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Description	

A Taxonomy of Congestion Control Techniques for TCP in Wired and Wireless Networks

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***Abstract*—TCP is developed to provide a reliable end-to-end data delivery over untrustworthy networks. In general, the performance of a specific TCP variant is defined by the congestion control technique. Meanwhile, a typical congestion in a network can cause long queuing delay, high packet loss, high frequent blocked of new connections, etc. Many congestion control techniques have been developed, but their categorization, association, strength, and limitation are not clearly specified. As a result, the developed congestion control technique may not be viable for a particular network environment. In this paper, we propose a novel taxonomy to classify 30 different congestion control techniques. Three main criteria of this taxonomy are (1) the device entity that is responsible for ensuring the congestion control technique; (2) the targeted domain of the congestion control technique; and (3) the congestion metric that is used to indicate the congestion status.**

Keywords—TCP; congestion control technique; taxonomy; wired and wireless networks

I. INTRODUCTION

Transmission Control Protocol (TCP) is the most widely used end-to-end transport protocol that delivers data reliably across the untrustworthy Internet today. The increased popularity of Internet use in business, entertainment, banking, security surveillance, and so on, can make the network congestion problem more prominent. As a result, many TCP congestion control techniques have been researched extensively. Congestion occurs whenever the demands exceed the maximum network capacity and the packets are lost due to the buffer overflows. During congestion, the network throughput may become zero and the end-to-end path delay may become extremely high [1]. In other words, congestion in a network can cause long queuing delay, high packet loss, high frequent blocked of new connections, etc.

TCP was first described by Cerf and Kahn [2]. It is fixed in the transport layer protocol provides a trustworthy way to send and receive variable length segments of information enclosed in the end-to-end communication networks. TCP consists of congestion control techniques to detect network congestion and to limit the packet transmission rate to mitigate the congestion. The end-to-end congestion control technique was first introduced in the TCP protocol in 1988 by Van Jacobson [3]. The four core TCP congestion control algorithms are: slow start, congestion avoidance, fast retransmit, and fast recovery for forming the basic framework of the TCP flow control and congestion control [2], [4]. These four TCP congestion control algorithms are executed at the source end and accomplish the congestion control through adjusting the parameters such as congestion window (CWND), round trip time (RTT), retransmission timeout (RTO), slow start threshold (ssthresh), etc.

The rapid growth of the Internet has caused new challenges and issues to emerge with the practical applications. Some advances in TCP congestion control technique do solve some particular issues successfully. Unlikely, they are not a universal technique to be deployable for other types of network. Moreover, these TCP congestion control techniques are not properly specified in terms of categorization, association, strength, and limitation. Although several surveys related to congestion control been constructed, they are comparing only a few types of congestion control techniques and focus on certain types congestion environment. In this paper, we present a comprehensive survey on thirty types of TCP congestion control techniques. In addition, tables and figures are used to emphasize the types of congestion control mechanisms, features, relationship, modification, etc. that makes them easy to understand.

The main contribution of this research is to provide a taxonomy of congestion control techniques with the novel viewpoint of classifying the congestion problem, i.e., single bottleneck problem and shared bottleneck problem. The taxonomy is well-arranged by extensively surveying thirty different congestion control techniques over the last twenty years. This taxonomy enables us to understand the TCP's basic and advanced characteristics, location of control, modification aspect, targeted domain, complexity level, features, and detection entities.

The rest of this paper is organized as follows. Section II is devoted to the congestion problem in a network and Section III discusses the TCP congestion control technique. Taxonomy of TCP congestion control technique is deeply discussed in the Section IV. We then make some discussion in Section V and conclude the paper in Section VI.

II. CONGESTION PROBLEM IN A NETWORK

In a general network, congestion occurs when a link is carrying data packets more than the bandwidth capacity of the network. In this paper, two types of congestion problems that

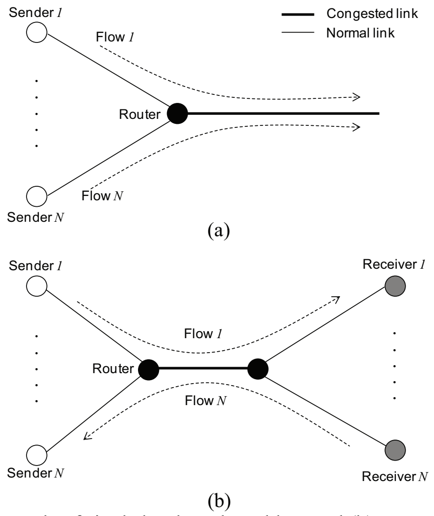

Fig. 1. (a) Example of single bottleneck problem and (b) Example of shared bottleneck problem.

may occur in the network are defined and illustrated in Fig.1. In a single bottleneck problem, multiple senders are sending their data packets to one destination via a router, which has a limited output bandwidth. This type of congestion can be called as a dumbbell-shaped congestion problem. We realize that the congestion is mainly caused by the one-way flow of the multiple senders. In a shared bottleneck problem, multiple senders are sending their data packets to multiple receivers through a chain of router. In the chain of router, their bandwidth cannot support the demands of the data transmission load. We indicate this type of congestion as a butterfly-shaped congestion problem. In the shared bottleneck problem, multiple receivers are able to communicate with multiple senders. This may lead to the two-way flow happened simultaneously in the connecting link.

In the single bottleneck problem, congestion will result in a high packet drop rate. On the other hand, the congestion will produce low network throughput for the shared bottleneck problem when the traffic load is stable at an instant of time. When the traffic load is increasing, it will create high packet drop rate. These two congestion problems share the common effect, i.e., the buffer overflow. Therefore, most of the congestion control techniques are focusing on solving this buffer overflow.

III. TCP CONGESTION CONTROL TECHNIQUE

The TCP congestion control technique is designed to have the following algorithms: slow start, congestion avoidance, fast retransmit, and fast recovery. When a TCP connection is established between a sender and a receiver, the connection first enters a slow start phase. The CWND is initialized to one segment and this value will increase exponentially each time the sender successfully receives an acknowledgement (ACK) message from the receiver. When the sender receives three duplicate ACK messages from the receiver or the set time limit expires, the sender will assume a network is congested and immediately starts the congestion avoidance algorithm. Subsequently, the ssthresh is set to half of the current CWND size and the CWND is increased linearly with the RTT [2], [5]. Since the CWND growth rate is slowed down, the transmission rate from the sender to the receiver will be reduced to minimize the congestion in the network. When a timeout occurs, the CWND size is reset to one. At the congestion avoidance stage, if the CWND is less than or equal to ssthresh, TCP will re-enter the slow start phase; if CWND is larger than the ssthresh, then TCP will execute the congestion avoidance algorithm.

In the fast retransmit algorithm, when the sender has determined the packet loss in the network, it directly retransmits the lost packets without waiting until the RTO expires. At this stage, the ssthresh is set to half the current CWND size and CWND is reduced to half of its original value [3], [6]. The time of RTO is decided by the estimation algorithm and is much longer than the maximum achievable RTT. By the fast retransmit algorithm, the transmission efficiency is improved through reducing the waiting time from RTO. The fast recovery algorithm is implemented along with the fast retransmit algorithm. The concept behind this algorithm is when fast retransmit detects three duplicate ACK messages; it starts the recovery process from congestion avoidance region and uses received ACK messages to control the pace the sending of data packets. When a non-duplicated ACK message is received, it exits the fast recovery phase, optimizing the fast retransmit stage. These four algorithms are the fundamental of the TCP congestion control technique and are widely used as the standard technique for TCP.

IV. TAXONOMY OF TCP CONGESTION CONTROL TECHNIQUE

A. Device Entity that is Responsible for Ensuring the Congestion Control Technique

In this section, we categorize the association of TCP variants with device entity, which is responsible to control the congestion control technique. There are four types of device entities: sender, receiver, sender and receiver, and sender or receiver. Sender entity is the most widely deployed TCP congestion control technique. It is called the sender-centric protocol (SCP), which is defined as a sender performing the important tasks such as congestion control, flow control, and reliable data transfer whereas a receiver transmits the feedback in the form of acknowledgements. The sender transmits a data packet to the receiver, and the receiver returns the feedback in acknowledgment. This data transfer is also referred as DATA-ACK message exchanges [7].

The receiver entity is the second most deployed TCP that was first introduced in 1997 [8-9]. In the receiver entity, the receiver is fully controlled the functionalities, i.e., congestion control, flow control and reliable data transfer. We called it as the receiver-centric protocol (RCP). RCP uses the same window based mechanism similar to the sender-centric protocol, but RCP uses the REQUEST-DATA exchange for data transfer. A receiver sends an explicit request (REQUEST) packet to a sender to request the sending data packets, and then the sender transmits data packets according to the transmission rate requested by the receiver. In RCP, the

TABLE I. COMPARISON OF TCP VARIANTS WITH DEVICE ENTITY IN WIRED AND WIRELESS NETWORKS

TCP Variant	Proposed People Name	Year of Proposal	Location of Control	Improvement Aspect	Nomenclature
Tahoe [2]	Van Jacobson	1988	Sender	LL	
Reno [15]	Van Jacobson	1990	Sender	LL	
NewReno [16]	Sally Floyd, et al.	1999	Sender	LL	
SACK [17]	Matt Mathis, et al.	1996	Sender	LL	Selective ACKnowledgment
Vegas [18]	Lawrence Brakmo, et al.	1995	Sender	LL	
Vegas A [19]	Srijith Krishnan Nair, et al	2005	Sender	LL	Vegas with Adaptation
Veno [20]	Cheng Peng Fu, et al.	2002	Sender	LL	VEgas and reNO
Westwood [21]	Saverio Mascolo, et al.	2001	Sender	LL	
TCPW CRB [22]	Ren Wang, et al.	2002	Sender	LL	Westwood with Combined Rate and Bandwidth estimation
TCPW BR [23]	Guang Yang, et al.	2003	Sender	LL	Westwood with Bulk Repeat
Casablanca [24]	Saâd Biaz, et al.	2005	Sender	LL	
STCP [25]	Tom Kelly	2003	Sender	BD	Scalable TCP
HS-TCP [26]	Sally Floyd	2003	Sender	BD	High-Speed TCP
BIC [27]	Lisong Xu, et al	2004	Sender	BD	Binary Increase Congestion control
CUBIC [28]	Injong Rhee, et al	2008	Sender	BD	
Hybla [29]	Carlo Caini, et al.	2004	Sender	BD	
FAST TCP [30]	Cheng Jin, et al.	2003	Sender	BD	
NewVegas [31]	Joel Sing, et al.	2005	Sender	BD	
Libra [32]	Gustavo Marfia, et al.	2005	Sender	BD	
Illinois [33]	Shao Liu, et al.	2006	Sender	BD	
Africa [34]	Ryan King, et al.	2005	Sender	BD	Adaptive and Fair Rapid Increase Congestion Avoidance
Fusion [35]	Kazumi Kaneko, et al.	2007	Sender	BD	
CTCP [36]	Kun Tan, et al.	2005	Sender	BD	Compound TCP
Nice [37]	Arun Venkatarammani, et al.	2002	Sender	LP	
LP [38]	Aleksandar Kuzmanovic, et al.	2002	Sender	LP	Low Priority
DSACK [39]	Sally Floyd, et al.	2000	Receiver	LL	Duplicate SACK
TD-FR [40]	Vern Paxson	1997	Receiver	PR	Time Delayed Fast Recovery
TCP-Real [41]	Vassilis Tsaoussidis, et al.	2002	Receiver	LL	
MCP [42]	Liang Zhang, et al.	2005	Sender or Receiver	LL	Mobile-host Control Protocol
TFRC [43]	Mark Handley, et al.	2003	Sender and Receiver	PR	TCP Friendly Rate Control
DOOR [44]	Feng Wang, et al.	2002	Sender and Receiver	PR	Detection of Out-of-Order and Response

Legend:
Lossy links (LL); high bandwidth-delay product networks (BD); low priority traffic (LP); packet reordering (PR)

receiver uses the incoming data packet to trigger the requests for new data. According to [10-12], the TCP performance can be significantly improved by increasing the functionalities of the receiver as the location of control.

When a TCP variant can operate the functionalities of congestion control, flow control and reliable data transfer at both sender and receiver sides, we called it as hybrid-centric protocol (HCP). For example, a receiver performs the function of flow control and participates the congestion control process by computing the CWND size. Then, a sender uses the receiver's information to adjust the CWND accordingly. Through this way, TCP can reduce the waiting time of the sender to alleviate the impact of timeout [13]. Mobile-host-centric transport protocol (MCP) is one of the sender or receiver entities. MCP utilizes either SCP or RCP that is depending on a mobile station is either a sender or a receiver [14]. In summary, Table I depicts a comparison of TCP variants with device entity in wired and wireless networks. The improvement aspect in Table I consists of lossy link (LL) that defines as a packet loss rate in a network link which greater than a given threshold; high bandwidth product network (BD) is the network that has a bandwidth delay product larger than the TCP receive window; low priority traffic (LP) and packet reordering (PR) is the network that contains the low priority flow packet and reordered packet with respectively. Based on Table I, we illustrate the association of TCP variants with the device entity and the targeted domain as shown in Fig. 2. Most of the existing TCP variants belong to the SCP, only a few from the rest of the device entity group.

B. Targeted Domain of the Congestion Control Technique

The targeted domains of the TCP variants are classified into four categories; congestion collapse, wireless environment, high speed/long delay condition, and low priority data transfer condition. The congestion collapse domain occurs at the throttle points in a network, in which the incoming data packets to a node are exceeding the outgoing data packet. In this condition, the link could be busy transmitting data packets that will only be dropped its bandwidth when the downstream of data flows is available. This leads to a huge waste of scarce bandwidth. While in wireless environment, the packet loss is not only due to buffer

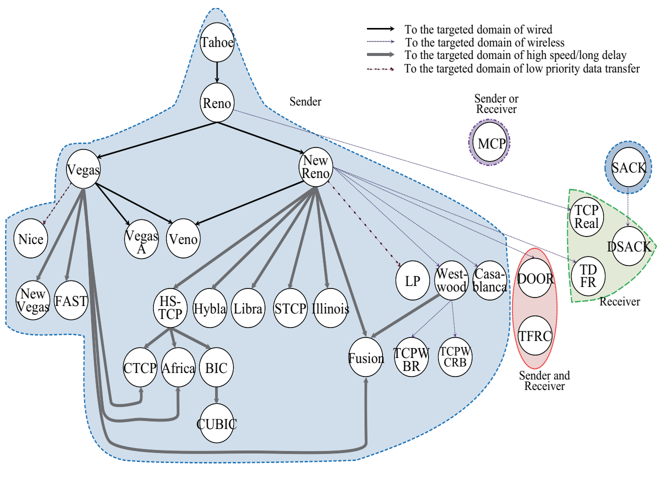

Fig. 2. Association of TCP variants with the device entity and the targeted network.

TABLE II. CHARACTERISTICS AND FEATURES OF TCP VARIANTS WITH TARGETED DOMAIN IN WIRED AND WIRELESS NETWORKS

Characteristics	**Tahoe [2]**	**Reno [15]**	**NewReno [16]**	**SACK [17]**	**Vegas [18]**	**Vegas A [19]**	**Veno [20]**	**Westwood [21]**	**TCPW CRB [22]**	**TCPW BR [23]**	**Casablanca [24]**	**STCP [25]**	**HS-TCP [26]**	**BIC [27]**	**CUBIC [28]**	**Hybla [29]**	**FAST TCP [30]**	**New Vegas [31]**	**Libra [32]**	**Illinois [33]**	**Africa [34]**	**Fusion [35]**	**CTCP [36]**	**Nice [37]**	**LP [38]**	**DSACK [39]**	**TD-FR [40]**	**TCP-Real [41]**	**MCP [42]**	**TFRC [43]**	**DOOR [44]**
Targeted Domain																															
Congestion collapse	o	o	o	o	o	o	o																								
Wireless environment								o	o	o	o															o	o	o	o	o	o
High-speed/long delay												o	o	o	o	o	o	o	o	o	o	o	o								
Low priority data transfer																								o	o						
Complexity Degree																															
Low	o	o	o	o							o			o			o	o	o		o	o	o								o
Medium					o	o	o					o	o		o	o				o				o	o	o	o	o	o	o	
High								o	o	o																					
Congestion Problem																															
Single bottleneck								o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Shared bottleneck	o	o	o	o	o	o	o					o	o	o	o	o	o	o	o	o	o	o	o	o	o						
Features																															
Slow start	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Congestion avoidance	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Fast retransmission	o	o	o	o			o				o			o	o						o				o	o	o	o	o	o	o
Fast recovery		o	o	o			o	o	o	o	o	o		o	o						o				o	o	o	o	o	o	o
Multiple losses			o	o						o	o			o	o											o					
Estimation technique							o	o	o							o			o		o	o									
Packet pacing technique																o		o													
Limited slow start													o	o	o																

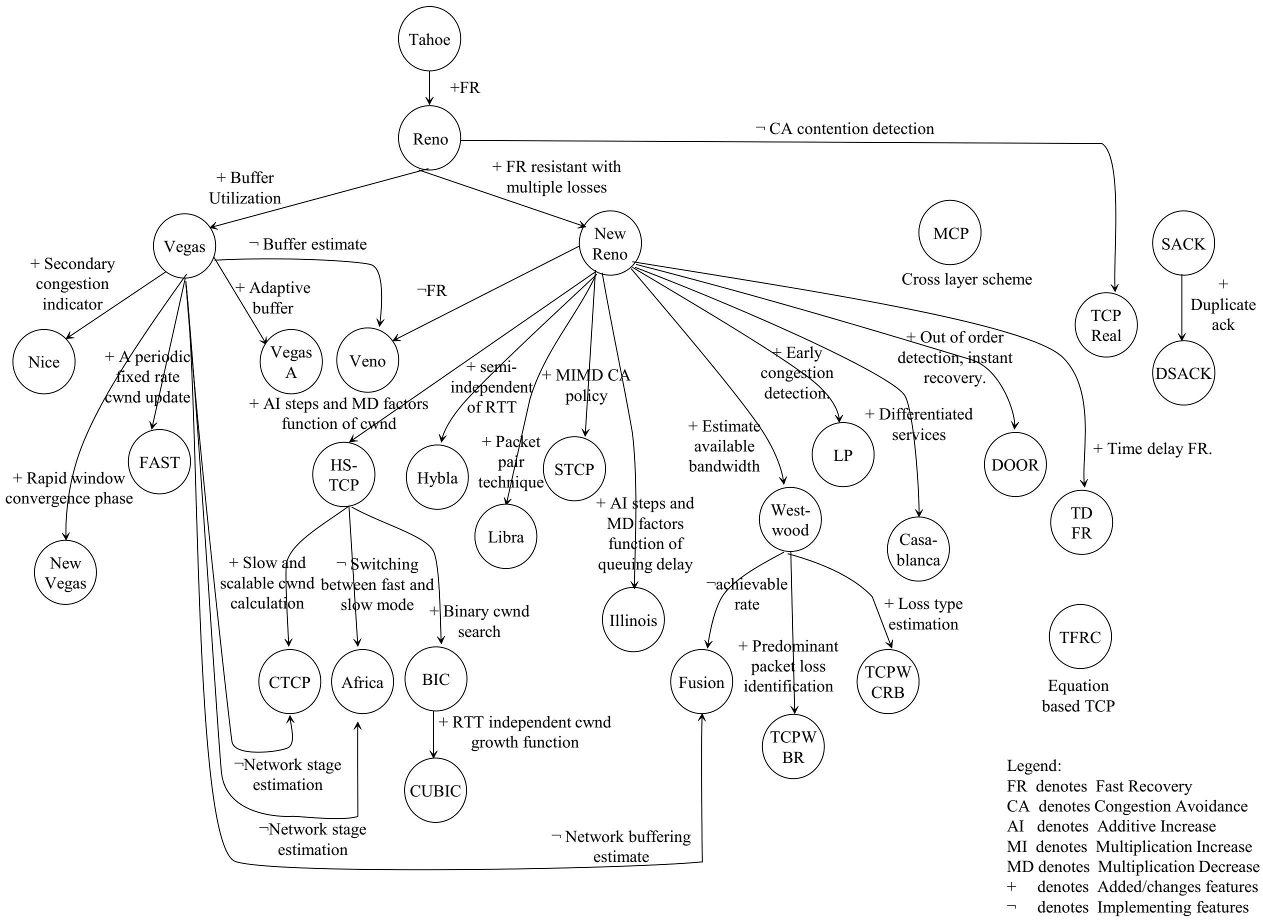

Fig. 3. Association of TCP variants with modified features.

overflow, but also the medium contention and poor radio link. As a result, several TCP variants have been proposed to resolve this problem. The high-speed/long delay consists of a condition in which the data have been transmitted but has not yet been received even though no data loss in the network. This problem is also referred as bandwidth-delay product (BDP) problem. Thus, the congestion control algorithms that focus on (1) efficient use of network resources, (2) fast respond to network change, and (3) fairness of all the flows is designed to resolve the BDP problem. For low priority data transfer, the TCP variants have been developed to provide a guarantee of transmission rate reduction in the presence of high priority data flows. The characteristics and features of the TCP variants with targeted domain are summarized in Table II. Three degrees of complexity: high, medium or low are identified. The set of algorithms (slow start, congestion avoidance, fast retransmission, and fast recovery) with a feedback ACK message are considered to be low complexity because it consists of the low overhead, whereas the set of the algorithms with feedback and monitoring in real-time are considered to be medium complexity as their overhead increases. The high complexity is the set of algorithms with feedback, the CWND is monitored periodically, and estimation of multiple control variables.

The common features of congestion control techniques are sorted into slow start, congestion avoidance, fast retransmit, fast recovery, multiple losses, estimation techniques, packet pacing technique, and limited slow start. Multiple losses in this context is referred to a single congestion event that causes by the several data packets loss; estimation technique includes the bandwidth estimation, transmission rate estimation, queue delay estimation, etc. to predict the congestion status in the linking network; the packet pacing technique is the time at which a packet is selected for transmission is determined by pacing protocol; and limited slow start refers to technique use to bound the maximum increase step during a slow start stage. In addition, the association of TCP variants with their modified features is presented in Fig. 3.

C. Congestion Metric that is Used to Indicate the Congestion Status

In this section, the TCP variants are classified based on the congestion metric that is used to indicate the congestion status as shown in Fig. 4. The congestion metric is divided into loss based scheme, delay based scheme, and hybrid based scheme that combines both losses based scheme and delay based scheme. An extended of loss based scheme with bandwidth estimation is also observed in the trend of TCP congestion control technique.

Loss based scheme is the earliest scheme that used to detect congestion status. This scheme is designed keeping in mind the end-to-end reliability of transport protocol. The receiver will transmit an ACK message to the sender after the data packet has been received. When the sender receives three duplicate ACK message from the receiver, it means that the packet is lost and indicates the network is in the congested status.

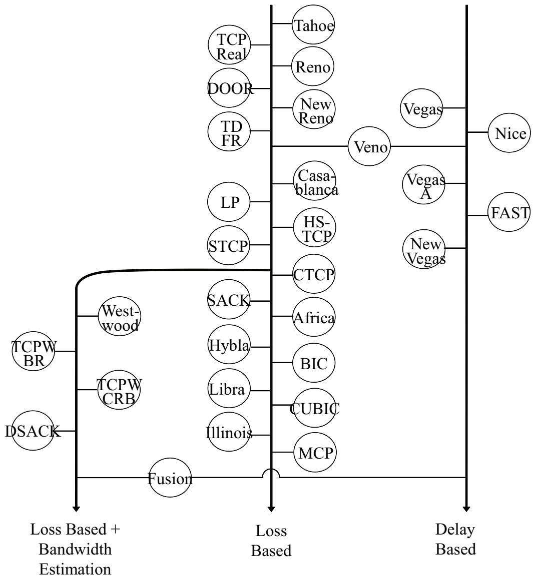

Fig. 4. Association of TCP variants with congestion metric.

The delay based scheme is closely tied to the level of available buffer along a communication path. When the level of available buffer is low, the throughput efficiency will be reduced due to the buffer empty when TCP flows backoff their CWND. On the other hand, if the level of available buffer is large, the TCP congestion control algorithm will try to fill the queue and lead to large queuing delays. Although these two aforementioned schemes are commonly used in detecting the congestion status, it does not give the precise congestion level especially in the wireless network. The hybrid based schemes provide more accurate congestion status determinations, but they consist of higher complexity in the computation.

In summary, the loss based scheme use packet loss to determine the probability of loss, packet loss rate, packet arrival rate, etc. Whereas, the delay based scheme use the RTT to calculate the queue length, queue delay, average delay, instantaneous delay, etc. In addition, bandwidth is also an important metric that can be used for identifying the congestion status. The bandwidth is used to calculate the instantaneous estimation, estimation of average bandwidth to mitigate fluctuation in the networks.

V. DISCUSSIONS

The hybrid techniques in the TCP variants are the trend nowadays, but they still need improvements. The prediction, compression and network coding techniques shall add into the congestion control technique in order to improve the resource utilization and congested networks. The prediction techniques can be used to predict future states of network congestion for better congestion control. While the compression techniques are able to reduce the transmission packet size, at the same time increase the transmission time. Moreover, the compression ratio depends on the types of data. If the data packets consist of high redundancy, the compression ratio also increase. In the network coding technique, the transmission rate can suppress to 1.5 of the conventional transmission rates by Slepian Wolf coding [45], as long as the data packets are correlated. Therefore, if these three techniques can jointly operate in congestion control, the congested network can significantly reduce.

VI. Concluding Remarks

We have presented a comprehensive review of more than thirty end-to-end TCP congestion control techniques in both wired and wireless networks. Based on these classifications, we can conclude that a plethora of TCP congestion control technique uses the SCP with loss based scheme. In the future work, the joint technique of prediction, compression, and network coding will be studied.

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