A Model for Behavioral Tendency of TCP Congestion Control Variants in LTE Cellular and 802.11ac Networks

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***Abstract*—As a reliable protocol, TCP protocol configuration requires many parameters to be set before the actual packet transmissions happen. However, the TCP parameters need to be changed from the initial fixed default values to suit the network requirements since it is utilized on many dissimilar mobile networks, including the LTE cellular and the 802.11ac. On the other hand, LTE cellular and 802.11ac networks also have their own design parameters. In this case, utilizing the TCP in these networks will result in the TCP parameters to interact with LTE and 802.11ac parameters, which subsequently can optimize or degrade the network performance due to correct or poor parameters setting. Therefore, it is highly important to determine the correct values for both protocol parameters and network parameters to achieve optimal network performance. This work presents a model to determine the interaction between the TCP protocol parameters, including the congestion control variants and the size of packets and network parameters that include RLC modes in LTE and A-MPDU aggregation mechanism in 802.11ac. Drawn from an extensive set of scenarios and experiments, the results show significant performance improvements achieved by the verified matching parameters.**

***Index Terms*—LTE; 802.11ac; TCP Variants; Congestion Control; RLC Modes; NS3.**

I. INTRODUCTION

The Internet-based applications are mostly accessed through the Transmission Control Protocol (TCP) protocol. The performance of TCP applications depends on various parameters, such as the type of congestion control variant, size of TCP packets, and design features of the underlying network. In relation to this, the main focus of this work is the exchange of TCP packets.

Congestion control variant, namely the TCP as a reliable transport protocol, has a critical impact on the network's stability and performance. This is achieved via its congestion control variants, which try to avoid network congestion. The main objective of the TCP congestion control variants is to appropriately reduce and adjust the network sending rate by forbidding the sender from sending more data than the network capacity can handle when congestion happens in the networks. However, there is no way for TCP protocol to precisely determine the occurrence of congestion in the network. Therefore, by taking into account various congestion indicators, a variety of different TCP congestion control variants have been provided so that they can determine the congestion state of the network. Based on the type of the congestion indicator, the TCP variants can be classified into three groups [1].

The first group is the loss-based TCP variant, in which increasing the number of lost packets is regarded as the congestion. These TCP variants assume that the loss is an indicator of congestion; thus, the sender needs to reduce its sending rate. While this condition can work on wired networks, it is not always accurate on the wireless networks. Due to propagation on the air, packet losses frequently happen on wireless links by the random bit errors and external interferences [2]. This will result in unnecessary TCP rate reduction, which is not necessarily an indicative of congestion. The loss-based TCP variants include Bic, Hybla, NewReno, HighSpeed, Htcp, and Scalable [3, 4, 5].

The second group is the delay-based TCP variants. Here, the congestion indicator is the Round Trip Time (RTT) delay in the network. The RTT is the time that takes a packet to the receiver from the sender and gets back the acknowledgment. Thus, a long RTT will be regarded as the congestion occurrence in the network and the reason to reduce transfer rate. The RTT is not an accurate congestion indicator in the wireless links due to some reasons, such as channel fading, handoff, ARQ retransmissions, and packet scheduling, which impose delays that result in higher RTT in wireless networks than wired networks [6]. The delay-based TCP variants include Vegas, Veno, and Westwood [3,4,5].

The third group is the loss-delay-based TCP variants. These variants adopt both delay and packet loss indicators to efficiently use the available bandwidth and to avoid overloading in the network. The loss-delay-based TCP variants include Illinois and Yeah [3,4,5].

Size of TCP packets: Besides the type of TCP variant, the TCP performance also relies on the size of TCP packets. The Maximum Transmission Unit (MTU) determines whether the TCP packets are fragmented or not during transmission. If the packet is larger than the MTU, the fragmentation is performed to divide the packet to a smaller size to meet the MTU requirements. If the packet size is less than MTU, no fragmentation happens. Fragmentation increases the number of packets and thereby it will affect the performance of TCP transmission.

Design features of the underlying network: Furthermore, the features of the underlying network over which the TCP packets are transmitted also influence the TCP performance.

This work considers design features of Long Term Evolution (LTE) and 802.11ac that affect the performance of TCP transmissions. The features include the Radio Link Control (RLC) modes in LTE and the aggregation mechanism called Aggregate Medium Access Control Service Data Unit (A-MPDU) in 802.11ac.

RLC modes in LTE: In order to transmit the actual user data in either uplink or downlink directions, the user plane protocol stack is used in LTE networks. The user plane protocol stack has sublayers in physical and data link layers. The data link sublayers include Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC), and Medium Access Control (MAC). The RLC in LTE network supports three types of transmission mode, which are directly involved in retransmissions and acknowledgment of the packets. The RLC modes include Unacknowledged Mode (UM), Acknowledged Mode (AM), and Transparent Mode (TM) each with different features. The RLC UM mode, as the name implies, does not require acknowledgment from the receiver upon receiving the data. Therefore, this mode is mainly used for delay-sensitive applications, in which error-free delivery is not required. In contrast, RLC AM requires acknowledgment from the receiver which improves reliability and makes RLC AM mode more suitable for carrying TCP traffics and error-sensitive applications. In addition to performing all functions of RLC UM, retransmissions also are done by RLC AM, which makes it the most complicated mode of RLC. In UM RLC mode, the RLC functions are not performed [8] and thereby its use is very limited.

A-MPDU aggregation in 802.11ac: By using frame aggregation, several data frames are grouped into one large frame to reduce the amount of header overheads that are added to each individual data frame. The Aggregate Media Access Control Service Data Unit (A-MPDU) is the default frame aggregation used in 802.11ac networks, in which several MPDUs coming from the MAC sublayer are grouped in PHY layer to form one large frame and then one single PHY header is added to this large frame. Thus, the frame aggregation mechanisms in 802.11ac networks are directly involved with the size of transmitted packets.

Despite using the TCP protocol in LTE cellular and 802.11ac networks, the structural design of these networks is substantially different from the wired networks. This results in the different behavior of TCP variants on wireless networks from the wired networks. Taking into account the significant growth of wireless services particularly for the smartphones end-users, and considering that Internet-based applications are mostly accessed over the TCP [2] to improve the performance of the TCP-based services, it is significantly important to determine how LTE cellular and 802.11ac networks respond to different TCP variants based on different network features. The rest of this work is organized as follows: Section 2 discusses the related works. Section 3 describes the model and the implementation details. Section 4 presents the results and discussion, while Section 5 concludes the work.

II. RELATED WORKS

The authors in [7] mentioned that while TCP protocol was initially designed for wired networks, it has also been used over mobile data networks. Since the mobile networks have substantially different characteristics, the TCP protocol has a lower performance over these networks compared to the wired networks. Thus, they present a transport protocol optimization over LTE network, which includes Cubic, Reno, Westwood, and Veno TCP variants that use a custom measurement tool. However, the work does not specify other important TCP variants and RLC modes or 802.11ac networks.

The majority of the Internet connections in the world are based on TCP due to its reliability, which is based on the ability to control congestion in the networks [9]. The authors stated that there are many variants of TCP designed to provide a better performance for the networks among which they investigated TCP NewReno and TCP Vegas over LTE using the NS2 network simulator tool. The performance of the variants was analyzed in terms of RTT, end-to-end delay, throughput, and packet loss, and the results showed higher throughput for NewReno but lower delay and packet loss for Vegas. However, other TCP variants and the RLC modes were not investigated while 802.11ac networks were not taken into account.

The authors in [10] asserted that while TCP is the main protocol for Internet traffics, it suffers performance degradation when it comes to wireless links. Thus, it is imperative to introduce effective solutions for the TCP congestion control over the wireless networks. They investigated the performance of the Westwood, Hybla, Highspeed, and NewReno TCP variants in LTE networks using NS3 simulation tool. The results in terms of fairness, throughput, and delay showed that there was throughput performance in the presence of Highspeed variant, Westwood variant had the lowest delay and Hybla variant had better fairness. However, the work did not investigate other important TCP variants and RLC modes while 802.11ac wireless links were not implemented.

The 802.11ac and 802.11n WLANs were investigated and compared for TCP performance in [11]. A testbed was set up and Iperf and tcpprobe tools were used in 13.04 Ubuntu to evaluate the Bic, CUBIC, Highspeed, Htcp, Hybla, Illinois, Scalable, Vegas, Veno, Westwood, and Yeah TCP variants. The results were obtained in terms of congestion window behavior and throughput. The work did not analyze the performance of the TCP variants over LTE cellular networks. A testbed was also used in this regard in [12]. The Reno, Illinois, Hybla, Westwood, CUBIC, Yeah, and CDG TCP variants were investigated over LTE networks in [13] to understand their behavior in terms of throughput, queueing delay and cwnd evolution using NS3 tool. The RLC mode was set to AM, although the UM mode was not implemented. Their results showed that loss-based mechanisms could reach full link utilization, thus inducing high queuing delays and unnecessary packet losses. Further, their results showed that the delay-based mechanisms reduce the average queue length and amount of dropped packets, although they have lower throughput. The work did not provide a comparative study over 802.11ac networks. The AM mode was also investigated in [14], while the AM and UM modes were used in [15, 16] to investigate the TCP performance, although the TCP variants were not taken into consideration.

The Intra and RTT bandwidth fairness, throughput, and loss ratio as a function of buffer size in high-speed networks were investigated in [17]. The TCP variants include

Compound, Cubic, Fusion, Bic, Highspeed, Htcp, Illinois, Scalable, and Yeah. However, the work did not particularly define the type of high-speed network. The TCP performance in Mobile Ad Hoc Network (MANET) in an ad-hoc environment was investigated in [18], using Optimized Network Evaluation Tool (OPNET). The performance of Reno, New Reno, and Sack TCP variants were evaluated in terms of the upload response time, download response time and retransmission attempts, while varying the number of nodes and their speed. The Tahoe, Reno, New Reno, Sack and Vegas in MPLS Networks [19], the CUBIC, NewReno and Westwood in 3G and 3.5 G networks [20], the CUBIC in highway [21], the NewReno, CUBIC, Compound, Hybla, and Westwood in satellite links [22] were also investigated.

Based on the current works, the limitation relies on the lack of a comprehensive comparative model to determine the performance efficiency of all the common TCP variants over two widely used networks i.e. 802.11ac and LTE cellular, while considering features of frame aggregation and RLC transmission modes. This work attempts to address the limitation by presenting a model for LTE and 802.11ac networks with the following main contributions.

- The TCP variants, each of them have their own design features, in which they respond differently by varying the fragmentation state of the TCP transmissions. Thus, the model implements three groups of the TCP variants based on the different size of the TCP packets. The aim is to verify the interaction between each TCP variant and fragmentation/no-fragmentation of the TCP packets and to determine which variant performs the best for which packet size.
- The model supports and implements the A-MPDU default frame aggregation since the frame aggregation mechanisms in 802.11ac networks are directly involved with the size of transmitted packets.

The RLC AM is suitable for error-sensitive traffics with retransmission ability, while the RLC UM is suitable for delay-sensitive traffics. The structural differences between these two modes can directly affect the overall performance of TCP transmissions. Thus, the model is designed so that it is able to implement both the RLC AM and RLC UM modes to determine which mode is more efficient for which TCP variant.

The authors in [1] evaluated the performance of TCP, Stream Control Transmission Protocol (SCTP), Datagram Congestion Control Protocol (DCCP), and User Datagram Protocol (UDP) for MPEG-4 video data transmission in LTE environment. The corresponding effects were measured by varying the number of nodes using the NS3 simulation tool. However, the key factors for the network load were not investigated, and there was no performance comparison with 802.11ac network.

The effect of the TCP packets size on network performance was investigated in [2]. Using the NS2 simulator network tool, the authors determined the size of TCP packets as a factor that can degrade the network performance. Variable packet sizes range from 500 to 1650 bytes were examined for the TCP packets. The results revealed that as the size of packets increases beyond 1500B, the throughput performance of the wired network degrades. However, other performance metrics were not investigated and the work did not include wireless and LTE networks.

The possible changes in UDP performance under variation of the UDP packet size and traffic load on network performance were examined in [3]. NS2 network simulator tool was used to measure the delay and throughout factors derived from the simulation of two packet sizes as 1550B and 2048B and 0 to 25 packets per second in intervals of 5. The results prove dependency of the UDP performance to these factors, in which the delay and throughput increases for higher packet size and traffic load. However, the work focused on wired network rather than the current 802.11ac and LTE networks: Other traffic types such as TCP were not investigated.

The authors in [4] investigated the performance of IEEE 802.11 b/g/n standards. The impact of the factors such as traffic type, length, and rate were investigated in terms of throughput, response time, encryption overheads, frame loss, and jitter. Unfortunately, their approach did not take into account the current 802.11ac and LTE networks. The IEEE 802.11ac performance in Vehicular Ad hoc Network (VANET) was investigated by the authors in [5]. The impacts of the packet size, number of users, and traffic rate were measured in terms of goodput. The results were compared with 802.11P and 802.11n, although the LTE was not included. The authors in [6] varied the number of users (5, 10, 20) and packet size (512B, 1024B) for TCP and UDP to measure the possible impacts on throughput in the LTE network only.

The authors in [7] investigated the 802.11ac networks under 15.5Mbps CBR and 35Mbps bursty UDP traffics along with the 15.5Mbps CBR TCP traffics, while varying the number of access points. The impact on the number of users per cell and data rate on TCP performance in LTE networks was examined in [8,9].

As shown in the related works, any variation in the load-based parameters consists of packet size, data rate, and packet type can highly influence the overall performance of the networks. However, despite its importance, there have been no studies to determine the actual impacts in an experimental comparative method between the two commonly used networks i.e. LTE and 802.11ac. In an attempt to address these limitations and ambiguities, the aim of this work is to propose a comprehensive framework called load-base factors (LBF), to first analyze the impact of the different load-based parameters that consist of the traffic source rate, traffic type, and packet size on performance of LTE and 802.11ac networks, and secondly, to determine the actual effective values suited for the performance optimality of these networks. The NS3 simulation tool is used to implement and validate the framework in terms of a variety of scenarios and performance metrics, including the throughput, loss ratio, delay, and jitter.

III. IMPLEMENTATION

The model presented in this work verifies the interaction between TCP parameters, including the congestion control variants and size of TCP packets. This includes the network parameters, which are the RLC AM and RLC UM modes in LTE and A-MPDU aggregation in 802.11ac. The purpose of this model is to determine which TCP parameters are more suitable with the features of LTE and 802.11ac networks in order to optimize their performance. The model includes both 802.11ac and LTE core networks. In LTE network, the 14 mobile users are connected to eNodeB, which in turn is connected to packet data network gateway (PGW). The eNodeB configures the two RLC modes (UM and AM) and the number of resource blocks to 100, which provides 20MHz channel bandwidth. In 802.11ac network, the 14 mobile users are connected to the access point, which in turn connected to PGW. The access point configures the A-MPDU frame aggregation and the modulation coding scheme, similar as in the LTE core. For both networks, the PGW is connected to a TCP server with a bandwidth of 100Gbps, propagation delay of 0.010 second, and 1500B MTU. The TCP server can generate TCP flows with 1Mbps data rates and different parameters. For congestion control variants, all the three groups, which are from the loss-based group Bic, Hybla, NewReno, Highspeed, Htcp, and Scalable, from the delay-based group Vegas, Veno, and Westwood, and from the loss-delay-based group Illinois and Yeah TCP variants were investigated. For the packet size parameter, the 1000B and 3000B sizes are selected to determine the impact of no-fragmentation and fragmentation respectively. The model includes a wide range of scenarios and experiments to determine the desired interactions. The NS3 simulation tool is used to design these scenarios and implement the model. The results are obtained in terms of the network performance indicators including the throughput, loss ratio, delay, and jitter. The visual presentation of the model along with the simulation parameters including common, LTE-specific, and 802.11ac-specific parameters, which are provided in Figure 1, Table 1, Table 2, and Table 3 respectively.

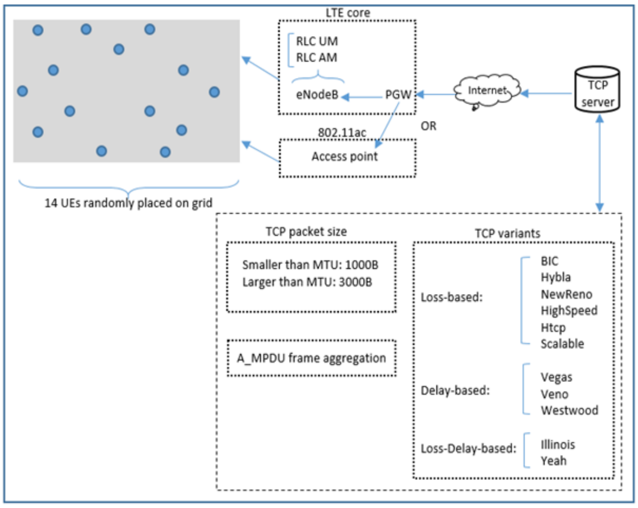

Figure 1: LBF framework configuration setup

Table 1
Common Simulation Parameters for Both LTE and 802.11ac

Traffic type	TCP (TcpSocketFactory)
MTU	1500B
TCP socket type variant	• Loss-based: Bic, Hybla, TcpNewReno, Highspeed, Htcp, Scalable • Delay-based: Vegas, Veno, Westwood • Loss-Delay-based: Illinois, Yeah
Packet size	1000B (no fragmentation) 3000B (fragmentation)
Number of TCP server	1
Simulation tool	NS3
Performance metrics	Throughput End-to-End Delay Packet loss ratio Jitter

Table 2
LTE Simulation Parameters

Number of resource blocks	100
Channel width	20MHz
RLC mode	UM and AM
Modulation algorithm	64QAM
Coding rate	5/6
Data Rate	1Mbps
LTE network elements	14 hybrid user equipment (UEs) 1 eNodeb 1 SGW/PGW

Table 3
802.11ac Simulation Parameters

Modulation coding scheme	VhtMcs7
Aggregation mechanism	A-MPDU (default)
Physical channel width	20MHz
Number of 802.11ac AP	1
Wi-Fi type	SpectrumWifiPhy
802.11ac network elements	14 hybrid wireless stations 1 Vht access point

IV. RESULTS AND ANALYSIS

This section provides the results from the implementation of the proposed model. This section is divided into three sub-sections. The loss-based TCP variants are investigated in the first sub-section. The second sub-section presents the second category of TCP variants including delay-based. In the third sub-section, the results regarding the loss-delay-based TCP variants are provided.

A. Loss-based TCP Variants

The changes in the performance of LTE and 802.11ac networks are identified and compared in this sub-section on the basis of adopting the loss-based variants including Bic, Hybla, NewReno, HighSpeed, Htcp, and Scalable, while varying the size of TCP packets and LTE RLC modes in the presence of A-MPDU 802.11ac frame aggregation.

1) Bic TCP Variant

In order to identify the impact of Bic variant on the performance of LTE and 802.11ac networks, the model is implemented and Figure 2 presents the obtained results.

The results reveal that Bic variant provides better performance in LTE than 802.11ac. Based on the obtained results, RLC AM mode provides better results in contrast to RLC UM mode. The throughput manages to reach full link utilization (1Mbps) for the LTE network when the AM mode is enabled by the eNodeB. However, this throughput improvement in AM mode comes at the price of losing efficiency in terms of higher delay, jitter, and the number of lost packets. Due to exchanging connection establishments packets between the TCP server and 14 end-users simultaneously at the beginning of the time, a heavy load is imposed on both networks and consequently, we observe a very significant performance reduction regardless of the adopted parameters.

Moreover, the performance achieved from the use of 1000B packet size differs from the 3000B packet size in both LTE and 802.11ac network. In the LTE network, the 1000B TCP packets perform better than the larger 3000B packets. The result is due to the fragmentation and subsequent extra overheads imposed to the network. However, for 802.11ac networks, the A-MPDU frame aggregation is able to aggregate the frames and decreases the header overheads, which helps to improve the performance

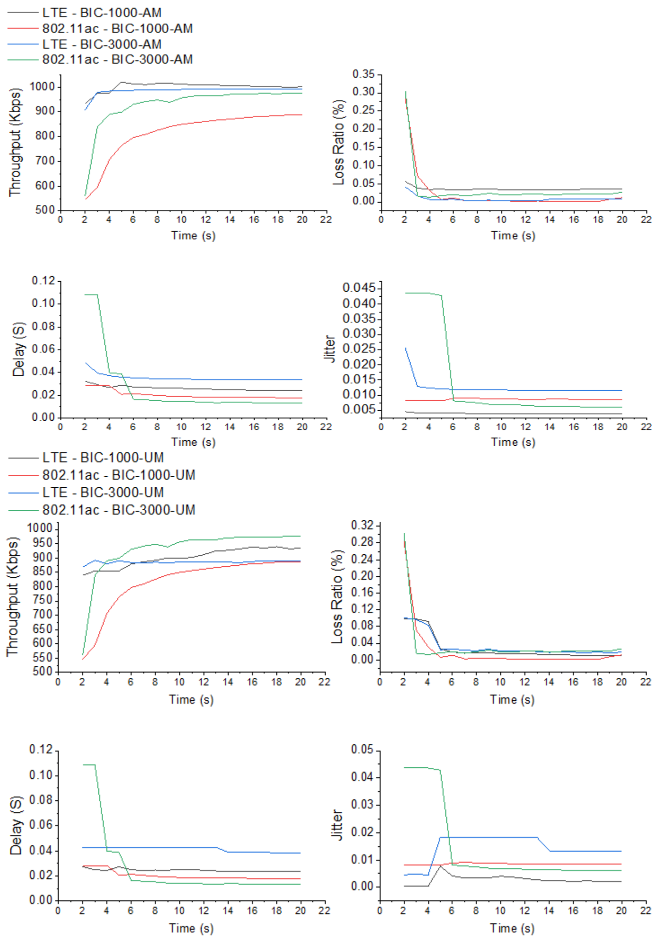

Figure 2: Bic TCP variant performance

2) Hybla TCP variant

In an attempt to evaluate the performance of LTE and 802.11ac networks in the presence of Hybla variant, the results from the implementation of the model are demonstrated in Figure 3.

The results from utilizing Hybla variant in TCP transmissions confirm that the LTE throughput is higher than 802.11ac in the AM mode, while the differences are not significant in the UM mode. Further, the average throughputs are close. Thus, unlike in the UM mode, there is a remarkable throughput difference between LTE and 802.11ac in the AM mode. Accordingly, the LTE average delay is less in the UM mode compared to the AM mode. In the AM mode, the end-users in the LTE network experience less delay than the users in 802.11ac network. However, an opposite behavior is observed in the UM mode, in which 802.11ac achieves less delay than the LTE for larger packets. Furthermore, the comparison of the the Bic and Hybla variants reveals that Bic is more suitable in terms of better performance for both the LTE and 802.11ac networks

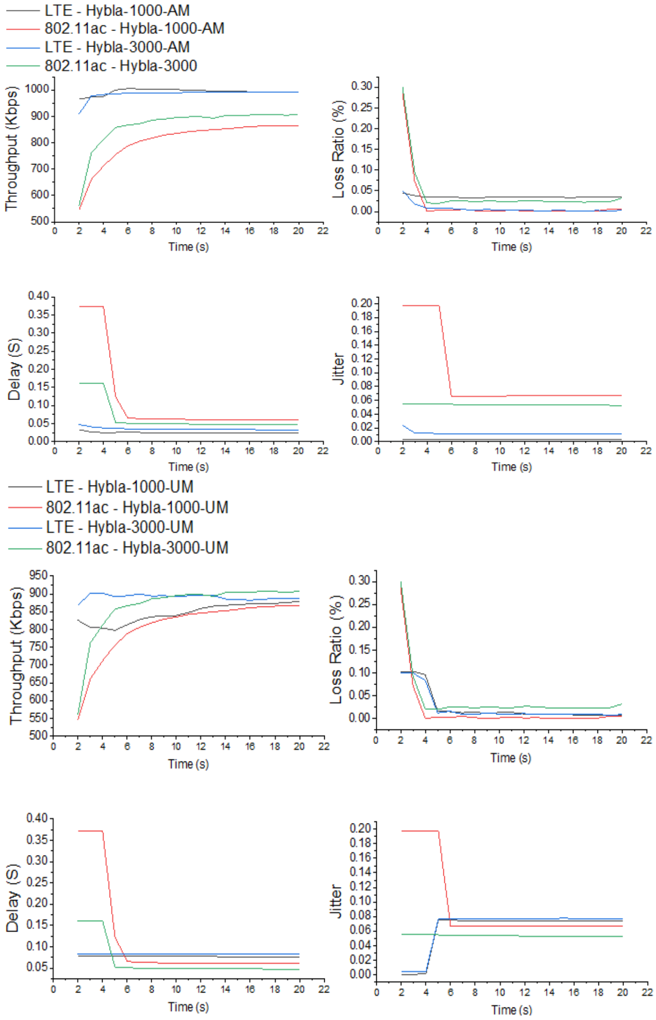

Figure 3: Hybla TCP variant performance

3) NewReno TCP Variant

In an effort to evaluate the performance of NewReno variant in LTE and 802.11ac networks, the model is implemented and the obtained results are illustrated in Figure 4.

Based on the results as shown in Figure 4, LTE can achieve higher throughput in both RLC modes compared to 802.11ac network. By contrast, in the RLC AM mode, the LTE throughput is higher than when the UM mode is used in communications. This reduces the throughput differences between the LTE and 802.11ac in UM mode. Furthermore, based on the packet size, the results in LTE AM mode indicate that the size of packets does not influence the amount of achieved throughput. However, when UM mode is applied in LTE RLC, the bigger packets provide higher throughput. The results show no significant differences in the throughput of 802.11ac network, when varying the size of transmitted packets.

In terms of loss ratio, the results prove that the ratio of lost packets in LTE network is higher when the AM mode is used. In this case, the size of packets has a direct impact on increasing the number of lost packets so that smaller packets result in higher number of lost packets. The results prove opposite findings in 802.11ac network, where bigger packets cause almost twice loss ratio compared to smaller packets

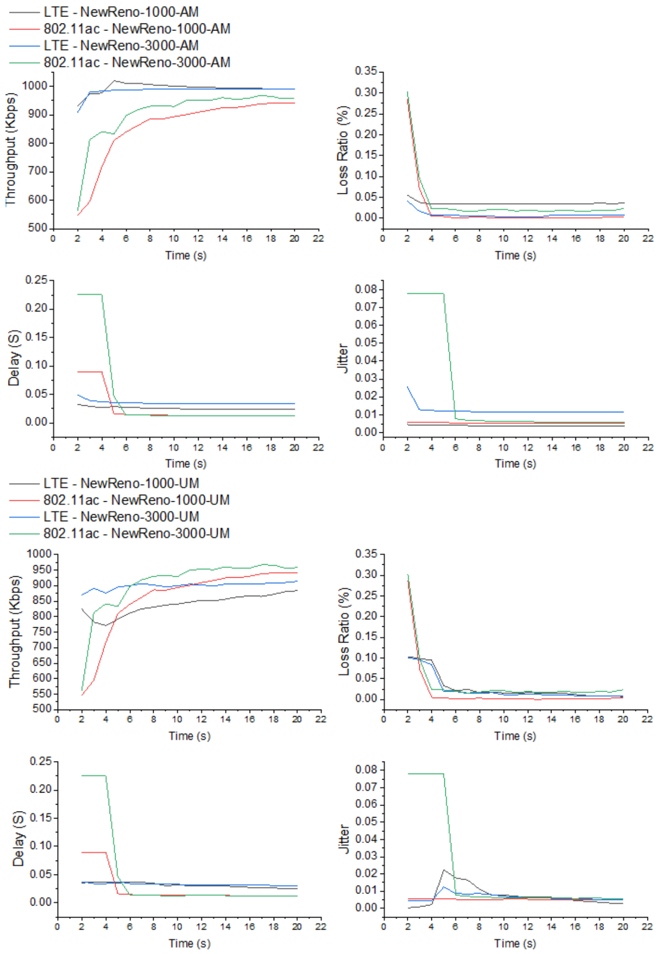

Figure 4: NewReno TCP variant performance

The delay results prove less delay in the LTE network in the presence of the AM mode. In this case, for smaller packets both LTE and 802.11ac networks achieve the same level of delay. However, as the size of packets increases, the delay in both networks tends to increase:The increase for LTE network is less than 802.11ac network. Thus, for the real time services, such as VoIP and video streaming, smaller packets in 802.11ac network provide a better user experience. The NewReno delay results are compared with the above Bic and Hybla experiments which shows that while among this three variants, Hybla causes the worst delay performance, the functionality of NewReno is close to Bic for LTE AM mode, while Bic performs better than NewReno in 802.11ac network.

The jitter results confirm a better performance for NewReno in the LTE AM mode than the 802.11ac. When smaller packets are exchanged in the RLC AM mode, jitter decreases. However, the results are different in the RLC UM mode, in which smaller packets lead to higher jitter in the LTE network.

4) HighSpeed TCP Variant

This experiment is carried out in order to have a better understanding of the influences of Highspeed variant on the performance of LTE and 802.11ac. The results are presented in Figure 5.

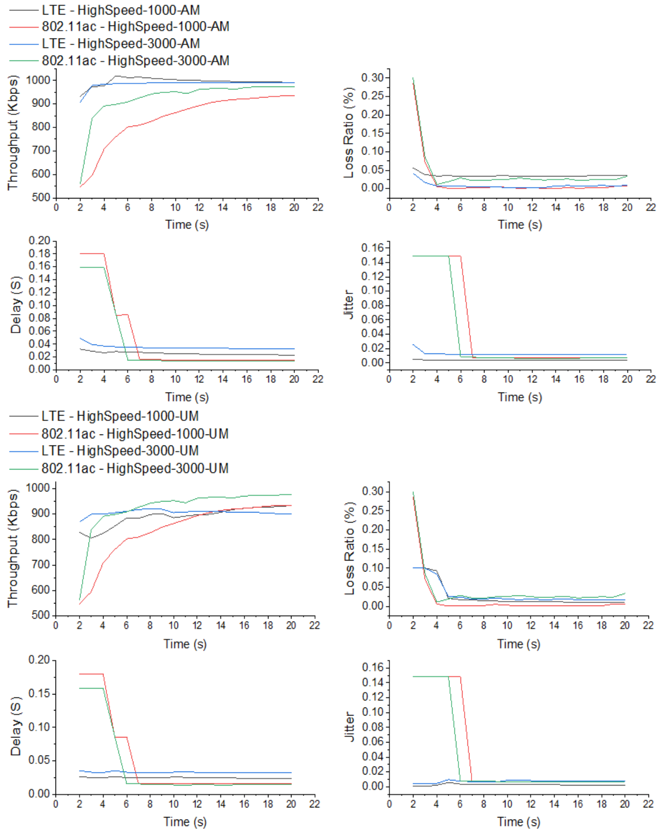

Figure 5: HighSpeed TCP variant performance

The throughput results show higher values for LTE compared to 802.11ac network, while it is higher in RLC AM mode than RLC UM mode. A comparison of the throughput achieved by Highspeed variant with those of our earlier experiments in Bic, Hybla, and NewReno shows that they all achieve the same throughput in RLC AM mode regardless of the size of packets. However, the throughput for 802.11ac varies based on the size of packets so that Highspeed variant achieves higher throughput when the packets are bigger.

The loss ratio also tends to increase in 802.11ac network consistent with the increase in the size of packets. This is opposite in LTE RLC AM mode, where the number of lost packets is higher when the size of packets reduces. In contrast, in the UM mode, a higher loss ratio is obtained when larger packets are transmitted in the network.

The delay results show that Highspeed variant performs better in terms of less delay in LTE network regardless of the RLC mode than 802.11ac network, where the delay is much higher. The delay in LTE is higher when the size of packets is larger. For 802.11ac network, a lower delay is achieved when smaller packets are transmitted. Therefore, while the size of packets does not impact the delay in the LTE in the presence of Highspeed variant, it is highly effective in the 802.11ac network, in which based on the results, larger packets are more suitable for TCP data. A comparison between the delay achieved by Highspeed with those of our previous experiments in Bic, Hybla, and NewReno proves the same results for LTE in AM mode. However, in UM mode, Highspeed provides better results in terms of less delay than Bic and Hybla, in which its performance is close to NewReno variant.

The jitter results show higher values in LTE AM mode compared to the UM mode for larger packets while they are the same for smaller packets in both AM and UM modes.

The jitter for 802.11ac network in the presence of Highspeed variant is higher when smaller packets are transmitted in the network. Moreover, the Highspeed jitter is higher than Bic and NewReno but it is lower than Hybla in 802.11ac network. In LTE network, the Highspeed jitter is the same as Bic, NewReno, and Hybla in AM mode. However, it is lower than all of them in the UM mode.

5) Htcp TCP Variant

This experiment is set up to quantify and determine the functionality of Htcp variant in both LTE and 802.11ac for which the results are presented in Figure 6.

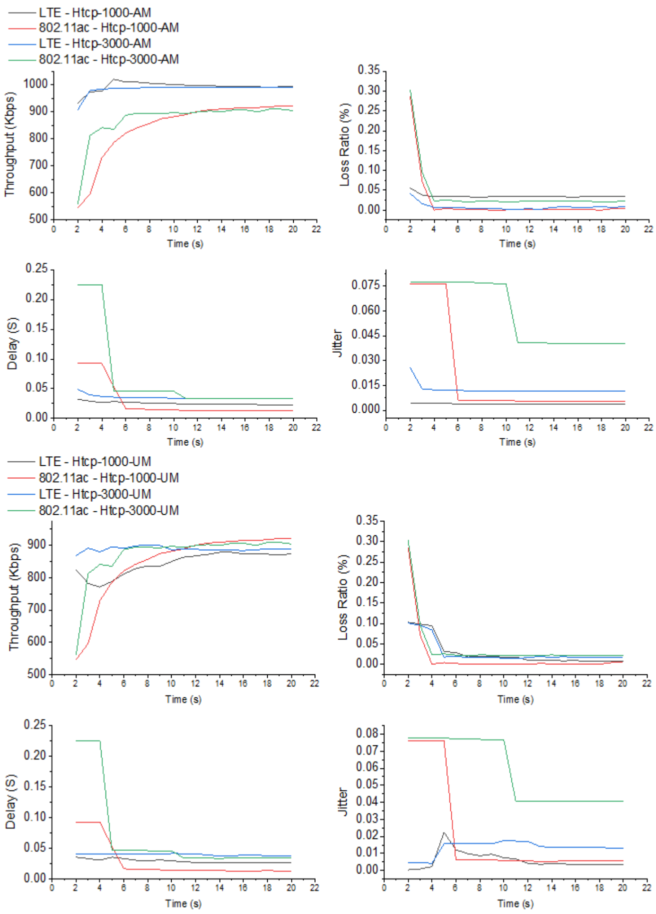

Figure 6: Htcp TCP variant performance

The results of throughput for Htcp variant show better performance in terms of higher throughput for the LTE than 802.11ac network, regardless of the type of RLC mode. The throughput results show that the size of packets does not have a remarkable impact on the performance of neither the LTE nor the 802.11ac networks.

However, the results of the loss ratio results prove that there is a significant impact of the packet size in both networks. In the LTE network, when the RLC mode is AM, the loss ratio is about three times higher for the smaller packets. On the contrary, when the UM mode is used, the differences decreases and the loss ratio of small and large packets are nearly the same. In the 802.11ac network, the larger packets result in a higher delay, which reaches about twice the amount compared to the smaller packets. A comparison of the delay results shows the same performance for the LTE network in both AM and UM modes. In both modes, the delay is less for smaller packets. In 802.11ac networks, the delay increases as the size of packets increases.

A comparison of the delay results of Htcp variant with those of our earlier experiments in Bic, Hybla, NewReno, and Highspeed shows the same performance in the LTE networks in AM mode. However, in the UM mode, the delay of Htcp variant is close to Bic, higher than NewReno and Highspeed, and less than Hybla. The same comparison over 802.11ac network also shows that the Htcp delay is higher than Bic and NewReno, while it is less than Hybla and Highspeed for smaller packets. For the larger packets, the Htcp has the worst performance in terms of the highest delay compared to Bic, Hybla, NewReno, and Highspeed variants.

The jitter results are also consistent with the delay results. The jitter in LTE network is less than 802.11ac network in both AM and UM modes, while the smaller packets achieve less jitter than the larger packets. In the 802.11ac network, the jitter is much higher than the LTE and for larger packets. It reaches about twice the amount in comparison to the smaller packets. The jitter comparison of Htcp variant with those of our previous variants experiments shows that the Htcp jitter in the 802.11ac network is higher than Bic and NewReno with smaller packets, while it is less than Hybla and Highspeed for the larger packets. The Htcp jitter is higher than Bic, Hybla, NewReno, and Highspeed, which is not desirable for the applications with high sensitivity to the delay variations. The jitter comparison of Htcp variant with those of our previous variants experiments in LTE network shows the same performance for all of them in AM mode. In contrast, in UM mode, the Htcp variant has less jitter than Hybla and NewReno, while it has higher jitter than Bic and Highspeed variants.

6) Scalable TCP Variant

This experiment is carried out in order to further evaluate the performance of Scalable TCP variant in both the LTE and 802.11ac networks. In this context, the model is implemented and the results are illustrated in Figure 7.

The results of the scalable variant throughput show higher delay values for the LTE than the 802.11ac network in both RLC modes. The impact of the size of packets in RLC AM mode is not significant as both packet sizes achieve the same level of throughput. However, in UM mode, the larger packets cause lower throughput in the LTE network. In 802.11ac, the larger packets cause higher throughput. The throughput comparison of scalable variants with the previous experiments variants show that in AM mode the scalable variant achieves the same performance regardless of the size of packets as the other variants. However, in AM mode the scalable throughput is higher than Hybla, NewReno, and Highspeed, while it is close to Bic variant for the smaller packets. In contrast to the larger packets, the scalable variant achieves less throughput than the other variants. In the 802.11ac network, the scalable variant performs better in terms of higher throughput than Bic, Hybla, Highspeed, and Htcp, while it achieves the same throughput as NewReno variant for smaller packets. In the presence of larger packets, the scalable variant performs better than Htcp, NewReno, Highspeed, and Hybla while it has the same performance as the Bic variant.

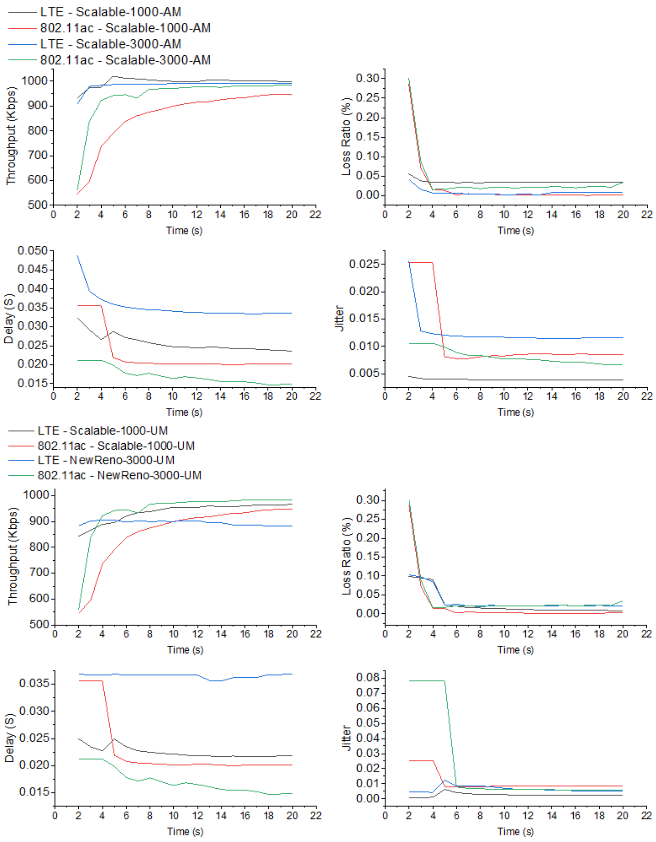

Figure 7: Scalable TCP variant performance

In terms of loss ratio, the scalable variant results show a higher number of lost packets in the RLC AM mode. In this case, the larger packets provide higher loss ratio, while an opposite behavior is observed in UM mode. The larger packets provide higher loss ratio than the smaller packets in the 802.11ac network. The loss ratio comparison of scalable variant with the previous experiments variants show the same behavior in AM mode, except for Hybla with less loss ratio for larger packets., the loss ratio of the scalable variant is less than all of them for the smaller packets in the UM mode. In contrast, the scalable variant has highest loss ratio among Bic, Hybla, Newreno, Highspeed, and Htcp. for the larger packets.

In terms of delay, the scalable variant has less delay in the LTE network with smaller packets in both RLC modes. The 802.11ac network behaves the same as the LTE with smaller packets but for the larger packets, the 802.11ac delay is much less than the LTE (about half).

The delay comparison between the scalable variant with other loss-based variants results in LTE shows the least delay for smaller packets in the UM mode, while for larger packets, the scalable variant has less delay than Bic, Hybla, and Htcp. It also has higher delay than NewReno and Highspeed in AM mode and the scalable delay is the same as the other variants. In the 802.11ac networks, the scalable delay for smaller packets is less than Hybla, NewReno, Highspeed, and Htcp and it is higher than Bic variant. For larger packets, the scalable variant delay is smaller than all other loss-based variants.

In terms of jitter, the scalable results show the same performance in LTE AM mode, in which the larger packets provide higher jitter to the network in the UM mode. In 802.11ac, the scalable variant provides higher jitter for the smaller packets. The comparison between the scalable variant jitter with other loss-based variants shows no significant difference in the AM mode. For the smaller packets in the UM mode, the scalable variant has the same jitter as Bic and Highspeed while the Hybla, NewReno, and Htcp have higher delay than the scalable. For the smaller packets in UM mode, the scalable variant has higher value than NewReno and Highspeed and has lower value than Bic, Hybla, and Htcp. In 802.11ac network, the scalable jitter for the smaller packets is less than Hybla, Highspeed, and Htcp and for larger packets, it is lower than all of them.

For better visualization, a summary of all loss-based TCP variants for AM and UM modes are provided in Figure 8 and Figure 9, respectively.

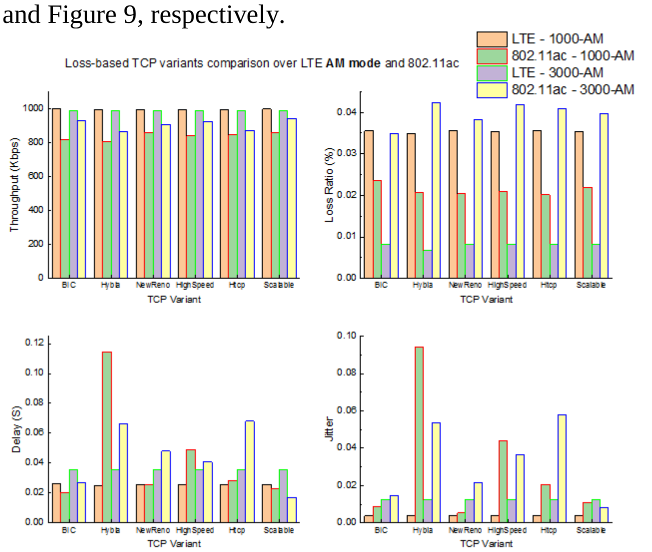

Figure 8: Comparison of loss-based TCP variants in AM mode

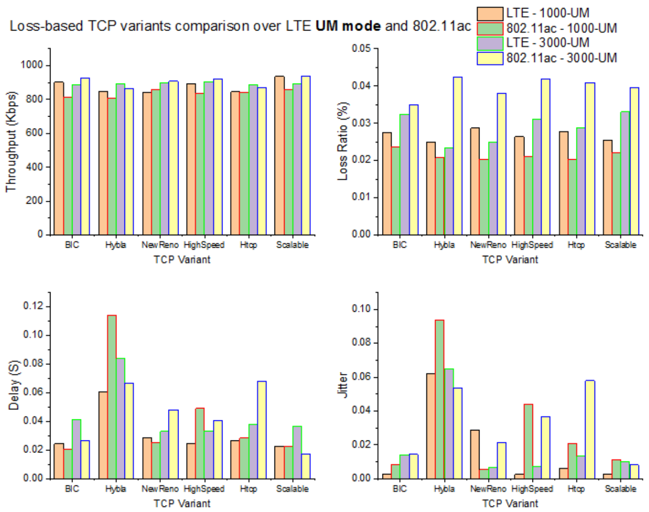

Figure 9: Comparison of loss-based TCP variants in UM mode

The above figures clearly verify the interaction between the TCP protocol parameters, including the congestion control variants and the size of packets and network parameters which include the RLC modes in LTE and A-MPDU aggregation mechanism in 802.11ac. In the LTE networks, the AM mode provides better performance than the UM mode. The size of packet shows that the larger packets do not have a considerable impact on LTE throughput but decrease the loss ratio and end-to-end delay. Thus, in this case, larger packets are better for LTE networks. Furthermore, the loss-based variants perform closely in the LTE networks, which means the performance of LTE networks is more affected by the mode of RLC as an

LTE-specific parameter than the TCP variants as transport layer specific parameter. In contrast, the performance of 802.11ac networks is highly affected by the type of TCP variant. The Hybla, Htcp, Newreno, and Higspeed result in lower performance to the network compared to Bic and Scalable variants.

B. Delay-based TCP Variants

The aim of this sub-section is to verify statistical significance of delay-based TCP variants on the LTE and 802.11ac networks through the use of the proposed model.

1) Vegas TCP Variant

The proposed model is adapted in accordance with the analysis of the effectiveness of Vegas variant in LTE and 802.11ac networks. The results are illustrated in Figure 10.

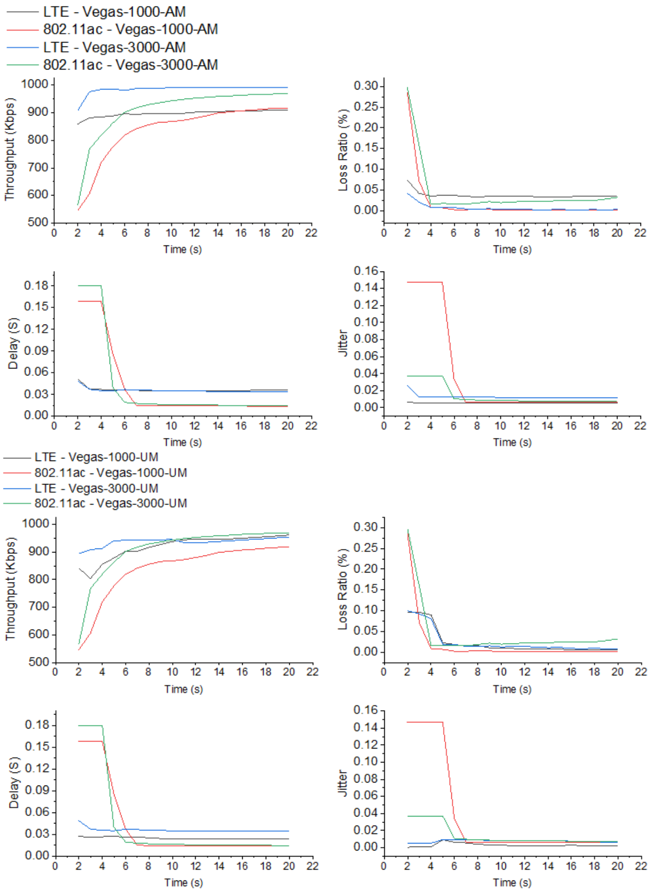

Figure 10: Vegas TCP variant performance

The throughput results of Vegas variant show better performance in the LTE network compared to the 802.11ac. In both networks, the larger packets achieve a higher throughput than the smaller packets. The results of the loss ratio, however, show different behavior. In the AM mode, the loss ratio for the smaller packets is higher, while in the UM mode, the smaller packets achieve lower number of lost packets. In the 802.11ac network, the smaller packets have lower loss ratio than the larger packets.

In terms of delay, the AM mode shows no significant dependence on the size of packets as both smaller and larger packets achieve the same amount of delay. On the contrary, in UM mode, the packets with smaller size have less delay than the larger packets. In 802.11ac network, no significant packet size dependency is observed in the results and there is similar observation for the delay. In terms of jitter, the LTE users experience less jitter in the presence of smaller packets regardless of the type of RLC mode. In contrast, the users in the 802.11ac network suffer from higher jitter when smaller packets are transmitted in the network, which is almost twice the amount of when the larger packets are exchanged in the network.

2) Veno TCP Variant

This experiment is outlined to statistically investigate the performance of the LTE and 802.11ac networks under different conditions in the presence of the Veno TCP variant. The results are illustrated in Figure 11.

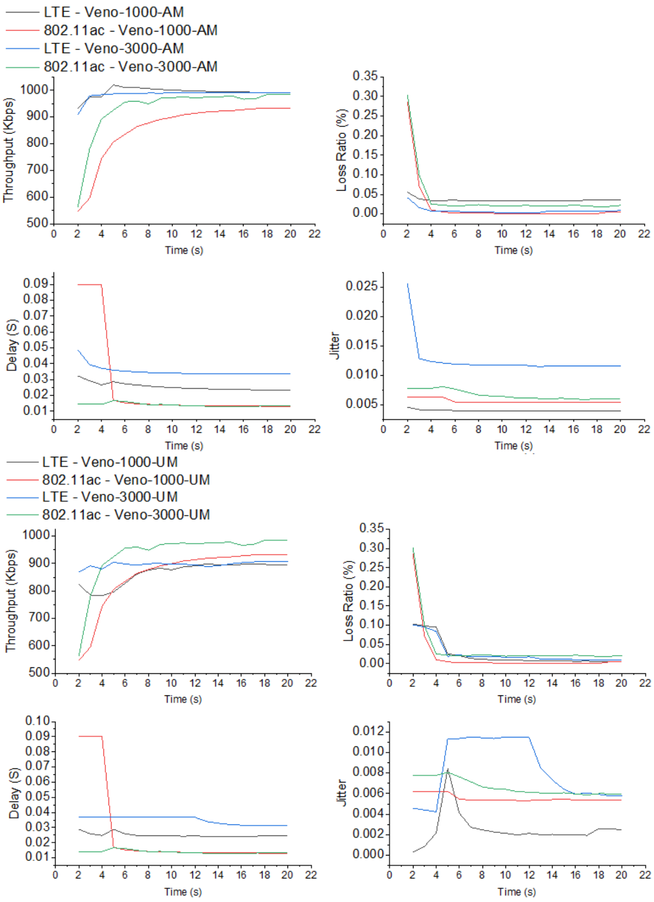

Figure 11: Veno TCP variant performance

The throughput results show an overall better performance of Veno variant in the LTE network compared to the 802.11ac. In AM mode, the smaller packets achieve the same throughput as the larger packets, while in the UM mode, the performance is better for the larger packets. In 802.11ac network, the throughput is higher in the presence of larger packets. The comparison between the throughput results on Veno and Vegas variants shows the better performance of Veno in AM mode compared to the better performance of Vegas in UM mode. In the 802.11ac network, Veno variant performs better than Vegas.

In terms of lost packets, the LTE in AM mode achieves less packet lost when larger packets are transmitted. In contrast, the number of lost packets in UM mode increases as the size of packets increases. In the 802.11ac network, larger packets cause a higher number of lost packets than the smaller packets. A comparison between Veno and Vegas variants shows better performance of Veno variant for both the LTE and 802.11ac in terms of a lower loss ratio.

In terms of delay, the results of Veno variant show the same behavior in LTE AM and UM modes. Here, the delay is higher with larger packets in both modes. On the contrary, an opposite behavior is observed in the 802.11ac network, where the delay is higher when larger packets are transmitted. A comparison between the delay of Veno and Vegas proves better performance is achieved by Veno variant compared to Vegas in terms of lower delay for both LTE and 802.11ac networks.

Additionally, jitter of larger packets is higher than smaller packets while the differences are not significant. A comparison analysis over jitter results of Veno and Vegas variants shows better performance of Veno over Vegas in terms of lower jitter for both LTE and 802.11ac networks regardless of the RLC mode or the size of packets.

3) Westwood TCP Variant

This experiment is a preliminary attempt to address the behavioral tendency of Westwood variant in LTE and 802.11ac networks under a variety of different conditions. In this regard, the model is implemented and the results are presented in Figure 12.

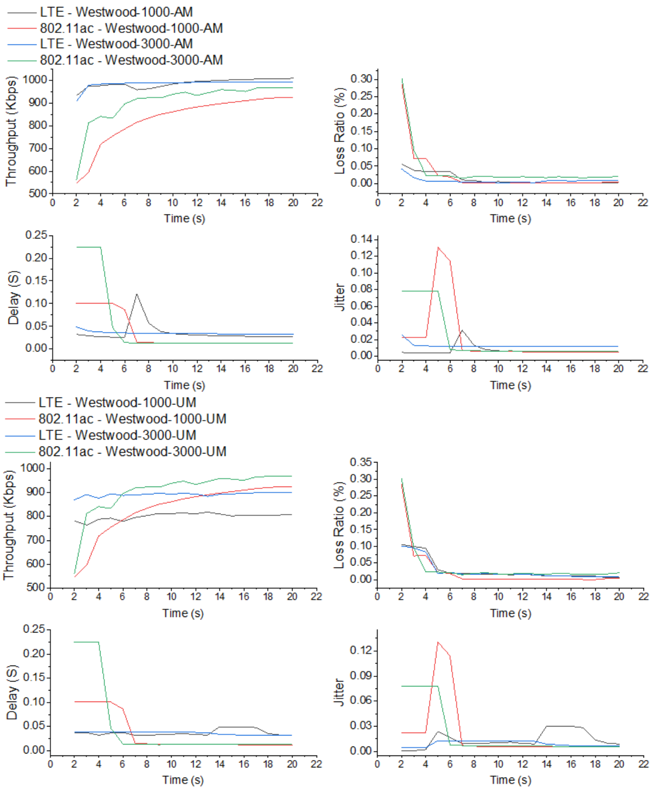

Figure 12: WestWood TCP variant performance

The throughput results of Westwood variant show better performance for the LTE in AM mode compared to the 802.11ac network. However, when the UM mode is enabled in the LTE, Westwood performs better in 802.11ac compared to LTE. The LTE results in AM mode show that smaller packets achieve the same throughput as the larger packets. In contrast, the throughput achievement is higher for larger packets in the UM mode. Similarly larger packets achieve higher throughput in the 802.11ac network also. A comparison between throughput results of Westwood with Vegas and Veno variants show that in, Westwood achieves the same throughput as Veno in the AM mode, which is higher than Vegas variant in the UM mode. However, Westwood has the least throughput among the rest of the delay-based variants. The throughput performance comparison shows the same amount for Westwood, Vegas, and Veno in 802.11ac networks. The loss ratio results show better performance in LTE compared to 802.11ac. The larger packets achieve less number of lost packets in both RLC modes, while the larger packets cause higher number of lost packet in the 802.11ac.

The loss ratio comparison between Westwood with Vegas and Veno shows that Westwood performs better in the AM mode, while it has the worst performance in the UM mode in comparison to Vegas and Veno. In 802.11ac network, Westwood performs better for larger packets, while it causes highest loss ratio compared to Vegas and Veno when smaller packets are transmitted.

In terms of delay, the Westwood results show the same amount in both the LTE AM mode and 802.11ac networks for smaller packets. In the LTE, the delay does not depend on the size of packets as both large and small packets achieve the same amount of delay. However, in the 802.11ac network, the larger packets provide higher delay to the network than the smaller packets. A delay comparison analysis shows that Westwood causes the highest amount of delay in both LTE and 802.11ac networks compared to Vegas and Veno variants, while the best is Veno.

The results of the jitter show better performance of Westwood variant in the LTE than 802.11ac network. In the AM mode, the smaller packets achieve better jitter performance, while larger packets achieve less jitter in UM mode. In the 802.11ac network, the jitter does not depend on packet size so that both sizes of the packets achieve the same amount of jitter. The jitter comparison analysis between the delay-based variants shows that the performance of Westwood variant is lower than Veno and better than Vegas variant in both LTE and 802.11ac networks.

Figure 13 and Figure 14 provide a visualization to summarize and organize the obtained results focusing on the comparison of the delay-based TCP variants in the AM and UM modes respectively.

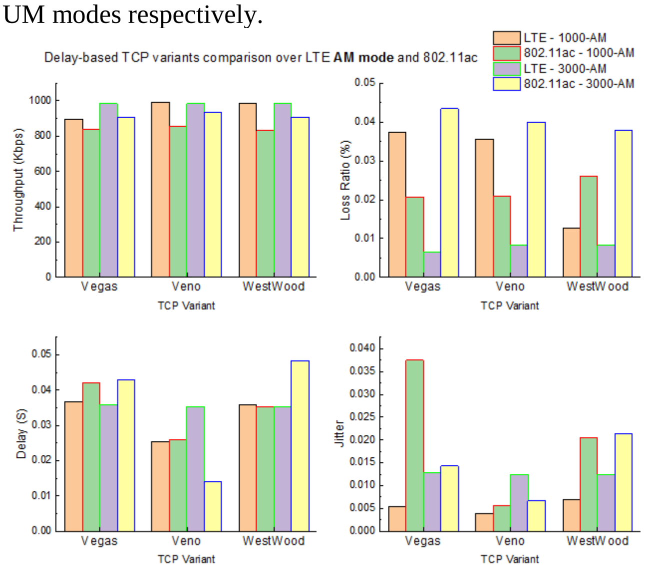

Figure 13: Comparison of delay-based TCP variants in AM mode

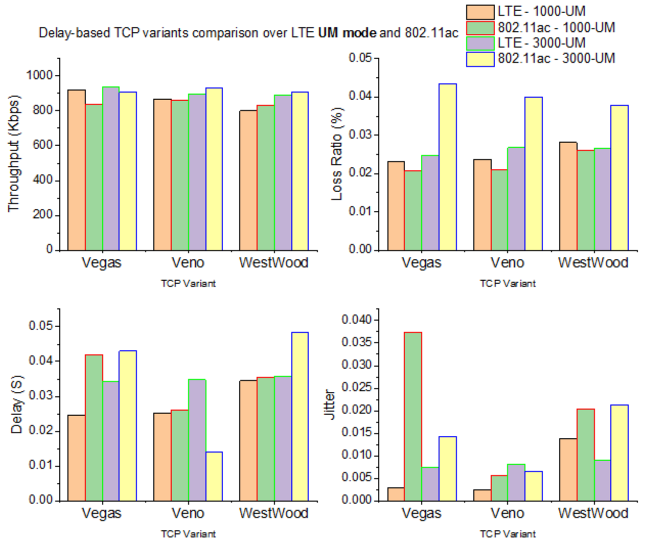

Figure 14: Comparison of delay-based TCP variants in UM mode

The above figures show the relation between the type of delay-based TCP variants, size of packets, and network parameters, including the RLC modes in the LTE and A-MPDU aggregation mechanism in the 802.11ac. In the LTE networks, the Westwood variant is more suitable as it results in better network performance among the other delay-based variants. Furthermore, like loss-based variants, the larger packets provide better LTE network performance than the smaller packets. The results prove that the UM RLC mode achieves better performance, unlike the loss-based variants when the delay-based variants are used in LTE networks. Moreover, the Veno variant suits better in the 802.11ac, unlike the LTE network. Although it enables the A-MPDU, the larger packets degrade the 802.11ac performance.

C. Loss-Delay-based TCP Variants

The design of experiments in this sub-section is based on quantifying the behavioral tendency of loss-delay-based TCP variants to distinguish their functionality and performance differences under different network conditions in the LTE and 802.11ac. The results of the experiments are described below.

1) Illinois TCP Variant

This experiment enables us to statistically examine the performance of LTE and 802.11ac networks using Illinois TCP variant. The results are presented in Figure 15.

The throughput results of Illinois variant show that the performance in LTE network is better than the 802.11ac. In both RLC modes, the LTE throughput is not affected by the size of packets as both small and large packets achieve the same amount of throughput. In the 802.11ac network, the larger packets achieve higher throughput compared to the smaller packets. In terms of loss ratio, the smaller packets cause higher loss ratio in the LTE (regardless of RLC mode) than the larger packets. In the 802.11ac network, the larger packets cause higher loss ratio to the network.

In terms of delay, the Illinois variant provides better performance for LTE in both the RLC modes compared to the 802.11ac when the smaller packets are exchanged. However, for the larger packets, the 802.11ac achieves less delay than the LTE.

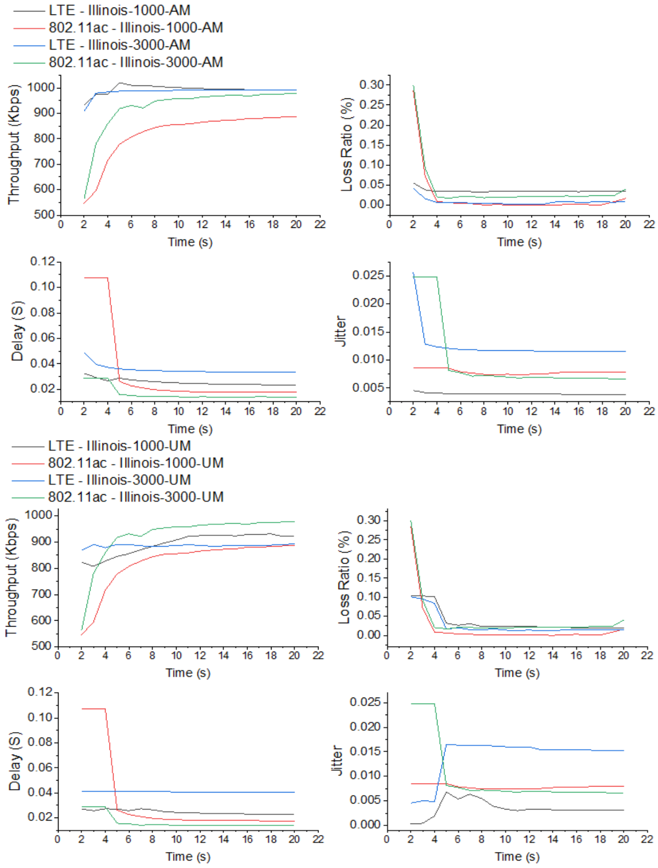

Figure 15: Illinois TCP variant performance

Furthermore, the results of the Illinois jitter confirm the same behavior of the LTE and 802.11ac in the delay experiments regardless of the RLC mode. In this regard, when the size of packets is smaller, the LTE performs better than the 802.11ac, in terms of lower jitter. However, as the size of packets increases, the jitter increases higher in the LTE than the 802.11ac network. The overall jitter of the LTE network in the UM mode is higher compared to the AM mode.

2) Yeah TCP Variant

This scenario is characterized to assess the performance of the Yeah TCP variant in both the LTE and 802.11ac networks. The results are presented in Figure 16.

The throughput results of the Yeah variant show better performance for the LTE than the 802.11ac network. In the AM mode, the throughput is the same for both the small and large packets. In the 802.11ac network, the throughput of the larger packets is higher than the smaller packets, while the differences are not remarkable. Further comparison analysis between the throughput of Yeah and Illinois shows better performance of Yeah variant, while the differences are insignificant. The loss ratio results of Yeah variant show that in the AM mode, the loss ratio is higher for the smaller packets while for the larger packets the loss ratio decreases to about three times. In UM mode, the smaller packets have a loss ratio higher than the larger packets with insignificant differences. In the 802.11ac network, the larger packets have higher loss ratio.

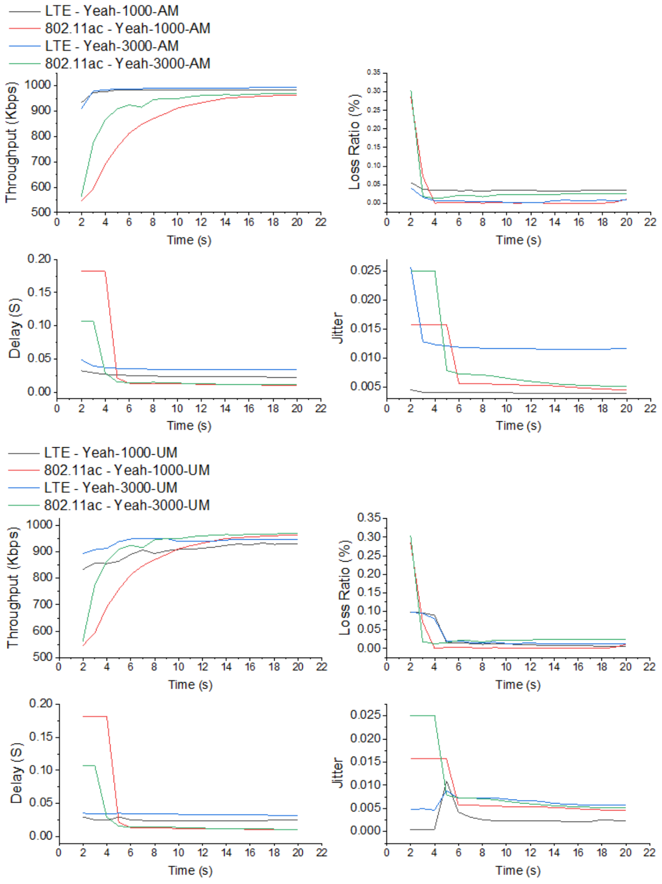

Figure 16: Yeah TCP variant performance

A comparison analysis between Yeah and Illinois variants shows a better performance of Yeah in terms of lower loss ratio in both LTE and 802.11ac networks. The delay results of Yeah variant show better performance in the LTE than the 802.11ac network for smaller packets. Regardless of the type of RLC mode, when the packets are smaller, delay is less in the LTE compared to the 802.11ac network. However, as the size of packets increases, the delay of Yeah variant decreases in the 802.11ac, which is lower than the LTE. A comparison analysis between Yeah and Illinois variants shows better performance of Illinois in terms of less delay. The Jitter results of Yeah variant confirm better performance in the LTE for smaller packets and in th e802.11ac for larger packets. In the LTE, regardless of the type of RLC mode, the jitter is less than the 802.11ac when small packets are transmitted. However, for larger packets, the LTE jitter is higher than in the 802.11ac network. A jitter comparison analysis between Yeah and Illinois show better performance of Yeah in both networks compared to Illinois variant.

A summary of the loss-delay-based TCP variants in the AM and UM modes are provided in Figure 17 and Figure 18 respectively. From the both figures, a comparison between the Illinois and Yeah variants prove similar results on the performance of the LTE networks. Like before, the larger packets can improve the overall performance. The results also show that in the presence of loss-delay-based variants, there is no difference between the UM and AM RLC modes. In contrast, in the 802.11ac network, the Illinois variant performs better than the Yeah. Furthermore, smaller packets achieve better performance in the 802.11ac networks

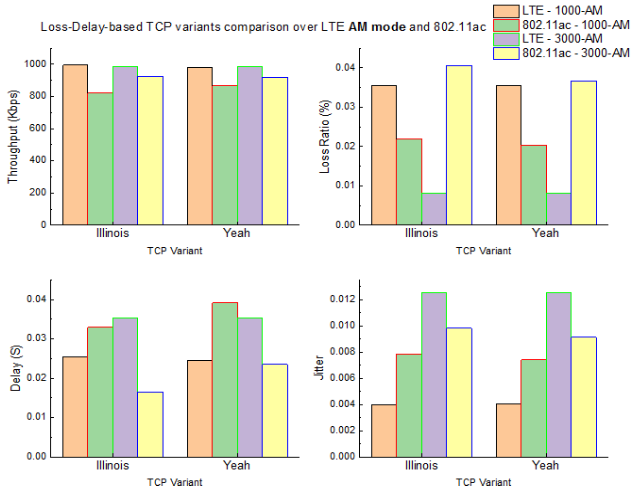

Figure 17: Comparison of loss-delay-based TCP variants in AM mode

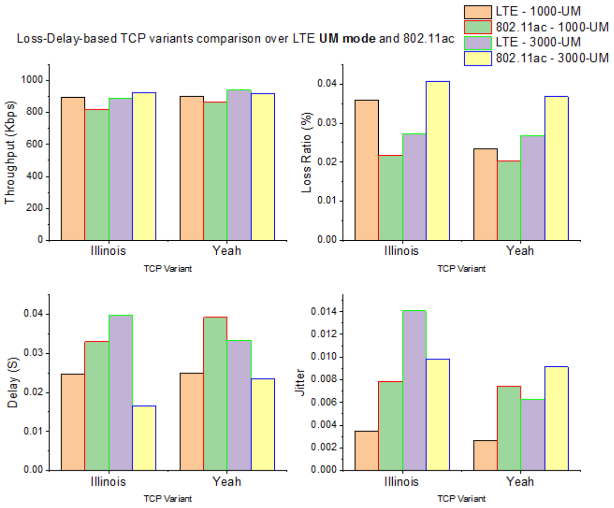

Figure 18: Comparison of loss-delay-based TCP variants in UM mode

V. CONCLUSION

In this work, a model was proposed to compare the performance of the three categories of the TCP variants, namely the loss-based, delay-based, and loss-delay-based in the LTE and 802.11ac networks for two RLC modes that include the AM and UM modes under small and large TCP packet sizes. The results from the implementation of the model in the NS3 under a variety of different scenarios found significant differences. Based on the results, the size of the TCP packets has a direct effect on the performance of both networks. In the RLC AM mode of the LTE, larger packets provide the same throughput and lower loss ratio, but cause higher delay. In contrast, in the UM mode of the LTE and 802.11ac, larger packets provide higher throughput but higher delay and loss ratio. For the 802.11ac network, based on the loss-based variants, the Bic, NewReno, and Scalable variants provide better functionality compared to the poor performance of Hybla, Htcp, and Highspeed. In this regard, based on the delay-based variant, Veno performs better than Vegas and Westwood. From the category of loss-delay-based variants, the Yeah variant performs better than the Illinois. For the LTE in AM mode, the loss-based and the loss-delay-based variants all perform similarly, while in the category of delay-based variants, Westwood and Veno perform better than Vegas. For the LTE in UM mode, the Bic, Highspeed, and Scalable variants in the loss-based category perform better than the Hybla, NewReno, and Htcp variants. In contrast, in the delay-based category, Vegas and Veno perform better than Westwood. In the loss-delay-based category, similar to the 802.11ac, LTE performs better in the presence of Yeah variant compared to Illinois.

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