila corak pergerakan dan keadaan rangkaian selari, sekali gus mengekalkan kepuasan tinggi dan mengurangkan kos. Model ini disahkan melalui analisis kepekaan dan dinilai berdasarkan metrik prestasi seperti kepuasan pengguna, nisbah pemindahan, dan kos. Hasil kajian menunjukkan bahawa IHDMDP mengatasi pendekatan alternatif dengan peningkatan kepuasan pengguna sebanyak 40% dan pengurangan nisbah serta kos pemindahan melebihi 80%, membuktikan keberkesanan dan kecekapan kosnya. Simulasi menunjukkan bahawa pengguna di zon isyarat yang kuat dipilih secara optimum untuk dipindahkan, manakala pengguna di zon marginal dielakkan bagi mengelakkan penurunan kepuasan. Kajian ini turut menekankan kepentingan pemprofilan pengguna dan parameter kualiti rangkaian dalam pemilihan pengguna yang sesuai untuk dipindahkan, serta menyumbang secara signifikan kepada pengurusan rangkaian mudah alih yang lebih cekap.

Kata kunci: Pemindahan trafik mudah alih, Pemindahan WiFi-Selular, Kepuasan pengguna, Proses keputusan Markov.

Abstract

Recent technological advancements have significantly increased the Internet's demand, resulting in an increased load on cellular networks. Thus, the Mobile Network Operator (MNO) needs to offload part of the users to the WiFi networks. However, indiscriminate offloading without considering user preferences and mobility can degrade satisfaction and increase unnecessary offloading costs. Current offloading techniques often focus on either network or user-centric criteria, neglecting the interplay between them. This study aims to minimise the offloading ratio and cost while maximizing the offloaded user satisfaction. Thus, this study presents a novel mobility-aware offloading framework based on an Infinite-Horizon Discounted Markov Decision Process (IHDMDP). The model integrates location, user velocity, network condition, and user preferences to guarantee a rational offloading decision. By placing mobility at the core of its strategy, the approach ensures that users are only offloaded when their movement patterns and network conditions align, thereby maintaining high satisfaction and reducing costs. The model is then validated through sensitivity analysis and evaluated using performance metrics, including user satisfaction, offloading ratio, and costs. The study reveals that IHDMDP significantly outperforms other alternative approaches by a 40% increase in user satisfaction while simultaneously reducing offloading ratio and cost by over 80%, demonstrating its efficiency and cost-effectiveness. Simulation results indicate that users located in stronger signal zones are optimally chosen for offloading, whereas the model avoids transferring users from marginal zones to prevent satisfaction degradation. The study highlights the importance of user profiling and network quality parameters when selecting a suitable user to be offloaded. It has also contributed significantly to mobile network management, and this study has the potential to improve the efficiency of cellular networks.

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Keywords: Mobile traffic offloading, Cellular-WiFi offloading, User satisfaction, Markov decision process.

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List of Abbreviations

AP	Access Point
AHP	Analytical Hierarchy Process
ANDSF	Accessed Network Discovery Selection Function
BS	Base Station
CART	Classification and Regression Trees
COWO	Congestion-Optimal WiFi Offloading
D2D	Device-to-Device
DDQN	Double Deep Q-Network
DP	Dynamic Programming
DPWSM	Dynamic Programming Winner Selection Method
DRAIM	Delay-constrained and Reversed Auction-based Incentive Mechanism
DT	Decision Tree
DYCORS	Dynamic Coordinate Search
eNB	Evolve Node B
GWSM	Greedy Winner Selection Method
HRA	Heterogeneous Resource Allocation
LTE	Long Term Evolution
MADM	Multi-Attribute Decision Making
MDP	Markov Decision Process
MDOP	Mobile Data Offloading Protocol
MNO	Mobile Network Operator
MU	Mobile User
MUBTA	Marginal Utility-Based Traffic Allocation
MS	Mobile Subscriber
QoE	Quality of Experiences
QoS	Quality of Services
RWSM	Random Winner Selection Method
SBS	Small Base Station
SCN	Small Cell Network
SDBR	Satisfaction-based Dynamic Bandwidth Reallocation
SMAB	Stochastic Multi-Armed Bandit

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TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
UCB	Upper Confidence Bound
VCG	Vickrey-Clark-Groves
VCOWO	Virtualized Congestion Optimal WiFi Offloading

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CHAPTER ONE
INTRODUCTION

1.1 Research Background

Recent technological advancements have significantly increased society's dependence on technology, making everyday tasks easier for the community. According to [1], at the start of 2025, the number of Internet users was approximately 5.56 billion, marking an increase of 136 million or equivalent to 2.5 per cent growth compared to 2024. This convergence is largely driven by the abundance of smartphones and the growing demand for high-data-rate applications, including real-time video conferencing, file downloads, and Voice over Internet Protocol (VoIP) [2]. In addition to user-driven demand, the rapid progression of technologies such as the Internet of Things (IoT) [3], the Internet of Everything (IoE) [4], and the Internet of Medical Things (IoMT) [5] are accelerating digital transformation across industries.

The resulting shift enables more efficient communication, faster access and analysis of information, streamlined business transactions, and enhanced participation in social and civic interactions [3]. These innovations, while enhancing operational efficiency and connectivity, have led to an exponential surge in mobile traffic, placing significant stress on cellular infrastructure, especially during periods of peak usage [6].

1.2 Research Motivation

While digital transformation offers immense benefits, its rapid adoption introduces critical challenges that demand further investigation. The increasing demand for the Internet, coupled with the limited capacity of cellular networks, has placed considerable pressure on Base Stations (BS) [7]. This situation often makes the user experience degrade in Quality of Service (QoS) [8]. In addition, it also forces

REFERENCES

[1] S. Kemp, "Digital 2025: Global overview report - datareportal – global digital insights," Feb 2025. [Online]. Available: https://datareportal.com/reports/digital-2025-global-overview-report

[2] C. Casetti, "The 5g ecosystem forges ahead as remote services take center stage [mobile radio]," *IEEE Vehicular Technology Magazine*, vol. 16, no. 1, pp. 7–13, 2021.

[3] H. Tran-Dang and D.-S. Kim, "The physical internet in the era of digital transformation: Perspectives and open issues," *IEEE Access*, vol. 9, pp. 164 613–164 631, 2021.

[4] A. Chakraborty and A. K. Kar, "How does internet of everything enable digital transformation: A review and a research agenda from an editorial perspective," *Management Dynamics*, vol. 22, no. 2, p. 9, 2022.

[5] B. Lin and S. Wu, "Digital transformation in personalized medicine with artificial intelligence and the internet of medical things," *OMICS: A Journal of Integrative Biology*, vol. 26, no. 2, pp. 77–81, 2022, pMID: 33887155. [Online]. Available: https://doi.org/10.1089/omi.2021.0037

[6] M. Banafaa, I. Shayea, J. Din, M. H. Azmi, A. Alashbi, Y. I. Daradkeh, and A. Alhammadi, "6g mobile communication technology: Requirements, targets, applications, challenges, advantages, and opportunities," *Alexandria Engineering Journal*, vol. 64, pp. 245–274, 2023.

[7] D. Liu, L. Khoukhi, and A. Hafid, "Prediction-based mobile data offloading in mobile cloud computing," *IEEE Transactions on Wireless Communications*, vol. 17, no. 7, pp. 4660–4673, 2018.

[8] H. T. Thien, V.-H. Vu, and I. Koo, "Game theory-based smart mobile-data offloading scheme in 5g cellular networks," *Applied Sciences*, vol. 10, no. 7, 2020. [Online]. Available: https://www.mdpi.com/2076-3417/10/7/2327

[9] N. Bhooanusas, S.-I. Sou, and K.-C. Cheng, "Satisfaction-based dynamic bandwidth reallocation for multipath mobile data offloading," *Computer Networks*, vol. 185, p. 107594, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1389128620312287

[10] T. Wang, P. Li, X. Wang, Y. Wang, T. Guo, and Y. Cao, "A comprehensive survey on mobile data offloading in heterogeneous network," *Wireless Networks*, vol. 25, no. 2, pp. 573–584, 2019.

[11] N. Bhooanusas and S.-I. Sou, "Performance modeling of multipath mobile data offloading in cellular/wifi networks with bandwidth uncertainty," *Computer Networks*, vol. 197, p. 108351, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1389128621003431

Universiti Utara Malaysia

[12] A. Agamy and A. M. Mohamed, "Impact of Offloading on the Efficiency of Wireless Access Networks," *Int. J. Wirel. Inf. Networks*, vol. 28, no. 1, pp. 134–146, 2021. [Online]. Available: https://doi.org/10.1007/s10776-020-00498-0

[13] A. S. Tan and E. Zeydan, "Performance maximization of network assisted mobile data offloading with opportunistic device-to-device communications," *Computer Networks*, vol. 141, pp. 31–43, 2018.

[14] M. A. Khan, E. Baccour, Z. Chkirbene, A. Erbad, R. Hamila, M. Hamdi, and M. Gabbouj, "A survey on mobile edge computing for video streaming: Opportunities and challenges," *IEEE Access*, vol. 10, pp. 120 514–120 550, 2022.

[15] Y. Luu, "What i would (not) do for sustainability: The impact of environmentally friendly social media design on user experience," 2024.

[16] S. Kurkovsky, "Limitations of caching in mobile social media applications," in *2025 International Conference on Information Networking (ICOIN)*. IEEE, 2025, pp. 704–706.

[17] H. S. Kim, Y. Jang, S. H. Lee, and S. Kim, "How to relieve mobile network overload from mobile over-the-top (ott) traffic: Proposing a user-based content-sharing solution," *Telecommunications Policy*, vol. 49, no. 4, p. 102931, 2025.

[18] C. Zhang, B. Gu, Z. Liu, K. Yamori, and Y. Tanaka, "A reinforcement learning approach for cost- and energy-aware mobile data offloading," in *2016 18th Asia-Pacific Network Operations and Management Symposium (APNOMS)*, 2016, pp. 1–6.

[19] K. R. Singh, R. Chaudhry, V. Rishiwal, and M. Yadav, "Model-free qoe-aware seamless handoff in heterogeneous wireless networks," *Mobile Networks and Applications*, pp. 1–13, 2024.

[20] Y. Kim, J. Lee, J. Jeong, and S. Chong, "Multi-flow management for mobile data offloading," *ICT Express*, vol. 3, no. 1, pp. 33–37, 2017. [Online]. Available: http://dx.doi.org/10.1016/j.icte.2016.08.011

[21] L. Sun and Q. Zhu, "WiFi Offloading Algorithm Based on Q-Learning and MADM in Heterogeneous Networks," *Mob. Inf. Syst.*, vol. 2019, 2019.

[22] X. Song, L. Qin, H. Qi, S. Li, H. Qian, L. Dong, and Y. Ni, "Incentive framework for mobile data offloading market under qoe-aware users," *IET Communications*, vol. 14, no. 13, pp. 2151–2161, 2020. [Online]. Available: https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/iet-com.2019.0498

[23] P. Sharma, T. V. P. S, N. Kamath, and B. R. Tamma, "Velocity based dynamic flow mobility in converged lte/wi-fi networks," in *2016 Twenty Second National Conference on Communication (NCC)*, 2016, pp. 1–6.

[24] K. Sun, J. Yu, W. Huang, H. Zhang, and V. C. M. Leung, "A multi-attribute handover algorithm for qos enhancement in ultra dense network," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 5, pp. 4557–4568, 2021.

[25] P. Trakas, "Traffic offloading in future, heterogeneous mobile networks," 2019.

[26] F. Mehmeti and T. Spyropoulos, "Performance analysis of "on-the-spot" mobile data offloading," in *2013 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2013, pp. 1577–1583.

[27] H. Ko, J. Lee, and S. Pack, "Performance optimization of delayed wifi offloading in heterogeneous networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 10, pp. 9436–9447, 2017.

[28] H. Zhou, H. Wang, X. Li, and V. C. Leung, "A survey on mobile data offloading technologies," *IEEE Access*, vol. 6, pp. 5101–5111, 2018.

[29] D. De and A. Mukherjee, "Group handoff management in low power microcell-femtocell network," *Digital Communications and Networks*, vol. 3, no. 1, pp. 55–65, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352864816300852

[30] S. Kumari and B. Singh, "Comparative study of power consumption in different small cell networks," in *2017 2nd IEEE International Conference on Recent Trends in Electronics, Information Communication Technology (RTEICT)*, 2017, pp. 1948–1951.

[31] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell networks: a survey," *IEEE Communications Magazine*, vol. 46, no. 9, pp. 59–67, 2008.

[32] S. A. Khan, A. Kavak, K. Kucuk, and M. Asshad, "A new fractional frequency reuse method for interference management in lte-a hetnets," in *2019 27th Signal Processing and Communications Applications Conference (SIU)*. IEEE, 2019, pp. 1–4.

[33] A. Aijaz, H. Aghvami, and M. Amani, "A survey on mobile data offloading: technical and business perspectives," *IEEE Wireless Communications*, vol. 20, no. 2, pp. 104–112, 2013.

[34] X. Zhang, L. Guo, M. Li, and Y. Fang, "Motivating human-enabled mobile participation for data offloading," *IEEE Transactions on Mobile Computing*, vol. 17, no. 7, pp. 1624–1637, 2017.

[35] Y. Zhao, K. Xu, Y. Zhong, X.-Y. Li, N. Wang, H. Su, M. Shen, and Z. Li, "Incentive mechanisms for mobile data offloading through operator-owned wifi access points," *Computer Networks*, vol. 174, p. 107226, 2020.

[36] J. Lee, Y. Yi, S. Chong, and Y. Jin, "Economics of wifi offloading: Trading delay for cellular capacity," *IEEE Transactions on Wireless Communications*, vol. 13, no. 3, pp. 1540–1554, 2014.

Universiti Utara Malaysia

[37] M. Nitti, G. A. Stelea, V. Popescu, and M. Fadda, "When social networks meet d2d communications: A survey," *Sensors*, vol. 19, no. 2, 2019. [Online]. Available: https://www.mdpi.com/1424-8220/19/2/396

[38] D. Liu, L. Khoukhi, and A. Hafid, "Prediction-based mobile data offloading in mobile cloud computing," *IEEE Transactions on Wireless Communications*, vol. 17, no. 7, pp. 4660–4673, 2018.

[39] U. N. Kar and D. K. Sanyal, "A critical review of 3gpp standardization of device-to-device communication in cellular networks," *SN Computer Science*, vol. 1, no. 1, pp. 1–18, 2020.

[40] B. Feng, C. Zhang, J. Liu, and Y. Fang, "D2d communications-assisted traffic offloading in integrated cellular-wifi networks," *IEEE Internet of Things Journal*, vol. 6, no. 5, pp. 8670–8680, 2019.

[41] R. I. Ansari, C. Chrysostomou, S. A. Hassan, M. Guizani, S. Mumtaz, J. Rodriguez, and J. J. Rodrigues, "5g d2d networks: Techniques, challenges, and future prospects," *IEEE Systems Journal*, vol. 12, no. 4, pp. 3970–3984, 2017.

[42] A. S. Andrae and T. Edler, "On global electricity usage of communication technology: trends to 2030," *Challenges*, vol. 6, no. 1, pp. 117–157, 2015.

[43] E. Björnson and E. G. Larsson, "How energy-efficient can a wireless communication system become?" in *2018 52nd Asilomar conference on signals, systems, and computers*. IEEE, 2018, pp. 1252–1256.

[44] F. Li, X. Wang, J. Cao, R. Wang, and Y. Bi, "A state transition-aware energy-saving mechanism for dense wlans in buildings," *IEEE access*, vol. 5, pp. 25 671–25 681, 2017.

[45] Y. Song, P.-Y. Kong, and Y. Han, "Minimizing energy consumption through traffic offloading in hetnets with two-class traffic," *IEEE Communications Letters*, vol. 19, no. 8, pp. 1394–1397, 2015.

[46] C.-W. Huang and P.-C. Chen, "Joint demand forecasting and dqn-based control for energy-aware mobile traffic offloading," *IEEE Access*, vol. 8, pp. 66 588–66 597, 2020.

[47] X. Chen, J. Wu, Y. Cai, H. Zhang, and T. Chen, "Energy-efficiency oriented traffic offloading in wireless networks: A brief survey and a learning approach for heterogeneous cellular networks," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 4, pp. 627–640, 2015.

[48] M. Ozturk, A. I. Abubakar, J. P. B. Nadas, R. N. B. Rais, S. Hussain, and M. A. Imran, "Energy optimization in ultra-dense radio access networks via traffic-aware cell switching," *IEEE Transactions on Green Communications and Networking*, vol. 5, no. 2, pp. 832–845, June 2021.

[49] Y. Wu, Y. He, L. P. Qian, J. Huang, and X. Shen, "Optimal resource allocations for mobile data offloading via dual-connectivity," *IEEE Transactions on Mobile Computing*, vol. 17, no. 10, pp. 2349–2365, 2018.

[50] D. Saliba, R. Imad, S. Houcke, and B. E. Hassan, "WiFi dimensioning to offload LTE in 5G networks," *2019 IEEE 9th Annu. Comput. Commun. Work. Conf. CCWC 2019*, pp. 521–526, 2019.

[51] A. Apostolaras, G. Iosifidis, K. Chounos, T. Korakis, and L. Tassiulas, "C2m: Mobile data offloading to mesh networks," in *2014 IEEE Global Communications Conference*, 2014, pp. 4877–4883.

[52] X. Zhang, P. Huang, L. Guo, and Y. Fang, "Social-aware energy-efficient data offloading with strong stability," *IEEE/ACM Trans. Netw.*, vol. 27, no. 4, pp. 1515–1528, 2019.

[53] W. Wang, H. Li, W. Zhang, and S. Wei, "Energy efficiency for data offloading in d2d cooperative caching networks," *Wireless Communications and Mobile Computing*, vol. 2020, 2020.

[54] Y. Qiao, Y. Li, and J. Li, "An Economic Incentive for D2D Assisted Offloading Using Stackelberg Game," *IEEE Access*, vol. 8, pp. 136 684–136 696, 2020.

[55] Z. Pan and J. Yang, "Deep reinforcement learning-based optimization method for d2d communication energy efficiency in heterogeneous cellular networks," *IEEE Access*, 2024.

[56] L. Zheng, J. Chen, C. Joe-Wong, W. T. Chee, and M. Chiang, "An economic analysis of wireless network infrastructure sharing," in *2017 15th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, 2017, pp. 1–8.

[57] G. Feng, F. Xia, Y. Zhang, D. Su, H. Lv, H. Wang, and H. Lv, "Optimal cooperative wireless communication for mobile user data offloading," *IEEE Access*, vol. 6, 2018.

[58] H. Zhou, X. Chen, S. He, J. Chen, and J. Wu, "Draim: A novel delay-constraint and reverse auction-based incentive mechanism for wifi offloading," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 4, pp. 711–722, 2020.

[59] D. Liu, A. Hafid, and L. Khoukhi, "Multi-item auction based mechanism for mobile data offloading: A robust optimization approach," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 4, pp. 4155–4168, 2020.

[60] D. Liu, L. Khoukhi, and A. Hafid, "Data offloading in mobile cloud computing: A markov decision process approach," in *2017 IEEE International Conference on Communications (ICC)*, 2017, pp. 1–6.

[61] Y. Li, J. Li, and M. Ahmed, "A three-stage incentive formation for optimally pricing social data offloading," *Journal of Network and Computer Applications*, vol. 172, p. 102816, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1084804520302873

[62] M. H. Cheung and J. Huang, "Dawn: Delay-aware wi-fi offloading and network selection," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 6, pp. 1214–1223, 2015.

[63] G. Feng, H. Lv, C. Wang, F. Xia, H. Lv, H. Wang, and Q. Zhao, "A non-cooperative game-theoretical approach to mobile data offloading," *2018 IEEE Glob. Commun. Conf. GLOBECOM 2018 - Proc.*, pp. 1–6, 2018.

[64] Y. Li, J. Zhang, X. Gan, L. Fu, H. Yu, and X. Wang, "A contract-based incentive mechanism for delayed traffic offloading in cellular networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 8, pp. 5314–5327, 2016.

[65] S. Shao, M. Nazzal, A. Khreishah, and M. Ayyash, "Self-optimizing data offloading in mobile heterogeneous radio-optical networks: A deep reinforcement learning approach," *IEEE Network*, vol. 36, no. 2, pp. 100–106, 2022.

[66] E. Fakhfakh and S. Hamouda, "Optimized q-learning for wifi offloading in dense cellular networks," *IET Communications*, vol. 11, 08 2017.

[67] A. M. Alagrami, M. M. Elmesalawy, and A. M. El-Haleem, "Enhanced ANDSF WiFi discovery mechanism using machine learning for mobile data offloading," *ICENCO 2019 - 2019 15th Int. Comput. Eng. Conf. Util. Mach. Intell. a Better World*, pp. 138–143, 2019.

[68] M. S. Bali, K. Gupta, D. Koundal, A. Zaguia, S. Mahajan, and A. K. Pandit, "Smart architectural framework for symmetrical data offloading in iot," *Symmetry*, vol. 13, no. 10, p. 1889, Oct 2021. [Online]. Available: http://dx.doi.org/10.3390/sym13101889

[69] B. Liu, Q. Zhu, W. Tan, and H. Zhu, "Congestion-Optimal WiFi Offloading with User Mobility Management in Smart Communications," *Wirel. Commun. Mob. Comput.*, vol. 2018, 2018.

[70] I. Matei and J. S. Baras, "Performance evaluation of the consensus-based distributed subgradient method under random communication topologies," *IEEE Journal of Selected Topics in Signal Processing*, vol. 5, no. 4, pp. 754–771, 2011.

[71] D. Mochizuki, Y. Abiko, T. Saito, D. Ikeda, and H. Mineno, "Delay-tolerance-based mobile data offloading using deep reinforcement learning," *Sensors*, vol. 19, no. 7, 2019. [Online]. Available: https://www.mdpi.com/1424-8220/19/7/1674

[72] B. Majumder and T. Venkatesh, "Mobile data offloading based on minority game theoretic framework," *Wireless Networks*, vol. 28, no. 7, pp. 2967–2982, 2022.

[73] M. J. Kadhim, R. Sadeghi, A. S. Abdalrada, B. Arandian, and R. Khorsand, "Performance improvement of data offloading using krill herd optimization algorithm," *Majlesi Journal of Electrical Engineering*, vol. 19, no. 1 (March 2025), pp. 17–17, 2025.

[74] Y. Pan, C. Pan, H. Zhu, Q. Z. Ahmed, M. Chen, and J. Wang, "On Consideration of Content Preference and Sharing Willingness in D2D Assisted Offloading," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 4, pp. 978–993, 2017.

Universiti Utara Malaysia

[75] H. Zhou, X. Chen, S. He, C. Zhu, and V. C. M. Leung, "Freshness-aware seed selection for offloading cellular traffic through opportunistic mobile networks," *IEEE Transactions on Wireless Communications*, vol. 19, no. 4, pp. 2658–2669, 2020.

[76] X. Yan, Y. A. Şekercioğlu, and S. Narayanan, "A survey of vertical handover decision algorithms in fourth generation heterogeneous wireless networks," *Computer networks*, vol. 54, no. 11, pp. 1848–1863, 2010.

[77] U. Ayesta, "Reinforcement learning in queues," *Queueing Systems*, vol. 100, no. 3, pp. 497–499, 2022.

[78] M. L. Puterman, *Markov decision processes: discrete stochastic dynamic programming*. John Wiley & Sons, 2005.

[79] S. Chakraborty, "Topsis and modified topsis: A comparative analysis," *Decision Analytics Journal*, vol. 2, p. 100021, 2022.

[80] E. F. Morales and H. J. Escalante, "A brief introduction to supervised, unsupervised, and reinforcement learning," in *Biosignal processing and classification using computational learning and intelligence*. Elsevier, 2022, pp. 111–129.

[81] F. Garcia and E. Rachelson, "Markov decision processes," *Markov Decision Processes in Artificial Intelligence*, pp. 1–38, 2013.

[82] P. Chen, "Effects of the entropy weight on topsis," *Expert Systems with Applications*, vol. 168, p. 114186, 2021.

[83] S. K. Sahoo and S. S. Goswami, "A comprehensive review of multiple criteria decision-making (mcdm) methods: advancements, applications, and future directions," *Decision Making Advances*, vol. 1, no. 1, pp. 25–48, 2023.

[84] B. Singh, R. Kumar, and V. P. Singh, "Reinforcement learning in robotic applications: a comprehensive survey," *Artificial Intelligence Review*, vol. 55, no. 2, pp. 945–990, 2022.

[85] M. Littman, "Markov decision processes," in *International Encyclopedia of the Social & Behavioral Sciences*, N. J. Smelser and P. B. Baltes, Eds. Oxford: Pergamon, 2001, pp. 9240–9242. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B0080430767006148

[86] A. A. Thabit, E. Alzidi, M. A. Mohammed, and P. Palchyk, "Development of a system based on a graphical user interface using matlab tools," in *2024 35th Conference of Open Innovations Association (FRUCT)*. IEEE, 2024, pp. 744–754.

[87] I. Tomozei, T. Axinte, and L. Paraschiv, "A brief introduction to the matlab program," 2023.

[88] A. Apostolaras, G. Iosifidis, K. Chounos, T. Korakis, and L. Tassiulas, "A mechanism for mobile data offloading to wireless mesh networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 9, pp. 5984–5997, 2016.

[89] L. Chen and H. Li, "An mdp-based vertical handoff decision algorithm for heterogeneous wireless networks," in *2016 IEEE Wireless Communications and Networking Conference*, 2016, pp. 1–6.

[90] H. Mohsin, K. Abdulameer, and Z. N. Khudhair, "Study and performance analysis of received signal strength indicator (rssi) in wireless communication systems," *International Journal of Engineering and Technology*, vol. 6, pp. 195–200, 01 2017.

[91] S. A. Brinkerhoff, W. M. Murrah, Z. Hutchison, M. Miller, and J. A. Roper, "Words matter: instructions dictate "self-selected" walking speed in young adults," *Gait & Posture*, vol. 95, pp. 223–226, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0966636219303522

[92] L. Chen and H. Li, "An mdp-based vertical handoff decision algorithm for heterogeneous wireless networks," in *2016 IEEE wireless communications and networking conference*. IEEE, 2016, pp. 1–6.

[93] H. Hu, Y. Yang, Q. Zhao, and C. Zhang, "On the role of discount factor in offline reinforcement learning," in *International Conference on Machine Learning*. PMLR, 2022, pp. 9072–9098.

[94] H. C. Tijms, *A first course in stochastic models*. John Wiley and sons, 2003.

[95] G. Liang, X. Guo, G. Sun, J. Fang, H. Yu, and M. Lin, "Multi-attribute access selection algorithm for heterogeneous wireless networks based on uncertain network attribute values," *IEEE Access*, vol. 10, pp. 74 071–74 081, 2022.

[96] S. Razavi, A. Jakeman, A. Saltelli, C. Prieur, B. Iooss, E. Borgonovo, E. Plischke, S. L. Piano, T. Iwanaga, Becker, and William, "The future of sensitivity analysis: an essential discipline for systems modeling and policy support," *Environmental Modelling & Software*, vol. 137, p. 104954, 2021.

[97] H. Christopher Frey and S. R. Patil, "Identification and review of sensitivity analysis methods," *Risk analysis*, vol. 22, no. 3, pp. 553–578, 2002.

[98] X. Zhou, u. Ye, and T. T. Lee, "Designing and analysis of a Wi-Fi data offloading strategy catering for the preference of mobile users," *J. Ind. Manag. Optim.*, 2021.

[99] A. P. King and R. J. Eckersley, "Chapter 7 - inferential statistics iv: Choosing a hypothesis test," in *Statistics for Biomedical Engineers and Scientists*, A. P. King and R. J. Eckersley, Eds. Academic Press, 2019, pp. 147–171. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780081029398000165

[100] N. M. Razali, Wah, and Y. Bee, "Power comparisons of shapiro-wilk, kolmogorov-smirnov, lilliefors and anderson-darling tests," *Journal of statistical modeling and analytics*, vol. 2, no. 1, pp. 21–33, 2011.

[101] K. J. H. Kwak Sang Kyu, "Statistical data preparation: management of missing values and outliers," *kja*, vol. 70, no. 4, pp. 407–411, 2017. [Online]. Available: http://www.e-sciencecentral.org/articles/?scid=1156715

[102] C. H. Sim, F. F. Gan, and T. C. Chang, "Outlier labeling with boxplot procedures," *Journal of the American Statistical Association*, vol. 100, no. 470, pp. 642–652, 2005.

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