A Review of End-to-end Congestion Control Algorithms for High-speed Wired Network

Vandana Kushwaha, Ratneshwer
Department of Computer Science, Banaras Hindu University, India

Abstract

This paper presents a review of end-to-end Congestion control approaches in high-speed wired network. The purpose of this study is to review the end-to-end Congestion control research for high-speed wired network and characterize the different approaches to Congestion control design, by considering their advantages and limitations.

1. Introduction

The Internet provides us a global infrastructure for information exchange that has revolutionized the social, economic, and political aspects of our lives. One of the most crucial building blocks of the Internet is a mechanism for resource sharing and controlling congestion on the Internet. Congestion can be defined as a network state in which the total demand for resources, e.g. bandwidth, among the competing users, exceeds the available capacity leading to packet or information loss and results in packet retransmissions[1].

The purpose of this study is to review the end-to-end Congestion control approaches for high-speed wired network. An attempt has been made to analyze major end-to-end congestion control approaches by considering their relative merits and demerits. In this way this study will trace a better picture of major issues, challenges and possible solutions of network congestion problem using end-to-end based approaches.

The paper is organized as follows: In Section 2, a brief review of previous reviews, conducted on end-to-end based Internet congestion control, has been mentioned. The phenomenon of Congestion control is briefly defined in Section 3. Section 4 presents the main observations found during the review. Finally Section 5 concludes the paper.

2. Related works

In Literature, the problem of Congestion has been studied widely in the context of high speed network, wireless network, satellite network, ad-hoc network etc. Substantial survey works have been reported regarding Congestion control. Some significant survey works related to the topic are as follows. Yang et al [2] have first proposed a taxonomy of Congestion control approaches in packet switched network, based on control theory. This taxonomy contributes a framework which helps in comparative study of the existing approaches and set a path toward the development of new congestion control approaches. Reddy et al [3] (2008) have first made an effort to comparatively analyze the high speed end-to-end based congestion control protocols based on various performance metrics like Throughput, Fairness, Stability, Performance, Bandwidth Utilization and Responsiveness and further they studied the limitations of these protocols meant for the High Speed Networks. Ho et al [4] (2008) surveyed state-of-the-art of fast retransmit and fast recovery mechanisms of end-to-end based congestion control algorithms to address the lost packet problem, and presented a description of some useful algorithms, design issues, advantages, and disadvantages. They also presented taxonomy for fast retransmit and fast recovery mechanisms of some existing transport protocols which provides a unified terminology and a framework for the comparison and evaluation of this class of protocols. Chandra et al [5] (2010) have presented a brief survey of major congestion control approaches, categorization characteristics, elaborates the TCP-friendliness concept and then a state-of-the-art for the congestion control mechanisms designed for network. They pointed out the major pros and cons of the various congestion control approaches and evaluated their characteristics. Afanasyev et al [6] (2010) have done a comprehensive survey of various end-to-end based congestion control algorithms for different network environments. Their survey reflects that over the last 20 years many end-to-end techniques have been developed that addressed several problems with different levels of reliability and precision. They described each congestion control alternative, its strengths and its weaknesses further they highlighted the fact that the research focus has changed with the development of the Internet, from the basic problem of eliminating the congestion collapse phenomenon to problems of using available network resources effectively in different types of environments (wired, wireless, high-speed, long-delay, etc.).

3. Congestion Control in High speed networks

One of the most crucial building blocks of the Internet is a mechanism for resource sharing and controlling congestion on the Internet. Congestion can be defined as a network state in which the total demand for resources, e.g. bandwidth, among the competing users, exceeds the available capacity leading to packet or information loss and results in packet retransmissions[1]. At the time of congestion in a computer network there will be a simultaneous increase in queuing delay, packet loss and number of packet re-transmissions. In other words Congestion refers to a loss of network performance when a network is heavily loaded. Keshav [7] has defined it as “A network is said to be congested from the perspective of a user if the service quality noticed by the user decreases because of an increase in network load.”

Congestion control refers to techniques and mechanisms that can either prevent congestion, before it happen, or remove congestion, after it has happened. Yang et al [2] have divided congestion control mechanisms into two broad categories: congestion avoidance (open-loop congestion control) and congestion recovery (closed-loop congestion control). The strategy of congestion avoidance is preventive in nature; it is aimed to keep the operation of a network at or near the point of maximum power, so that congestion will never occur. Whereas, the goal of congestion recovery is to restore the operation of a network to its normal state after congestion has occurred. Without a congestion recovery scheme, a network may crash entirely whenever congestion occurs. Therefore, even if a network adopts a strategy of congestion avoidance, congestion recovery schemes would still be required to retain throughput in the case of abrupt changes in a network that may cause congestion. Congestion control is a (typically distributed) algorithm to share network resources among competing traffic sources.

A network with a large bandwidth-delay product is commonly known as a high-speed network or long fat network (shortened to LFN and often pronounced "elephant"). As defined in RFC 1072 [8], a network is considered an LFN if its bandwidth-delay product is significantly larger than 105 bits (12500 bytes).In data communications, bandwidth-delay product refers to the product of a data link's capacity (in bits per second) and its end-to-end delay (in seconds). The result, an amount of data measured in bits (or bytes), is equivalent to the maximum amount of data on the network circuit at any given time, i.e. data that has been transmitted but not yet received.

4. Observations

We have summarized the observations, during literature review, in the form of tables. The observations are summarized in Table I for end-to-end based congestion control approaches for high-speed wired network.

In earlier phase of internet, Nagle [9] (1984) considered ‘congestion control’ a recognized problem in complex networks. He observed a severe problem of ‘congestion collapse’ also known as Internet meltdown, which results in a serious downgrade of network throughput. Jacobson [10] (1988) has proposed the earliest solution of congestion collapse termed as TCP based congestion avoidance method. Yang et al [2] (1995) have given a prime concern to congestion control in network research and development due to increasing network bandwidth and diverse network applications and have considered network congestion an actual hazard to the development of internet and communication applications. Afanasyev et al [6] (2010) stated that the research focus has changed with the development of the Internet, from the basic problem of eliminating the congestion collapse phenomenon to problems of using available network resources effectively in different types of environments (wired, wireless, high-speed, long-delay, etc.). The Evolution of high speed network raised different issues while designing congestion control mechanisms for large bandwidth delay product network. Congestion control was considered as a serious issue for high speed network and many research issues are identified like S. Floyd [11] (2003), T. Kelly [12] (2003), Jin et al [13] (2004), Xu et al [14] (2004), Tan et al [15] (2006).

End-to-end based congestion control methods are reactive in nature i.e. Source host reacts after getting congestion signals from the networks, by reducing its transmission speed. TCP uses implicit congestion signals: packet loss or delay or the combination of both. Based on the types of congestion signals, source based approaches are further categorized as: **Loss based** approach, **Delay based** approach and **Hybrid** approach.

The earliest **loss based** end to end solution for congestion control in high speed network, ‘High Speed- TCP’ was proposed by S. Floyd [11] (2003). He commented that congestion control mechanisms of the Standard TCP limit the congestion windows that can be achieved by TCP in actual environments which results in poor utilization of network bandwidth.

TABLE I. LIST OF END-TO-END CONGESTION CONTROL APPROACHES FOR HIGH-SPEED WIRED NETWORK

S.No.	Year	Publication Title	*Method for Congestion Control*		*Performance metrics*
			Approach	*Features*	
1.	***2003***	*HighSpeed TCP for Large Congestion Windows(RFC-3649)*	*loss based*	*AIMD with factors as functions of the congestion window size, Limited Slow-Start*	*Throughput, TCP friendliness*
2.	***2003***	*Scalable TCP: improving performance in highspeed wide area networks –T. Kelly*	*loss based*	*MIMD*	
3.	***2003***	*FAST TCP: from theory to experiments - Cheng Jin David X. Wei Steven H. Low*	*delay based*	*Equation-Based window adjustment*	*throughput, fairness, responsiveness, stability*
4.	***2004***	*H-TCP: TCP for high-speed and long-distance networks - D. Leith, R. Shorten*	*loss based*	*AIMD with new adaptive parameters*	*Fairness, friendliness, responsiveness, throughput*
5.	***2004***	*Binary increase congestion control (BIC) for fast long-distance networks -Lisong Xu, Khaled Harfoush, and Injong Rhee*	*loss based*	*BIMD, Limited Slow-Start*	*TCP friendliness, bandwidth scalability, RTT unfairness*
6.	***2005***	*TCP-Africa: An adaptive and fair rapid increase rule for scalable TCP -Ryan King, Richard Baraniuk, Rudolf Riedi*	*loss+delay based*	*Delay sensitive two-mode congestion avoidance rule.*	*utilization, efficiency, fairness, RTT unfairness*
7.	***2005***	*TCP-A Reno: Improving efficiency-friendliness tradeoffs of TCP congestion control algorithm -Hideyuki Shimonishi and Tutomu Murase*	*loss+delay based with b/w estimation*	*Dynamically adjusts the TCP response function based on congestion level estimation via RTT measurement.*	*TCP friendliness, efficiency*
8.	***2005***	*TCPW-A :TCP with sender-side intelligence to handle dynamic, large, leaky pipes (TCP Westwood with agile probing)*	*loss based with b/w estimation*	*Use eligible rate estimation (ERE) methods to intelligently set the congestion window (cwnd) and slow-start threshold (ssthresh) after a packet loss.(PNCD)*	*Throughput, fairness, friendliness, convergence*
9.	***2006***	*Compound TCP: A scalable and TCP-friendly congestion control for high-speed networks -Kun Tan Jingmin Song, Qian Zhang, Murari Sridharan*	*loss+delay based*	*Add a scalable delay-based component into the standard TCP Reno congestion avoidance algorithm.*	*bandwidth scalability , TCP-fairness.*
10.	***2006***	*L(layered) TCP: improving the performance of TCP in highspeed networks -Sumitha Bhandarkar, Saurabh Jain and A. L. Narasimha Reddy*	*loss based*	*uses the concept of virtual layers to increase the congestion window when congestion is not observed over an extended period of time.*	*convergence , link utilizing*
11.	***2007***	*TCP-fusion: A hybrid congestion control algorithm for high-speed networks - Kazumi KANEKO, Tomoki FUJIKAWA, Zhou SU and Jiro KATTO*	*loss+delay based with b/w estimation*	*TCP-Fusion exploits three useful characteristics of TCP-Reno, TCP-Vegas and TCP-Westwood in its congestion avoidance strategy*	*Efficiency, fairness, friendliness*
12.	***2007***	*YeAH TCP: Yet Another Highspeed TCP - Andrea Baiocchi, Angelo P. Castellani and Francesco Vacirca*	*loss+delay based*	*Uses two modes fast and slow. In Fast mode: increments the congestion window according to an Aggressive rule (STCP). In "Slow" mode, it acts as Reno TCP.*	*utilization, fairness, friendliness*
13.	***2008***	*TCP LogWestwood+ : Logarithmic window increase for TCP Westwood+ for improvement in high speed, long distance networks -Dzmitry Kliazovich a , Fabrizio Granelli,*, Daniele Miorandi*	*loss based with b/w estimation*	*Based on a logarithmic increase function, targeting adaptation to the high-speed wireless environment.*	*Efficiency, fairness, friendliness*
14.	***2008***	*CUBIC: A new TCP-friendly high-speed TCP variant -Sangtae Ha, Injong Rhee, Lisong Xu*	*loss based*	*Uses a cubic window growth function in order to improve the scalability*	*Intra-protocol fairness, RTT-fairness, TCP-friendliness.*
15.	***2009***	*Sync-TCP: A New Approach to High Speed Congestion Control- Xiuchao Wu, Mun Choon Chan, A. L. Ananda and Chetan Ganjiha*	*delay based*	*exploits synchronization, adaptive Queue-delay-based cwnd Decrease Rule, RTT-Independent cwnd Increase Rule*	*Throughput, TCP-friendliness.*
16.	***2010***	*TCP Libra: Derivation, analysis, and comparison with other RTT-fair TCPs - Gustavo Marfia Claudio E. Palazzi , Giovanni Pau , Mario Gerla, Marco Roccetti*	*loss based*	*multiplying the congestion window by the square of the RTT during the additive increase portion of the TCP algorithm.*	*RTT-fairness TCP-friendliness. Bandwidth scalability.*
17.	***2011***	*HCC TCP: Hybrid congestion control for high-speed networks -Wenjun Xu , Zude Zhou, D.T. Phamb,C.Ji, M. Yang , Quan Liu*	*loss+delay based (switching)*	*The two approaches (delay+loss) in the algorithm are dynamically transferred into each other according to the network status.*	*throughput, fairness, TCP-friendliness, robustness*

Therefore a new mechanism is required which effectively utilize a wide range of available bandwidths, and competes with Standard TCP more fairly in congested environments. T. Kelly [12] (2003) considered 'better utilization of network bandwidth' and 'fairness with Standard TCP' as two major challenges while designing TCP congestion control for high-speed network and proposed *'Scalable TCP'*. Leigh et al [16] (2004) raised the issue of backward compatibility of high speed TCP with Standard TCP while deployment of high speed TCP. He proposed '*H-TCP'* with focus on fairness, friendliness, responsiveness and throughput. Xu et al [14] (2004) commented that previous High speed TCP approaches only solved the bandwidth scalability and TCP friendliness problems. He pointed out another important issue termed as RTT (round trip time) unfairness for high speed congestion control and proposed *'BIC TCP'* as its solution. R. Wang [17] (2005) considered dynamic bandwidth utilization as another challenge for high speed TCP and proposed a sender side enhancement method '*TCPW-A* TCP' by using the concept of agile probing. Ha et al [18] (2008) proposed 'CUBIC TCP' by using a cubic window growth function and focused on improving the 'TCP-friendliness' and 'RTT-fairness' characteristic by making window growth rate RTT independent. Kliazovich et al [19] (2008) uses logarithmic increase function and proposed 'LogWestwood+ TCP' having low sensitivity with respect to RTT value, while maintaining high network utilization in a wide range of network settings. Marfia et al [20] (2010) considered RTT-fairness a severe problem because it adversely affect the long-RTT flow performance and proposed 'TCP Libra' which ensure fairness and scalability regardless of the RTT, while remaining friendly towards legacy TCP.

Due to continuous advancement in computing, communication and storage technology, Jin et al [13] (2003) considered poor bandwidth scalability of standard TCP, as a key challenge for TCP congestion control in high-speed network. He proposed a first **delay based** end to end method 'FAST TCP' for congestion control in high speed network and considered throughput, fairness, stability and responsiveness as key issues for High-speed TCP. Wo et al [21] (2009) have proposed 'Sync-TCP' a delay based solution for congestion control in high speed environment and proposed a concept of flow level coordination for handling congestion. 'Sync-TCP' guarantees a better tradeoff between throughput and friendliness which is a serious issue while deploying new high speed TCP.

King et al [22] (2005) have proposed a first **hybrid** method 'TCP- Africa' for high speed congestion control and raised a major issue of maintaining a careful balance between the increased aggressiveness and the fairness and safety while developing TCP for high bandwidth delay product network. Shimonishi et al [23] (2005) considered TCP-Reno efficiency – friendliness tradeoff as a most important issue in high speed TCP design because TCP-Reno unfriendliness is the major hurdle in the way of high speed TCP deployment in current Internet. They proposed 'TCP-AR' (Adaptive Reno) to ensure friendliness to TCP-Reno, as well as efficiency in high speed networks. Tan et al [15] (2006) emphasized that pure delay-based approaches may not work well if they compete with loss-based flows and proposed a hybrid approach 'Compound TCP' which provides very good bandwidth scalability and at the same time achieves good TCP-fairness. Kaneko et al [24] (2007) proposed 'TCP fusion' which exploits three useful characteristics of TCP-Reno, TCP-Vegas and TCP-Westwood in its congestion avoidance strategy and can obtain the highest throughput among existing TCP variants when there is unused residual capacity while its friendliness to the TCP-Reno is sufficiently satisfied, otherwise, it shares the same bandwidth to coexisting flows. Baiocchi et al[25] (2007) stated while designing high speed TCP, we should consider not only the full link utilization characteristic but preserve also the primary characteristic of congestion avoidance as it causes network instability and non-negligible degradations. They raised new issues like 'induced network stress' and 'robustness to random losses' for TCP in high speed environment. They proposed 'YeAH TCP' a a heuristic attempt to strike a balance among different opposite requirements. Xu et al [26] (2011) commented on existing high speed TCP, although these protocols perform successfully to improve the bandwidth utilization, they still have the weakness on the performance such as RTT-fairness, TCP-friendliness, etc. They stated that none of the existing approaches is overwhelmingly better than the other protocols and has the convincing evidence that could be generally deployed; the development of new high-speed TCP variants is still needed. They proposed 'HCC TCP' which satisfies the requirements for an ideal TCP variant in high-speed networks, and achieve efficient performance on throughput, fairness, TCP-friendliness, robustness, etc.

5. Conclusion

This work explores the literature review of end-to-end based congestion control algorithms in the context of high speed wired networks. We understand that the identified issues and challenges regarding the end-to-end based congestion control algorithms may help in future research in this area. This initial proposition of such a review may be purposefully used by the academician/researchers and the corresponding useful feedback may be analyzed.

References

[1] D. Papadimitriou, "RFC6077 - Open Research Issues in Internet Congestion Control", RFC, Internet Engineering Task Force, February 2011.

[2] C. Yang and A. Reddy, "A Taxonomy for Congestion Control Algorithms in Packet Switching Networks," *IEEE Network Magazine*, vol. 9, no. 4, pp. 34–45,1995.

[3] K. Satyanarayan Reddy and Lokanatha C. Reddy, "A survey on congestion control mechanisms in high speed networks," IJCSNS International Journal of Computer Science and Network Security, vol. 8, no. 1, pp. 187 – 195, 2008.

[4] CY Ho, YC Chen, YC Chan and CY Ho, "Fast Retransmit and Fast Recovery Schemes of Transport Protocols : A survey and taxonomy," *Journal of Computer Networks 52, pp. 1308–1327*, Feb 2008.

[5] E. Chandra and B. Subramani, "A Survey on Congestion Control," *Global Journal of Computer Science and Technology* Vol. 9 Issue 5,Verion 2.0, January 2010.

[6] A. Afanasyev, N. Tilley, P. Reiher, and L. Kleinrock, "Host-to-host congestion control for TCP," *IEEE Communications Surveys & Tutorials*, vol. 12, no. 3, 2010.

[7] S. Keshav, "What is congestion and what is congestion control", Presentation at *IRTF ICCRG Workshop*, *PFLDnet* 2007, Los Angeles (California), USA, February 2007.

[8] R. Braden and V. Jacobson, "RFC1072 - TCP extensions forlongdelay paths", *RFC*, Internet Engineering Task Force, Oct. 1988.

[9] J. Nagle, "RFC896—Congestion control in IP/TCP internetworks," *RFC*, 1984.

[10] V. Jacobson, "Congestion avoidance and control," *ACM SIGCOMM*, pp. 314–329, 1988.

[11] S. Floyd, "RFC3649 - HighSpeed TCP for Large Congestion Windows," *RFC*, 2003.

[12] T. Kelly, "Scalable TCP: improving performance in high speed wide area networks," *Computer Communications Review*, vol. 32, no. 2, April 2003.

[13] D. X. Wei, C. Jin, S. H. Low, and S. Hegde, "FAST TCP: motivation, architecture, algorithms, performance," *IEEE/ACM Trans. Netw.*,vol. 14, no. 6, pp. 1246–1259, 2006.

[14] L. Xu, K. Harfoush, and I. Rhee, "Binary increase congestion control for fast, long distance networks," in *Proc. IEEE INFOCOM*, vol. 4, pp. 2514–2524, March 2004.

[15] K. Tan and J. Song, "Compound TCP: A Scalable and TCP-friendly Congestion Control for High-speed Networks," *In Proc. PFLDNet*, 2006.

[16] D. Leith and R. Shorten, "H-TCP: TCP for high-speed and long distance networks," in *Proceedings of PFLDnet*, 2004.

[17] R. Wang, K. Yamada, M. Sanadidi, and M. Gerla, "TCP with sender side intelligence to handle dynamic, large, leaky pipes," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 235–248, February 2005.

[18] I. Rhee and L. Xu, "CUBIC: a new TCP-friendly high-speed TCP variant," *SIGOPS Operating Systems Review*, vol. 42, no. 5, pp. 64– 74, July 2008.

[19] D. Kliazovich, F. Granelli, and D. Miorandi, "Logarithmic window increase for TCP Westwood+ for improvement in high speed, long distance networks," *Computer Networks*, vol. 52, no. 12, pp. 2395– 2410, August 2008.

[20] G. Marfia, C. Palazzi, G. Pau, M. Gerla, M. Sanadidi, and M. Roccetti, "TCP Libra: Exploring RTT-Fairness for TCP," *UCLA Computer Science Department, Tech. Rep. UCLA-CSD TR-050037*, 2005.

[21] W. Xiuchao, C. MunChoon, A. L. Ananda, and C. Ganjihal, "Sync-TCP: A new approach to high speed congestion control, " *ICNP*, pp. 181-192, October 2009.

[22] R. King, R. Baraniuk, and R. Riedi, "TCP-Africa: an adaptive and fair rapid increase rule for scalable TCP," in *Proc. IEEE INFOCOM*, vol. 3, March 2005, pp. 1838–1848.

[23] H. Shimonishi and T. Murase, "Improving efficiency-friendliness tradeoffs of TCP congestion control algorithm," in *Proc. IEEE GLOBECOM*, 2005.

[24] K. Kaneko, T. Fujikawa, Z. Su, and J. Katto, "TCP-Fusion: a hybrid congestion control algorithm for high-speed networks," in *Proc. PFLDnet*, ISI, Marina Del Rey (Los Angeles), California, February 2007.

[25] A. Baiocchi, A. P. Castellani, and F. Vacirca, "YeAH-TCP: yet another highspeed TCP," in *Proc. PFLDnet*, ISI, Marina Del Rey (Los Angeles), California, February 2007.

[26] W. Xu, Z. Zhou, D. Pham, C. Ji, M. Yang, Q. Liu, "Hybrid Congestion Control for High-Speed Networks," *Journal of Network and Computer Applications*, vol.34, no.4, pp.1416-1428, Jul. 2011.