ENHANCING DATAGRAM CONGESTION CONTROL PROTOCOL FOR EFFICIENT LONG DELAY LINK

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DOCTOR OF PHILOSOPHY
UNIVERSITI UTARA MALAYSIA
2012

ENHANCING DATAGRAM CONGESTION CONTROL PROTOCOL FOR EFFICIENT LONG DELAY LINK

A thesis submitted to the Awang Had Salleh Graduate School of Arts and Sciences
in full fulfillment of the requirements for the degree of Doctor of Philosophy
Universiti Utara Malaysia

by

SHAHRUDIN AWANG NOR

Dedication

For my family ...

my late mother Allahyarhamah Hjh. Baayah

and my father Hj. Awang Nor

my wife Hjh. Mas Juliana

and our three precious ones,

Muhammad Solihin

Siti Madihah

Siti Munirah

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Abstrak

Kebanyakan aplikasi multimedia menggunakan Protokol Datagram Pengguna (UDP) sebagai protokol lapisan pengangkutan kerana ianya sesuai untuk penghantaran data multimedia dalam Internet. Walau bagaimanapun, penggunaan UDP boleh membahayakan kestabilan rangkaian kerana tiada kawalan kesesakan digunakan. Sehingga suatu tahap, rangkaian akan runtuh jika terlalu banyak aplikasi sewenang-wenangnya menggunakan protokol ini. Kemudiannya, selain menggunakan UDP, aplikasi mempunyai pilihan untuk menggunakan Protokol Kawalan Kesesakan Datagram (DCCP) yang mempunyai kawalan kesesakan terbina-dalam yang boleh membantu kearah rangkaian yang lebih baik. Meskipun begitu, mekanisma kawalan kesesakan dalam CCID-2 TCP-like mengakibatkan masalah apabila menghantar data multimedia melalui talian lengah panjang. Untuk mengatasi masalah seperti masa yang lebih panjang diambil untuk mencapai truput maksima dan turun-naik truput semasa fasa penghindaran, dua pendekatan telah digunakan iaitu penetapan nilai permulaan-lambat ambang yang sesuai dan manipulasi tetingkap kesesakan semasa fasa penghindaran kesesakan. Mekanisma kawalan kesesakan baru yang dipersembahkan dalam tesis ini dinamakan "Tetingkap Ambang Seperti-TCP (TCP-like TW)" dan direka berdasarkan kelebihan kedua-dua pendekatan ini. Ianya telah dibangun dan dimodelkan dalam Pensimulasi Rangkaian 2 (*ns-2*). TCP-like TW telah membuktikan dapat meningkatkan prestasi DCCP semasa penghantaran data multimedia melalui rangkaian talian lengah panjang, juga untuk talian lengah pendek. Bagi talian lengah panjang, mekanisma kawalan kesesakan TCP-like TW berkeupayaan untuk meminimakan masa yang diambil untuk mencapai truput maksima. Ia boleh meratakan truput yang naik-turun selepas truput maksima dicapai. Tambahan pula, untuk talian lengah pendek, truput maksima talian akan ditingkatkan disamping mengekalkan keramahan terhadap protokol kawalan-kesesakan yang lain.

Kata kunci: Protokol Kawalan Kesesakan Datagram, Tetingkap Ambang Seperti-TCP, kawalan kesesakan

Abstract

Most of the multimedia applications use the User Datagram Protocol (UDP) as a transport layer protocol because it is suitable for the delivery of multimedia data over the Internet. However, the use of UDP could endanger the stability of the network because there is no congestion control applied. To a certain extent, the network can collapse if too many applications deliberately use this protocol. Subsequently, instead of using the UDP, the applications have choices to use the Datagram Congestion Control Protocol (DCCP), which has a built-in congestion control that can provide a better network. Nevertheless, the congestion control mechanism in the CCID-2 TCP-like can cause problems when delivering multimedia data over a long delay link. To alleviate the problems, such as longer time taken for achieving maximum throughput, and throughput fluctuation during a congestion avoidance phase, two approaches have been used, i.e. setting of an appropriate slow-start threshold value and manipulating congestion window during a congestion avoidance phase. A new congestion control mechanism presented in this thesis, namely the "TCP-like Threshold Window (TCP-like TW)" is designed based on the advantages of the two approaches. It has been developed and modeled in the Network Simulator 2 (*ns-2*). The TCP-like TW has proven to enhance the performance of the DCCP when delivering multimedia data over long delay link networks, as well as over short delay. For a long delay link, the TCP-like TW congestion control mechanism is able to minimize the time taken to achieve the maximum throughput. It can smooth the fluctuation of throughput after achieving the maximum throughput. Furthermore, for the short delay link, the maximum throughput will be increased while maintaining the friendliness towards other congestion-controlled protocols.

Keywords: Datagram Congestion Control Protocol, TCP-like Threshold Window, congestion control

Declaration

Some of the works presented in this thesis have been published as listed below:

1. Shahrudin Awang Nor, Suhaidi Hassan, and Omar Almomani, "The Effect of Initial Slow-start Threshold Size in DCCP over Large Delay Link Networks", in the Proceedings of International Conference on Electronic Design 2008 (ICED 2008), Penang, Malaysia, 1-3 December 2008. Appear in IEEEXplore. Indexed by Scopus and IEEEXplore.

2. Shahrudin Awang Nor, Suhaidi Hassan, and Omar Almomani, "Simulated Performance of VoIP Using DCCP CCID2 Over Large Delay Link Networks", in International Conference on Network Applications, Protocols, and Services 2008 (NETAPPS 2008), Sintok, Kedah, Malaysia, vol. 1, 21-22 November 2008.

3. Shahrudin Awang Nor, Suhaidi Hassan, Osman Ghazali, and A. Suki M. Arif, "Friendliness of DCCP towards TCP over large delay link networks", in the Proceedings of The International Conference on Information and Network Technology 2010 (ICINT 2010), Shanghai, China, vol. 5, pp. 286-291, 22-24 June 2010. Appear in IEEEXplore. Indexed by INSPEC, Thomson ISI, Ei Compendex, Scopus and IEEEXplore.

4. Shahrudin Awang Nor, Suhaidi Hassan, Osman Ghazali, and A. Suki M. Arif, "On the Performance of TCP Pacing with DCCP", in The 2^{nd} International Conference on Network Applications, Protocols and Services 2010 (NETAPPS 2010), Alor Setar, Kedah, Malaysia, pp. 37-41, 22-23 September 2010. Appear in IEEEXplore, ACM Digital Library and IEEE Computer Society Digital Library. Indexed by INSPEC, Scopus and IEEEXplore.

5. Shahrudin Awang Nor, Suhaidi Hassan, Osman Ghazali, and Mohammed M. Kadhum, "Performance Enhancement of DCCP TCP-like over Long Delay Link Networks", in the Proceedings of The 2010 International Conference on Modeling, Simulation and Control 2010 (ICMSC 2010), Cairo, Egypt, pp. 247-251, 2-4 November 2010.

6. Shahrudin Awang Nor, Suhaidi Hassan, Osman Ghazali, and A. Suki M. Arif, "DCCP: A New TCP-Friendly Transport Protocol for Delivering Multimedia Data", in the Proceedings of The 5^{th} Social Economic and Information

Technology 2010 (SEiT 2010), Hatyai, Thailand, pp. 283-290, 23-25 November 2010.

7. Shahrudin Awang Nor, Suhaidi Hassan, Osman Ghazali, and Mohd. Hasbullah Omar, "The Performance of DCCP TCP-like with Initial Slow-start Threshold Manipulation", in the Proceedings of the 3^{rd} International Conference on Computing and Informatics 2011 (ICOCI 2011), Bandung, Indonesia, 8–9 June 2011.

8. Shahrudin Awang Nor, Suhaidi Hassan, and Osman Ghazali, "TCP-like TW: An Innovative Congestion Control Mechanism for Datagram Congestion Control Protocol", poster presentation at the International Conference and Exposition on Invention of Institutions of Higher Learning 2011 (PECIPTA 2011), Kuala Lumpur Convention Centre, Malaysia, 13–15 September 2011.

Acknowledgments

In the name of ALLAH, Most Gracious, Most Merciful.

Throughout my studies at the Universiti Utara Malaysia, I have been fortunate enough to have the help and support from many people. I would like to express my deep and sincere gratitude to my supervisor, Associate Professor Dr. Suhaidi Hassan, former Assistant Vice Chancellor, and currently Chair of the InterNetWorks Research Laboratory, School of Computing, UUM College of Arts and Sciences. His wide knowledge and his logical way of thinking have been of great value to me. His understanding, encouragement and personal guidance have provided a good basis for this thesis. My deep and sincere gratitude also goes to my co-supervisor, Dr. Osman Ghazali, Head of Computer Science Department, School of Computing, for his support throughout my studies.

Many thanks to Professor Vern Paxson, Dr. Sally Floyd and Mark Allman of the ICSI Networking Group, who I have never met them in person, for giving the meaningful suggestions at the very beginning period of my research, though through email but very helpful in assisting me choosing the right research area in the transport protocol of the Internet. Many thanks also to Dr. Arjuna Sathiaseelan of the University of Aberdeen, who shared with me his *ns-2* codes in the work of DCCP congestion control.

Many thanks go to all my colleagues in the InterNetWorks Research Laboratory including Dr. Mohamed M. Kadhum for his practical suggestions, all my friends, Dr. Ahmad Suki, Dr. Mohd. Hasbullah and all members, for their many useful and insightful discussions on networking and other random topics. My appreciation also goes to the *ns-2* community who have shared the knowledge and opinions.

I would also like to express my gratitude to my sponsors, the Universiti Utara Malaysia, and the Higher Education Ministry of the Government of Malaysia for granting my study leave and sponsoring the research.

Finally, my heartiest gratitude goes to my wife and children, who sacrificed their emotions and feelings, every time I had to leave for the PhD research camps which were conducted monthly, as well as other research workshops. I am also immeasurably grateful to my father, father-in-law, mother-in-law, brothers, sisters, and all my relatives for their kindness. My success would never be a reality without their support, and their affection and love make me stronger, and I appreciate them very much. May Allah SWT bless all of us and grant His forgiveness to continue the life in this world as His servant before we meet Him on the day of judgment, insyaAllah.

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3DA	Three Duplicate Acknowledgment
ACKs	Acknowledgments
AIMD	Additive-Increase/Multiplicative-Decrease
AQM	Active Queue Management
ASTRO	All Asia Television and Radio Company
BDP	Bandwidth-Delay Product
BIC	Binary Increase Congestion control
CA	Congestion Avoidance
CBR	Continuous/Constant Bit Rate
CCID-2	Congestion Control Identification 2
CCID-3	Congestion Control Identification 3
CCID-4	Congestion Control Identification 4
CCIDs	Congestion Control Identifiers
CCVal	Congestion Control Value
CONSER	Collaborative Network Simulation for Education and Research
CPU	Central Processing Unit
CsCov	Checksum Coverage
cwnd	Congestion Window state variable
cwsize	Congestion Window Size state variable
D-SACK	Duplicate-SACK
DARPA	Defense Advanced Research Projects Agency
DCCP	Datagram Congestion Control Protocol
DTLS	Datagram Transport Layer Security

ECN	Explicit Congestion Notification
ESACK	Enhanced SACK
EWMA	Exponentially Weighted Moving Average
FIFO	First-In First-Out
FTP	File Transfer Protocol
GEO	Geostationary Earth Orbit
HC-Receiver	Half-Connection-Receiver
HC-Sender	Half-Connection-Sender
ICTs	Information and Communication Technologies
IDE	Integrated Development Environment
IETF	Internet Engineering Task Force
IP	Internet Protocol
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
IW	Initial Window
kbps	Kilo Bits per Second
LEO	Low-Earth-Orbit
LFN	Long Fat Networks
LW	Loss Window
MAC	Medium Access Control
Mbps	Mega Bits per Second
nam	Network Animator
ns-2	Network Simulator 2
NSF	National Science Foundation

NUMDUPACKS Number of Duplicate Acknowledgments

OSI Open Systems Interconnection

PLR Packet Loss Ratio

RED Random Early Detection

Res Reserved

RFC Request for Comments

RTO Retransmission Timeout

RTT Round Trip Time

rwnd Receiver Window state variable

SACK Selective Acknowledgment

SAMAN Simulation Augmented by Measurement and Analysis for Networks

SMSS Sender Maximum Segment Size

SS Slow-start

*ssthres*h Slow-start Threshold state variable

TCP Transport Control Protocol state variable

TCP/IP Transmission Control Protocol / Internet Protocol

TEW Threshold Exponential Window

TFRC TCP-Friendly Rate Control

TFRC-SP TCP-Friendly Rate Control for Small Packet

TO Timeout

TW Threshold Window

UDP User Datagram Protocol

VBR Variable Bit Rate

VINT Virtual Inter Network Testbed

VoIP Voice over IP

CHAPTER ONE

INTRODUCTION

This thesis is about improving TCP-like, which is one of the congestion control mechanisms for Datagram Congestion Control Protocol (DCCP) to improve the control and avoid the congestion problem caused by multimedia traffic data delivered over long delay bottleneck link networks. DCCP is a transport protocol which is an unreliable protocol like User Datagram Protocol (UDP), but it provides congestion control like Transmission Control Protocol (TCP). In this thesis, a new congestion control mechanism will be introduced, code-named TCP-like Threshold Exponential Window (TCP-like TEW). It is anticipated to alleviate the congestion problem in DCCP and achieve maximum throughput faster than the traditional DCCP mechanisms over long delay link networks. In addition, it also can improve the throughput, jitter, and with acceptable packet loss. The aim of this chapter is to place the thesis in its context. In this chapter, the multimedia traffic over long delay link networks, the common transport layer protocols, and congestion control phases are provided in Sections 1.1, 1.2 and 1.3, respectively. Sections 1.4, 1.5, 1.6 and 1.7 of this chapter, respectively, include the research problem, motivation, scope, and objectives of the research presented in this thesis. The key research steps, research framework and contributions of the work done in this thesis are stated in Sections 1.8, 1.9 and 1.10, respectively, while the thesis organization is presented in Section 1.11 of this chapter.

The contents of the thesis is for internal user only

1.1 Multimedia Traffic over Long Delay Link Networks

Datagram Congestion Control Protocol (DCCP) is introduced as a solution to the friendliness issue of UDP when it coexists with other congestion-controlled transport protocol like TCP [1]. In fact, UDP, which is a popular transport protocol for the delivery of multimedia, data cannot share the bandwidth fairly when it coexists with TCP under limited bandwidth because it does not have any congestion control mechanism. At the first place, UDP will utilize all the bandwidth in the same limited bandwidth link and TCP will be out of bandwidth. As most of the traffic in the Internet nowadays are TCP flows, this can lead to the collapse of the entire network [2].

As DCCP is designed for the delivery of multimedia data over the network with the capability of having a congestion control mechanism, it can coexist fairly with TCP. The bandwidth is shared fairly between other congestion-controlled transport protocol like TCP.

The performance of DCCP when it coexists with TCP is fair over normal network scenario, i.e. over short delay link network. When it comes to a network link with long propagation delay, unlike UDP, the performance of DCCP, when delivering multimedia data is dropped significantly due to the high round trip time (RTT) introduced in such link, for example, the links for satellite and wireless [3]. This drawback of using DCCP as a transport protocol over long delay link networks leads to the research idea to improve the congestion control mechanism of DCCP over such links.

The contents of the thesis is for internal user only

[13] J. Postel, "User Datagram Protocol", RFC 0768, Internet Engineering Task Force, August 1980.

[14] E. Kohler, M. Handley, and S. Floyd, "Datagram Congestion Control Protocol (DCCP)", RFC 4340, Internet Engineering Task Force, March 2006.

[15] Ricardo N. Vaz Mario S. Nunes, "Selective Frame Discard for Video Streaming over IP Networks", in *Proceedings of the 7th Conference on Computer Networks (CRC2004)*, 2004.

[16] S. Floyd and E. Kohler, "Profile for Datagram Congestion Control Protocol (DCCP) Congestion Control ID 2: TCP-like Congestion Control", RFC 4341, Internet Engineering Task Force, March 2006.

[17] M. Mathis, J. Mahdavi, S. Floyd, and A. Romanow, "TCP Selective Acknowledgment Options", RFC 2018, Internet Engineering Task Force, 1996.

[18] E. Blanton, M. Allman, K. Fall, and L. Wang, "A Conservative Selective Acknowledgment (SACK)-based Loss Recovery Algorithm for TCP", RFC 3517, Internet Engineering Task Force, April 2003.

[19] S. Floyd, E. Kohler, and J. Padhye, "Profile for Datagram Congestion Control Protocol (DCCP) Congestion Control ID 3: TCP-Friendly Rate Control (TFRC)", RFC 4342, Internet Engineering Task Force, March 2006.

[20] S. Floyd, M. Handley, J. Padhye, and J. Widmer, "TCP Friendly Rate Control (TFRC): Protocol Specification", RFC 5348, Internet Engineering Task Force, September 2008.

[21] S. Floyd and E. Kohler, "Profile for Datagram Congestion Control Protocol (DCCP) Congestion ID 4: TCP-Friendly Rate Control for Small Packets (TFRC-SP)", RFC 5622, Internet Engineering Task Force, August 2009.

[22] S. Floyd, "Congestion Control Principles", RFC 2914, Internet Engineering Task Force, September 2000.

[23] M. Handley, J. Padhye, and S. Floyd, "TCP Congestion Window Validation", RFC 2861, Internet Engineering Task Force, June 2000.

[24] M. Allman, S. Floyd, and C. Partridge, "Increasing TCP's Initial Window", RFC 3390, Internet Engineering Task Force, October 2002.

[25] Jeonggyun Yu and Sunghyun Choi, "Modeling and analysis of TCP dynamics over IEEE 802.11 WLAN", in *Fourth Annual Conference on Wireless on Demand Network Systems and Services 2007 (WONS '07)*, January 2007, pp. 154 –161.

[26] Martin Arlitt and Carey Williamson, "An analysis of TCP reset behaviour on the internet", *ACM SIGCOMM Computer Communication Review*, vol. 35, pp. 37–44, January 2005.

[27] Quoc Truong Tong, H. Koga, K. Iida, and Y. Sakai, "TCP Fairness Improvement of DCCP Flow Control for Bursty Real-Time Applications", *First International Conference on Communications and Electronics 2006 (ICCE '06)*, pp. 66–71, October 2006.

[28] S. Takeuchi, H. Koga, K. Iida, Y. Kadobayashi, and S. Yamaguchi, "Performance evaluations of DCCP for bursty traffic in real-time applications", *Proceedings of The 2005 Symposium on Applications and the Internet (SAINT '05)*, pp. 142–149, 31 January-4 February 2005.

[29] Hao Jiang and Constantinos Dovrolis, "Why is the Internet traffic bursty in short time scales?", in *SIGMETRICS '05: Proceedings of The 2005 ACM SIGMETRICS International Conference on Measurement and Modeling of Computer Systems*, New York, NY, USA, 2005, pp. 241–252, ACM.

[30] Hans Kruse, "Performance Of Common Data Communications Protocols Over Long Delay Links: An Experimental Examination", in *3rd International Conference on Telecommunication Systems Modeling and Design*, 1995.

[31] V. Jacobson and R. Braden, "TCP Extensions for Long-Delay Paths", RFC 1072, Internet Engineering Task Force, 1988.

[32] K.A. Rahim, M. Ismail, and M. Abdullah, "Satellite Link Margin Prediction and Performance of ASTRO Malaysia", in *International Conference on Space Science and Communication 2009 (IconSpace 2009)*, October 2009, pp. 78 –82.

[33] V. Jacobson, "Congestion Avoidance and Control", in *Proceedings of the ACM Symposium on Communications Architectures and Protocols (SIGCOMM '88)*. 16-18 August 1988, pp. 314–329, ACM.

[34] Andrew S. Tanenbaum, *Computer Networks*, Pearson Education International, Prentice Hall PTR, Upper Saddle River, New Jersey, 4th edition, 2003.

[35] Douglas E. Comer, *Computer Networks and Internets with Internet Applications*, Pearson Prentice Hall, Upper Saddle River, New Jersey, 4th edition, 2004.

[36] James F. Kurose and Keith W. Ross, *Computer Networking: A Top-Down Approach*, Addison-Wesley, 5th edition, 2010.

[37] A. Chydzinski and A. Brachman, "Performance of AQM Routers in the Presence of New TCP Variants", in *Proceedings of Second Int Advances in Future Internet (AFIN) Conf*, 2010, pp. 88–93.

[38] S. Henna, "A Throughput Analysis of TCP Variants in Mobile Wireless Networks", in *Proceedings of Third International Confonference on Next Generation Mobile Applications, Services and Technologies (NGMAST '09)*, 2009, pp. 279–284.

[39] C. Grimm and H. Schwier, "Empirical Analysis of TCP Variants and Their Impact on Grid FTP Port Requirements", in *Proceedings of Third International Conference on Networking and Services (ICNS)*, 2007.

[40] Y. Iwanaga, K. Kumazoe, D. Cavendish, M. Tsuru, and Y. Oie, "High-Speed TCP Performance Characterization under Various Operating Systems", in *Proceedings of 5th International Conference on Mobile Computing and Ubiquitous Networking (ICMU 2010)*, Seattle USA, 26-28 April 2010.

[41] Sangtae Ha, Injong Rhee, and Lisong Xu, "CUBIC: A New TCP-Friendly High-Speed TCP Variant", *ACM SIGOPS Operating Systems Review - Research and developments in the Linux kernel*, vol. 42, pp. 64–74, July 2008.

[42] K. Tan, J. Song, Q. Zhang, and M. Sridharan, "A Compound TCP Approach for High-Speed and Long Distance Networks", in *Proceedings of 25th IEEE International Conference on Computer Communications, Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2006)*, 23-29 April 2006, pp. 1 –12.

[43] S. Floyd, J. Mahdavi, M. Mathis, and M. Podolsky, "An Extension to the Selective Acknowledgement (SACK) Option for TCP", RFC 2883, Internet Engineering Task Force, July 2000.

[44] S. Floyd and T. Henderson, "The NewReno Modification to TCP's Fast Recovery Algorithm", RFC 2582, Internet Engineering Task Force, April 1999.

[45] S. Floyd, T. Henderson, and A. Gurtov, "The NewReno Modification to TCP's Fast Recovery Algorithm", RFC 3782, Internet Engineering Task Force, April 2004.

[46] J. Postel, "User Datagram Protocol", RFC 768, Internet Engineering Task Force, August 1980.

[47] Shahrudin Awang Nor, Suhaidi Hassan, Osman Ghazali, and A. Suki M. Arif, "DCCP: A New TCP-Friendly Transport Protocol for Delivering Multimedia Data", in *the Proceedings of The 5th Social Economic and Information Technology 2010 (SEiT 2010)*, Hatyai, Thailand, 23-25 November 2010, pp. 283–290.

[48] K. K. Ramakhrishnan, S. Floyd, and D. Black, "The addition of explicit congestion notification (ECN) to IP", RFC 3168, Internet Engineering Task Force, September 2001.

[49] H. V. Balan, L. Eggert, S. Niccolini, and M. Brunner, "An Experimental Evaluation of Voice Quality Over the Datagram Congestion Control Protocol", pp. 2009–2017, 2007, TY - CONF.

[50] S. Floyd and E. Kohler, "Profile for Datagram Congestion Control Protocol (DCCP) Congestion Control ID 2: TCP-like Congestion Control", RFC 4341, Internet Engineering Task Force, March 2006.

[51] T. Phelan, "Datagram Congestion Control Protocol (DCCP) User Guide", Tech. Rep., April 2005.

[52] E. Rescorla and N. Modadugu, "Datagram Transport Layer Security", RFC 4347, Internet Engineering Task Force, April 2006.

[53] T. Phelan, "Datagram Transport Layer Security (DTLS) over the Datagram Congestion Control Protocol (DCCP)", RFC 5238, Internet Engineering Task Force, May 2008.

[54] S. Floyd, M. Handley, J. Padhye, and J. Widmer, "TCP Friendly Rate Control (TFRC): Protocol Specification", RFC 5348, Internet Engineering Task Force, September 2008.

[55] S. Floyd and E. Kohler, "TCP Friendly Rate Control (TFRC): The Small-Packet (SP) Variant", RFC 4828, Internet Engineering Task Force, April 2007.

[56] M. Handley, S. Floyd, J. Padhye, and J. Widmer, "TCP Friendly Rate Control (TFRC): Protocol Specification", RFC 3448, Internet Engineering Task Force, January 2003.

[57] I. S. Chowdhury, J. Lahiry, and S. F. Hasan, "Performance analysis of Datagram Congestion Control Protocol (DCCP)", in *12th International Conference on Computers and Information Technology 2009 (ICCIT '09)*, 2009, pp. 454–459.

[58] G. Sarwar, R. Boreli, and E. Lochin, "Performance of VoIP with DCCP for Satellite Links", in *Proc. IEEE International Conference on Communications ICC '09*, 14–18 June 2009, pp. 1–5.

[59] S. Nosheen, S. A. Malik, Y. Bin Zikria, and M. K. Afzal, "Performance Evaluation of DCCP and SCTP for MPEG4 Video over Wireless Networks", in *Proc. IEEE International Multitopic Conference INMIC 2007*, 28–30 December 2007, pp. 1–6.

[60] J. Van Velthoven, K. Spaey, and C. Blondia, "Performance of Constant Quality Video Applications using the DCCP Transport Protocol", in *Proc. 31st IEEE Conference on Local Computer Networks*, 14–16 November 2006, pp. 511–512.

[61] Changbin Xu, Ju Liu, and Caihua Zhao, "Performance analysis of transmitting H.263 over DCCP", in *IEEE International Workshop on VLSI Design and Video Technology*, 2005, pp. 328 – 331.

[62] Árpád Huszák and Sándor Imre, "DCCP-based Multiple Retransmission Technique for Multimedia Streaming", in *Proceedings of the 6th International Conference on Advances in Mobile Computing and Multimedia*, New York, NY, USA, 2008, MoMM '08, pp. 21–28, ACM.

[63] E. Kohler and S. Floyd, "Faster Restart for TCP Friendly Rate Control (TFRC)", Internet draft, Internet Engineering Task Force, June 2006.

[64] M.S. Abdalla, A.M. Abdelrahman, and B.M. Ali, "Optimisation of congestion window for TCP adaptation to LEO satellite networks", *Electronics Letters*, vol. 40, no. 10, pp. 634 – 636, 13 May 2004.

[65] J. Sing and Ben Soh, "Improving Congestion Window Growth in Large Bandwidth Delay Product Networks", in *15th IEEE International Conference on Networks 2007 (ICON 2007)*, 19-21 November 2007, pp. 382 –387.

[66] A. Misra and T.J. Ott, "The window distribution of idealized TCP congestion avoidance with variable packet loss", in *Proceedings of 18th IEEE International Conference on Computer Communications, Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '99)*, 21-25 March 1999, vol. 3, pp. 1564 –1572.

[67] M.I. Biswas and G. Fairhurst, "An Investigation of TCP Congestion Window Validation over Satellite Paths", in *4th Advanced Satellite Mobile Systems 2008 (ASMS 2008)*, 26-28 August 2008, pp. 37 –42.

[68] C. Sall, E. El Alaoui, S. Doubabi, and E. Warraki, "A robust controller for the TCP congestion window", in *IEEE Symposium on Computers and Communications 2008 (ISCC 2008)*, 6-9 July 2008, pp. 137 –142.

[69] M. Gerla, M.Y. Sanadidi, Ren Wang, A. Zanella, C. Casetti, and S. Mascolo, "TCP Westwood: congestion window control using bandwidth estimation", in *IEEE Global Telecommunications Conference 2001 (GLOBECOM '01)*, 2001, vol. 3, pp. 1698 –1702.

[70] M. Tekala, "TCP Westwood with Limited Congestion Window", in *International Conference on Advanced Computer Control (ICACC '09)*, 22-24 January 2009, pp. 687 –692.

[71] S. Floyd, "HighSpeed TCP for Large Congestion Windows", RFC 3649, Internet Engineering Task Force, December 2003.

[72] G. Sarwar, R. Boreli, G. Jourjon, and E. Lochin, "Improvements in DCCP congestion control for satellite links", in *IEEE International Workshop on Satellite and Space Communications 2008 (IWSSC 2008)*, October 2008, pp. 8 –12.

[73] S. Floyd, M. Allman, A. Jain, and P. Sarolahti, "Quick-Start for TCP and IP", RFC 4782, Internet Engineering Task Force, January 2007.

[74] G. Fairhurst and A. Sathiaseelan, "Quick-Start for the Datagram Congestion Control Protocol (DCCP)", RFC 5634, Internet Engineering Task Force, August 2009.

[75] Arjuna Sathiaseelan and Gorry Fairhurst, "Use of Quickstart for Improving the Performance of TFRC-SP Over Satellite Networks", in *International Workshop on Satellite and Space Communications (IWSSC2006)*, Spain, 14–15 September 2006, pp. 46–50.

[76] Suhaidi Hassan, *Simulation-based Performance Evaluation of TCP-friendly Protocols for Supporting Multimedia Applications in the Internet*, PhD thesis, Computer Science Department, University of Leeds, UK, 2002.

[77] R. Jain, *The Art of Computer Systems Performance Analysis: Techniques for Experimental Design, Measurement, Simulation, and Modeling*, John Wiley, 1991.

[78] A. M. Law and W. D. Kelton, *Simulation Modeling and Analysis*, McGraw-Hill, 2^{nd} edition, 1991.

[79] Srinivasan Keshav, *Congestion Control in Computer Networks*, PhD thesis, EECS Department, UC Berkeley, 1991.

[80] Riri Fitri Sari, *Performance Evaluation of Active Network-based Unicast and Multicast Congestion Control Protocols*, PhD thesis, Computer Science Department, University of Leeds, UK, 2003.

[81] R. E. Shannon, "Introduction to the Art and Science of Simulation", in *Proceedings of the 1998 Winter Simulation Conference*, 1998, vol. 1, pp. 7–14.

[82] Byron J.T. Morgan, *Elements of Simulation*, Chapman and Hall, London, 1984.

[83] M. Ghanbari, C.J. Hughes, M.C. Sinclair, and J.P. Eade, *Principles of Performance Engineering for Telecommunication and Information Systems*, Institution of Electrical Engineers, London, 1997.

[84] András Varga, "OMNet++", `http://www.omnetpp.org/`, retrieved on 20 January 2011.

[85] "OPNET", `http://www.opnet.com/`, retrieved on 20 January 2011.

[86] Nils-Erik Mattsson, "DCCP Contributed Code for ns-2", `http://nsnam.isi.edu/nsnam/index.php/Contributed_Code#Transport`, retrieved on 29 December 2010.

[87] Nils-Erik Mattsson, "A DCCP module for ns-2", Master's thesis, 2004.

[88] "The VINT Project. The Network Simulator - ns-2", `http://www.isi.edu/nsnam/ns/`, retrieved on 20 January 2011.

[89] Teerawat Issariyakul and Ekram Hossain, *Introduction to Network Simulator NS2*, Springer, New York, 2009.

[90] Marc Greis, "Tutorial for the Network Simulator "ns"", `http://www.isi.edu/nsnam/ns/tutorial/`, retrieved on 20 January 2011.

[91] Jae Chung and Mark Claypool, "Tutorial for the Network Simulator "ns"", `http://nile.wpi.edu/NS/`, retrieved on 20 January 2011.

[92] "ns-2 Wiki Contributed Code", `http://nsnam.isi.edu/nsnam/index.php/Contributed_Code`, retrieved on 20 January 2011.

[93] E. Jonckheere, K. Shah, and S. Bohacek, "Dynamic modeling of Internet traffic for intrusion detection", in *Proceedings of the 2002 American Control Conference*, 2002, vol. 3, pp. 2436–2442.

[94] C. Marcondes, C. Palazzi, M. Y. Sanadidi, M. Gerla, M. Martinello, and M. T. Torres, "Regenerating TCP Dynamics From Traces Path Characteristics", in *3rd International Conference on Testbeds and Research Infrastructure for the Development of Networks and Communities 2007 (TridentCom 2007)*, 2007, pp. 1–8.

[95] M. Alizadeh, B. Atikoglu, A. Kabbani, A. Lakshmikantha, Rong Pan, B. Prabhakar, and M. Seaman, "Data center transport mechanisms: Congestion control theory and IEEE standardization", in *Proceedings of 46th Annual Allerton Conference on Communication, Control, and Computing*, 2008, pp. 1270–1277.

[96] Ping Wang, Hong Chen, and Xiaohui Lu, "Dynamic matrix control for active queue management based on step response model", in *Proceedings of 8th World Congress Intelligent Control and Automation (WCICA)*, 2010, pp. 1093–1097.

[97] Kai Wang and Chuang Lin, "SRD Service: A Stochastic Network Calculus Approach for Service Differentiation Analysis", in *Proceedings of 2010 IEEE International Conference on Communications (ICC)*, 2010, pp. 1–5.

[98] Suman Kumar, Mohammed Azad, and Seung-Jong Park, "A Fluid-based Simulation Study: The Effect of Loss Synchronization on Sizing Buffers over 10Gbps High Speed Networks", in *The 8th International Workshop on Protocols for Future, Large-Scale and Diverse Network Transports (PFLDNeT)*. Franklin & Marshall College, Lancaster, Pennsylvania, USA, 28-29 November 2010.

[99] Thomas R. Henderson and Randy H. Katz, "Transport Protocols for Internet-Compatible Satellite Networks", 1999, vol. 17, pp. 326–344.

[100] Mark Allman, Chris Hayes, Hans Kruse, and Shawn Ostermann, "TCP Performance Over Satellite Links", in *Proceedings of Fifth International Conference on Telecommunications Systems*, Nashville, Tennessee, March 1997.

[101] Kevin Fall and Kannan Varadhan, "The ns Manual (formerly ns Notes and Documentation)", Tech. Rep., May 2010.

[102] The Eclipse Foundation, "The Eclipse Projects", `http://www.eclipse.org/`, retrieved on 8 February 2011.

[103] GNU General Public License, "Cygwin", `http://www.cygwin.com/`, retrieved on 24 April 2011.

[104] "Equinox (OSGi)", `http://equinoxosgi.org/`, retrieved on 20 January 2011.

[105] "OSGi Alliance, OSGi Service Platform Release 4", `http://www.osgi.org`, retrieved on 20 January 2011.

[106] B. Jerry, *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice*, John Wiley & Sons, 1998.

[107] H. Mahbub and J. Raj, *High Performance TCP/IP Networking: Concepts, Issues, and Solutions*, Prentice-Hall, 2003.

[108] Michael C. Fu, "Simulation optimization", in *Proceedings of the 33rd Conference on Winter Simulation*, Washington, DC, USA, 2001, WSC '01, pp. 53–61, IEEE Computer Society.

[109] Osman Ghazali, *Scaleable and Smooth TCP-Friendly Receiver-based Layered Multicast Protocol*, PhD thesis, Universiti Utara Malaysia, Malaysia, 2008.

[110] C. McLean and Swee Leong, "The expanding role of simulation in future manufacturing", in *Proceedings of Winter Simulation Conference*, 2001, vol. 2, pp. 1478–1486.

[111] S. Floyd, "Metrics for the Evaluation of Congestion Control Mechanisms", RFC 5166, Internet Engineering Task Force, March 2008.

[112] P. Raptis, V. Vitsas, P. Chatzimisios, and K. Paparrizos, "Voice and Data Traffic Analysis in IEEE 802.11 DCF Infrastructure WLANs", in *2nd International Conference on Advances in Mesh Networks 2009 (MESH 2009)*, June 2009, pp. 37 –42.

[113] Alessio Botta, Antonio Pescape, Giorgio Ventre, and Roger P. Karrer, "High-speed wireless backbones: measurements from MagNets", in *4th International Conference on Broadband Communications, Networks and Systems 2007 (BROADNETS 2007)*, September 2007, pp. 680 –689.

[114] K. Maheswari and M. Punithavalli, "Receiver based packet loss replacement technique for high quality VoIP streams", in *World Congress on Nature Biologically Inspired Computing 2009 (NaBIC 2009)*, December 2009, pp. 1669 –1672.

[115] P. Omprakash and R. Sabitha, "Performance analysis of TCP over WiMAX", in *3rd International Conference on Electronics Computer Technology 2011 (ICECT 2011)*, April 2011, vol. 6, pp. 348 –352.

[116] S. Bradner, "Benchmarking Terminology for Network Interconnection Devices", RFC 1242, Internet Engineering Task Force, July 1991.

[117] J. Padhye, V. Firoiu, D.F. Towsley, and J.F. Kurose, "Modeling TCP Throughput: a simple model and its empirical validation", *ACM SIGCOMM '98*, , no. 2, pp. 303 –314, April 1998.

[118] J. Padhye, V. Firoiu, D.F. Towsley, and J.F. Kurose, "Modeling TCP Reno performance: a simple model and its empirical validation", *IEEE/ACM Transactions on Networking*, vol. 8, no. 2, pp. 133 –145, April 2000.

[119] D. Frost and S. Bryant, "Packet Loss and Delay Measurement for MPLS Networks", RFC 6374, Internet Engineering Task Force, September 2011.

[120] C. Demichelis and P. Chimento, "IP Packet Delay Variation Metric for IP Performance Metrics (IPPM)", RFC 3393, Internet Engineering Task Force, November 2002.

[121] M. Allman, V. Paxson, and W. Stevens, "TCP Congestion Control", RFC 2581, Internet Engineering Task Force, April 1999.

[122] S. Bhattacharjee, *Active Networks: Architectures, Composition, and Applications*, PhD thesis, Georgia Institute of Technology, 1999.

[123] W. Stevens, "TCP Slow Start, Congestion Avoidance, Fast Retransmit, and Fast Recovery Algorithms", RFC 2001, Internet Engineering Task Force, January 1997.

[124] L.A. Grieco and S. Mascolo, "Taxonomy and Evaluation of TCP-Friendly Congestion-Control Schemes on Fairness, Aggressiveness, and Responsiveness", *Electronics Letters*, vol. 40, no. 5, pp. 354 – 355, 2004.

[125] Shih-Ching Tsao, Yuan-Cheng Lai, and Ying-Dar Lin, "Taxonomy and Evaluation of TCP-Friendly Congestion-Control Schemes on Fairness, Aggressiveness, and Responsiveness", *IEEE Network*, vol. 21, no. 6, pp. 6–15, November - December 2007.

[126] R. K. Jain, D.-M. W. Chiu, and W. R. Hawe, "A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer Systems", Technical Report DEC-TR-301, Digital Equipment Corporation, September 1984, `http://www1.cse.wustl.edu/~jain/papers/fairness.htm`, retrieved on 8 February 2011.

[127] Robert Denda, Albert Banchs, and Wolfgang Effelsberg, "The Fairness Challenge in Computer Networks", in *Proceedings of the First COST 263 International Workshop on Quality of Future Internet Services (QofIS '00)*, London, UK, 2000, pp. 208–220, Springer-Verlag.

[128] V. Tsaoussidis and Chi Zhang, "The dynamics of responsiveness and smoothness in heterogeneous networks", *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 6, pp. 1178 – 1189, June 2005.

[129] Jing Deng, Y.S. Han, and Ben Liang, "Fairness Index Based on Variational Distance", in *IEEE Global Telecommunications Conference 2009 (GLOBECOM 2009)*, 30 November - 4 December 2009, pp. 1 –6.

[130] A. Detti, A. Caricato, and G. Bianchi, "Fairness-oriented Overlay VPN topology construction", in *IEEE 17th International Conference on Telecommunications (ICT)*, April 2010, pp. 658 –665.

[131] D.T.-H. Kao and A. Sabharwal, "Impact of Network Topology Knowledge on Fairness: A Geometric Approach", in *Proceedings of 28th IEEE International Conference on Computer Communications, Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2009)*, 19-25 April 2009, pp. 2601 –2605.

[132] S. Floyd, "Limited Slow-Start for TCP with Large Congestion Windows", RFC 3742, Internet Engineering Task Force, March 2004.

[133] S. Bhatti, M. Bateman, and D. Miras, "A comparative performance evaluation of DCCP", in *International Symposium on Performance Evaluation of Computer and Telecommunication Systems 2008 (SPECTS 2008)*, 2008, pp. 433–440.

[134] Zhou Kaiyu, K. L. Yeung, and V. O. K. Li, "Throughput modeling of TCP with slow-start and fast recovery", in *IEEE Global Telecommunications Conference 2005 (GLOBECOM '05)*, 2005, vol. 1, p. 5.

[135] M. Marchese, "Proposal of a modified version of the slow start algorithm to improve TCP performance over large delay satellite channels", in *IEEE International Conference on Communications 2001 (ICC 2001)*, 2001, vol. 10, pp. 3145–3149 vol.10.

[136] Rung-Shiang Cheng, Hui-Tang Lin, Wen-Shyang Hwang, and Ce-Kuen Shieh, "Improving the ramping up behavior of TCP slow start", in *19th International Conference on Advanced Information Networking and Applications 2005 (AINA 2005)*, March 2005, vol. 1, pp. 807 – 812 vol.1.

[137] A. Chaintreau, F. Baccelli, and C. Diot, "Impact of TCP-like congestion control on the throughput of multicast groups", *IEEE/ACM Transactions on Networking*, vol. 10, no. 4, pp. 500–512, 2002.

[138] Na Seung-Gu and Ahn Jong-Suk, "TCP-like flow control algorithm for real-time applications", in *Proceedings of IEEE International Conference on Networks 2000 (ICON 2000)*, 5-8 September 2000, pp. 99–104.

[139] Yongsheng Zhao and Lihua Song, "Stability of TCP-Like Congestion Control Algorithm", in *2nd International Symposium on Computational Intelligence and Design 2009 (ISCID '09)*, 12-14 December 2009, vol. 1, pp. 374–377.

[140] "ITU-T Recommendation G.1010 End-user multimedia QoS catagories", Tech. Rep., International Telecommunication Union, March 2003.

[141] "ITU-T Recommendation H.263 Video Codec for Low Bit Rate Communication", Tech. Rep., International Telecommunication Union, February 1998.

[142] K. Rijkse, "H.263: Video Coding for Low-Bit-Rate Communication", *Communications Magazine, IEEE*, vol. 34, no. 12, pp. 42 –45, December 1996.

[143] "ITU-T Recommendation H.261 Video codec for audiovisual services at p x 64 kbit/s", Tech. Rep., International Telecommunication Union, 1993.

[144] F.H.P. Fitzek and M. Reisslein, "MPEG-4 and H.263 Video Traces for Network Performance Evaluation", *Network, IEEE*, vol. 15, no. 6, pp. 40 –54, 2001.

[145] Mohammed M. Kadhum and Suhaidi Hassan, "A Study of ECN Effects on Long-lived TCP Connections using RED and Drop Tail Gateway Mechanisms", in *International Symposium on Information Technology (ITSim)*, Malaysia, 2008, pp. 1–12.

[146] B. Braden, D. Clark, J. Crowcroft, B. Davie, S. Deering, D. Estrin, S. Floyd, V. Jacobson, G. Minshall, C. Partridge, L. Peterson, K. Ramakrishnan, S. Shenker, J. Wroclawski, and L. Zhang, "Recommendations on Queue Management and Congestion Avoidance in the Internet", RFC 2309, Internet Engineering Task Force, April 1998.

[147] S. Floyd and V. Jacobson, "Random Early Detection Gateways for Congestion Avoidance", *IEEE/ACM Transactions on Networking*, vol. 1, no. 2, pp. 397–413, April 1993.

[148] P. Adriano S. Leonardo and Jr M. Wagner, "Reactivity-based Scheduling Approaches for Internet Services", in *Proceedings of the Fourth Latin American Web Congress*. 2006, IEEE Computer Society.