JCSE International Journal of Computer Sciences and Engineering Open Access
Research Paper Vol.-6, Issue-8, Aug 2018 E-ISSN: 2347-2693

Performance Analysis of TCP Tahoe, Reno and New Reno for Scalable IoT Network Clusters in QualNet® Network Simulator

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Available online at: www.ijcseonline.org

Accepted: 13/Aug/2018, Published: 31/Aug/2018

***Abstract*—** In the era of Internet of Things, sensors and actuators equipped embedded devices are seamlessly connected over internet using TCP/IP stack to enable various M2M applications and services for users. Transmission Control Protocol (TCP) is a connection oriented protocol in Transport layer of OSI providing guaranteed service for various Internet of things (IoT) applications like HTTP, MQTT and CoAP (over TCP RFC 8323). Further, Congestion Avoidance and Control mechanism implemented in TCP makes it more adaptive to various network conditions. It is imperative to design an IoT network cluster aided with a reliable transport layer TCP for sending sensor data to a cloud server or to control actuators using HTTP Representational state transfer (REST) APIs. In this paper, three network performance matrices namely *Throughput*, *End-to-End delay* and *Packet deliver ratio* (PDR) are considered to evaluate the performance of TCP Tahoe, Reno and New-Reno in multiple network clusters designed for IoT applications. QualNet® 6.1 network simulator is used to simulate scalable wired (IEEE 802.3 Ethernet) and wireless (IEEE 802.11 Wireless LAN) IoT network clusters. From the perspective of this paper, multiple test cases of IoT network clusters are considered to analyze the performance of TCP variants with a scalable approach by varying node density and by varying Maximum Segment Size (MSS).

***Keywords*—** TCP, IoT, Cluster, Congestion Control, Tahoe, Reno, New Reno, QualNet®

I. INTRODUCTION

Design of a reliable and guaranteed service for IoT application layer protocol like MQTT, HTTP or even the recent RFC 8323 (Feb.2018) “CoAP over TCP” requires a connection oriented TCP at the transport layer of OSI. In this paper an Internet of Thing (IoT) based scalable cluster is taken into account to transport high volume data over a cluster of scalable nodes [1-2]. Fig.1 shows the IoT cluster in 3D using QualNet.

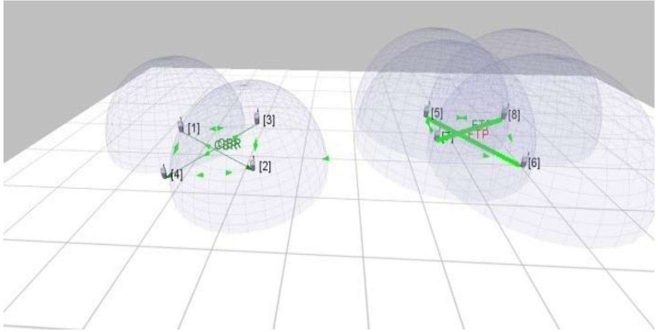


Figure 1. Internet of Things (IoT) cluster simulated in QualNet Network 3D-simulation

The performance of the network is quantized by three key parameters: throughput, end to end delay and packet delivery ration (PDR). The performance of the network is evaluated using two scenarios by varying the node density of the cluster and secondly varying the maximum segment size. This test bed is simulated using QualNet® simulator primarily for a IoT application for a small cluster based network for sending high volume FTP traffic for sending sensor based data to the cloud application. Three variants of TCP are considered for performance evaluation namely Tahoe, Reno and New Reno [3].

This paper is organized as follows, Section I contains the introduction of TCP as a reliable transport layer protocol of connection oriented IoT applications. Section II contains the related work on TCP Tahoe, Reno and New-Reno variants of TCP and their algorithm comparison. Section III contains the design and simulation of various wired and wireless IoT network cluster and their simulation parameters in QualNet® network simulator. Section IV contains the simulation results of the IoT network cluster performance parameters. Section V discusses the analysis of results. Section VI concludes research work with future directions.

II. RELATED WORK

Congestion Control mechanism using Tahoe is based on the 'conservation of packets' as suggested by Van Jacobson [4-5]. At the time when the TCP connection is running at the optimum bandwidth a new packet will be injected to the connection only when a packet is taken out. A packet with sequence number: *N* is delivered at the destination an acknowledgement no: *N+1* will be sent back to the sender, thus releasing that sequence number which will be taken out of the network. This also maintains the congestion window (*cwnd)* for the optimum network capacity. This can be achieved by determining the bandwidth and hence ensuring the equilibrium. The congestion control mechanism is implemented using *Slow-Start: Exponential Increase* (*SS:EI*), *Congestion Avoidance: Additive Increase* (*CA:AI*) phases as shown in Fig.2.

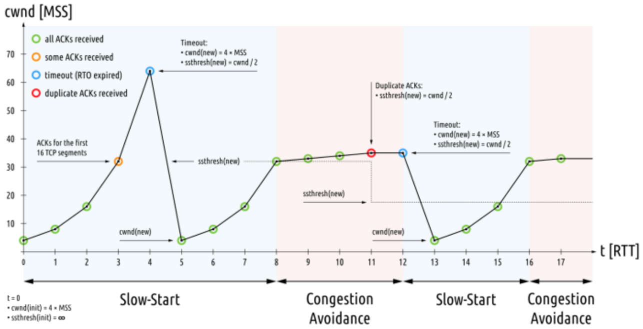


Figure 2. Congestion Control Mechanism of TCP

However, the biggest drawback of Tahoe is a packet loss that can be detected only after completion of a complete time-out interval, which in most implementation takes longer time due to coarse grain timeout. Further the *piggybacked* acknowledgement mechanism using *Go-Back-N ARQ* makes the scenario even worse as the packet loss has to wait in the pipeline for retransmission to occur. This increases the bandwidth delay product cost of the link.

TCP Reno variant is based on the same *SS:EI* and *CA:AI*, however with some intelligence to detect the packet loss scenario with a more prompt approach by sending instantaneous acknowledgement rather than waiting in pipeline till a complete timeout interval. Reno suggests a *'Fast Retransmit'* technique by detecting duplicate acknowledgement of previously received packet. In a scenario when sequence number: *N* packet is received a acknowledgement of *N+1* is sent from receiver to sender. In case of a delay in receiving the next expected data sequence *N+1*, the algorithm assumes that there is a highest probability that the packet is out of sequence because it has taken a longer path over the packet switched network or finally is lost. Under the circumstances where 3 duplicate *ACK* had been received the algorithm will consider a packet loss hence retransmitting the *N+1* data sequence without waiting for timeout. This approach of retransmitting while the pipeline is still almost full can minimize the bandwidth delay product cost of the link. Secondly, instead of making the *cwnd_size=1* the algorithm sets new *ssthreshold* and new *cwnd* as given in equation (1) and (2) respectively.

$$ssthreshold_{New} = \frac{1}{2}(cwnd_{Current}) \qquad (1)$$

$$cwnd_{New} = ssthreshold_{New} \qquad (2)$$

This strategy improves the pipeline and further helps in minimizing the bandwidth delay product cost of the link.

However TCP Reno performs better than Tahoe when there is a single packet lost inside one window. In case of an multiple packet lost in the same window the Reno fails to outperform the Tahoe as the 3 duplicate ACK strategy has to first deal with 1st packet lost with Round trip time (RTT) then for all subsequent packet loss it has to go though the same repetitive process. In this way the *ssthreshold* as well as the *cwnd* will also reduce multiplicative times each or one packet loss hence increasing the bandwidth delay product cost of the link. If the *cwnd* reduces to a very low value then there will not be enough sequence numbers in one window to receive any duplicate *ACK* for a *fast retransmit* and we would have to wait for a coarse grained timeout. Hence it cannot effectively detect multiple packet losses.

TCP New-Reno suggests a modified algorithm over Reno to deal with multiple segment loss in a single pipeline. If the outstanding data segments in New-Reno, which are present in the pipeline (segments which are not successfully acknowledged yet) then those data segments do not exit the *fast-recovery* phase unless they all are acknowledged successfully. The major drawback of Reno is that, it reduces the *cwnd* multiple times at the time of *fast-retransmit* when 3 duplicates *ACK*s are received. Although the New-Reno *fast-retransmit* phase is similar to that of Reno, the New-Reno overcomes the drawback of Reno by not reducing the *cwnd* size and hence maintaining an optimum throughput. The New-Reno *fast-recovery* phase facilitates multiple segment re-transmissions in the same pipeline of flow-control mechanism. Whenever a new *ACK* is received in New-Reno the algorithm reacts to it in two possible scenarios as below:

1) In a pipeline of a single *cwnd* if all the outstanding segments have received their respective *ACKs* then the algorithm exits the *fast-recovery*, sets the *cwnd* and *ssthreshold.* After that it enters into congestion avoidance phase identical to that of Tahoe.

2) In a pipeline if New-Reno receives partial *ACK*s for data segments then the algorithm detects the possibility of a lost segment and retransmits that particular segment. When all the data segments are acknowledged successfully, it resets the duplicate *ACK*s counter to zero and exits the fast-recovery phase [6-7].

The major drawback of New-Reno is that, it consumes a complete RTT to detect a single segment loss. Once the *ACK* of the first re-transmitted segment is received then only it can further proceed to all the subsequent segment loss which increases some delay in the pipeline.

III. QUALNET® SIMULATION

A. Experimental Setup:

Network Simulation Tool: *QualNet 6.1* is used to analyze the performance of scalable IoT network cluster to evaluate the performance of TCP Tahoe, Reno and New-Reno in this paper. Two network scenarios have been considered here for simulation: (i) IEEE 802.3 based Wired Network (ii) IEEE 802.11 based Wireless network with suitable routing protocols [8-9]. AODV has been selected for the preferred routing protocol of IEEE 802.11 wireless network as suggested in the research work especially for a MANET in the context of designing an IoT network cluster [10-11]. Simulation parameters for QualNet simulation are shown in Table.1.

Table.1: Simulation Parameters

Network Parameters	Wired Scenario Parameters	Wired Scenario Parameters
Simulation Time	300 Sec.	300 Sec.
Terrain Size	500x500	500x500
Routing Algorithm	Bellman-Ford	AODV
Server	FTP (running on TCP)	FTP(running on TCP)
Server Time	--	--

B. Performance Matrices:

The following performance matrices have been considered to evaluate the performance of the different TCP Variants in differed wired as well as wireless scenario. Table.2 shows the performance matrices chosen to quantify the network performance.

Table.2: Simulation Performance Matrices

Performance Matrices	1. Throughput 2. End-to End Delay 3. Packet-Delivery Ratio (PDR=R/S) (Packet Received/Packet Sent)

From the context of performance evaluation of TCP congestion control the test-bed for simulation is designed by taking motivations from various research papers [12-15]. In addition to that design of the network cluster is also been motivated by keeping the Internet of things (IoT) in scope as suggested for a typical healthcare application in [16]. For simulation in this paper and variable node density for both wired and wireless cluster of node size varying from 2,5,10 & 20 is considered typically for reliable guaranteed service application for sensor data and actuator control scenario. Motivation is also taken from the research works in the context of multi-hop & MANET for scalable IoT clusters [17-18]. A Cross-protocol MPLS protocol scenario as suggested in the research paper is studied for designing wireless clusters for simulation [19].

C. Performance Analysis TCP Variants Tahoe, Reno and New Reno based on Scalability of the Network:

First Experiment is focused towards finding out the performance trend of *TCP Variants Tahoe, Reno and New Reno based on* "Scalability of the Network". We have considered different scale of networks to understand the performance of above mentioned TCP variants.

From the perspective of this paper, we have considered node density 2,5,10 and 20. Figure 3, 4, 5 and 6 show 2,5,10 and 20 nodes for IEEE 802.3 LAN IoT clusters respectively. Similarly for wireless scenario: Figure. 7, 8, 9 and 10 show 2,5,10 and 20 nodes for IEEE 802.11 WLAN IoT clusters respectively which are simulated in QualNet.

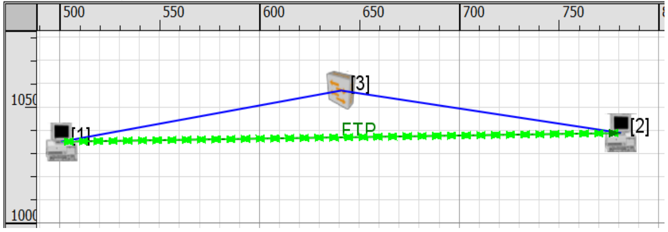


Figure 3. Simulation of 2 Nodes in wired network IEEE 802.3 MAC bus topology cluster using a single Switch

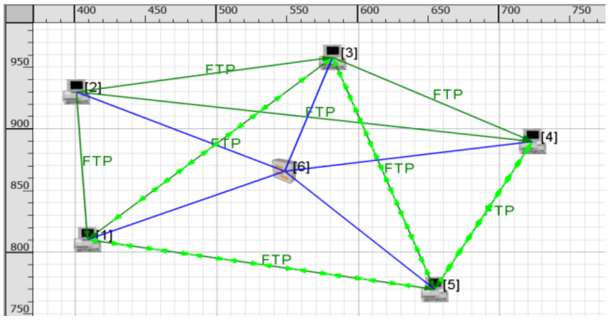


Figure 4. Simulation of 5 Nodes in wired network IEEE 802.3 MAC bus topology cluster using a single Switch

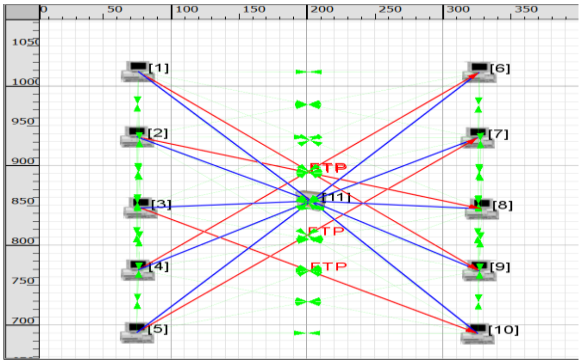


Figure 5. Simulation of 10 Nodes in wired network IEEE 802.3 MAC bus topology cluster using a single Switch

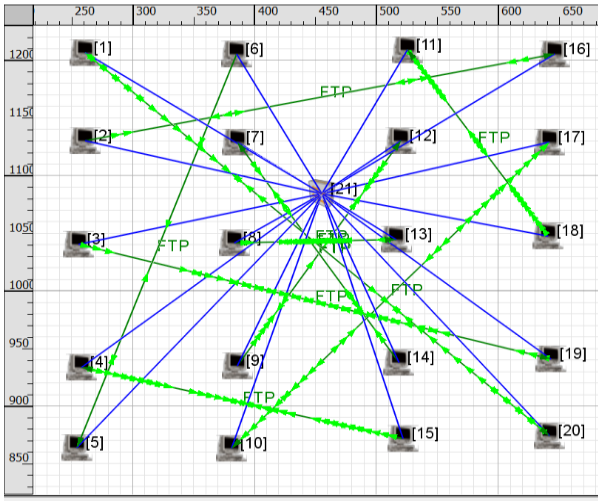


Figure 6. Simulation of 20 Nodes in wired network IEEE 802.3 MAC bus topology cluster using a single Switch

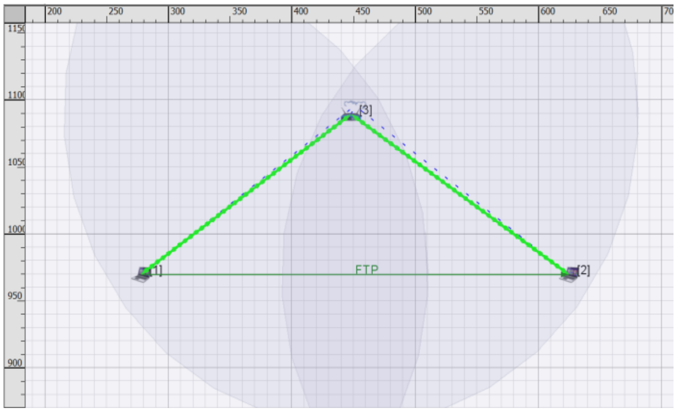


Figure 7. Simulation of 2 Nodes in wireless network IEEE 802.11 MAC PCF star topology cluster using a single access point as a point coordinator

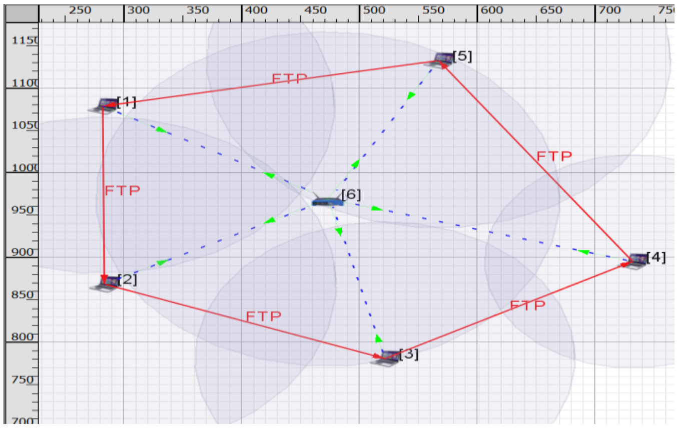


Figure 8. Simulation of 5 Nodes in wireless network IEEE 802.11 MAC PCF star topology cluster using a single access point as a point coordinator

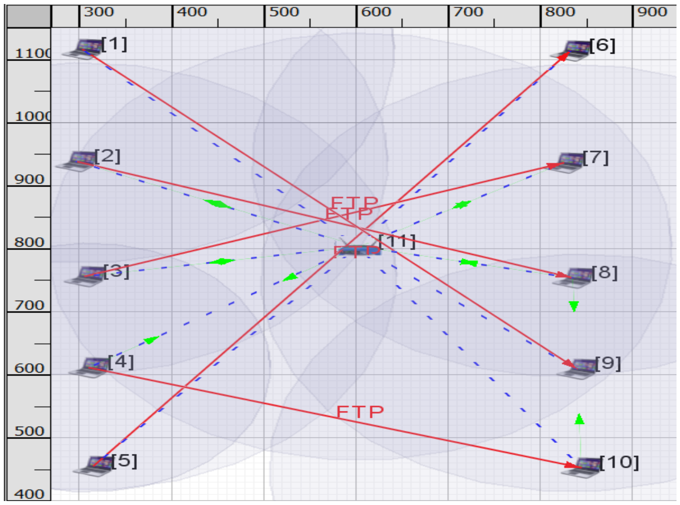


Figure 9. Simulation of 10 Nodes in wireless network IEEE 802.11 MAC PCF star topology cluster using a single access point as a point coordinator

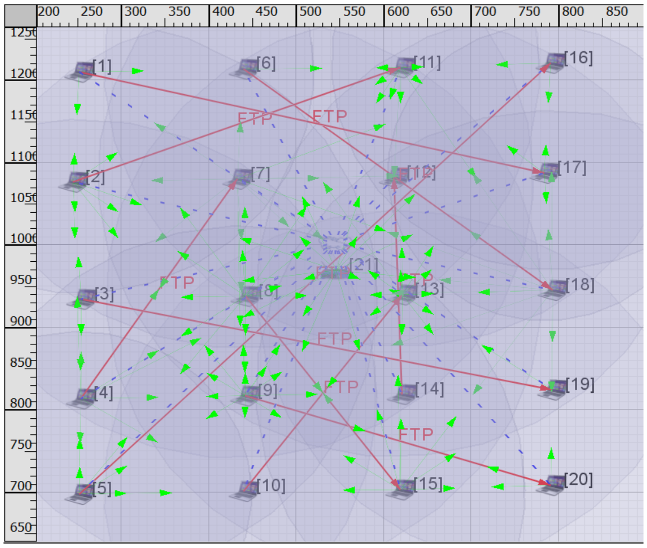


Figure 10. Simulation of 20 Nodes in wireless network IEEE 802.11 MAC PCF star topology cluster using a single access point as a point coordinator

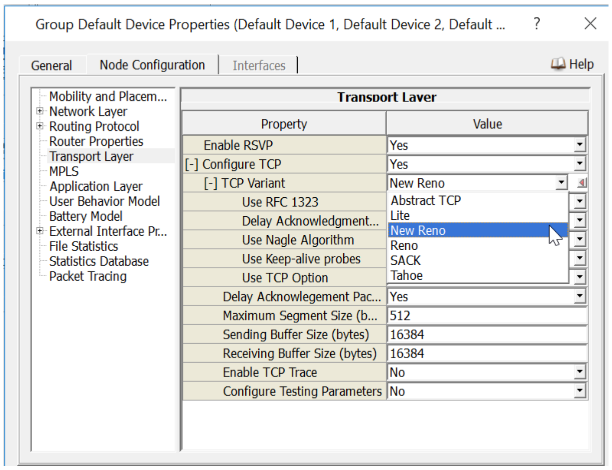
The simulations have been performed for the above mentioned node density for both wired and wireless scenarios. The performance of TCP Variants Tahoe, Reno and New Reno are measured by Throughput, End-to-End delay and PDR.

D. Performance Analysis TCP Variants Tahoe, Reno and New Reno based on Maximum Segment Size (MSS):

Second Experiment is focused towards finding out the performance trend of *TCP Variants Tahoe, Reno and New Reno based on “Maximum* Segment Size (MSS)”. From the scope of this paper, different segment Size is taken to understand the performance of above mentioned TCP variants. From the perspective of this paper, four different sizes of Maximum Segment Size (MSS) have been chosen for study are 512 bytes, 1024 bytes, 2048 bytes and 4096 bytes respectively.

These simulations have been performed for the above mentioned Segment Sizes for both wired and wireless and the performance of *TCP Variants Tahoe, Reno and New Reno* are measured by *Throughput, End-to-End delay and PDR.*

Figure 11 shows the Settings for Simulation parameters in QualNet 6.1 for configuring the Maximum Segment Size (bytes) for different variants of TCP Tahoe, Reno and New-Reno.



Transport Layer

Property	Value
Enable RSVP	Yes
[-] Configure TCP	Yes
[-] TCP Variant	New Reno
Use RFC 1323	
Delay Acknowledgment...	
Use Nagle Algorithm	
Use Keep-alive probes	
Use TCP Option	
Delay Acknowlegement Pac...	Yes
Maximum Segment Size (b...	512
Sending Buffer Size (bytes)	16384
Receiving Buffer Size (bytes)	16384
Enable TCP Trace	No
Configure Testing Parameters	No

Figure 11. Settings for Simulation parameters in QualNet 6.1 for varying the Maximum Segment Size (bytes) for different variants of TCP Tahoe, Reno and New-Reno

The IoT Network cluster size is kept constant as 7 nodes in a bus topology for IEEE 802.3 wired LAN and star topology for IEEE 802.11 WLAN with an access point as point coordinator. By keeping the node density constant only the maximum segment size is varied 512 ,1024, 2048 and 4096 bytes respectively.

IV. SIMULATION RESULTS

A. Performance results TCP Variants Tahoe, Reno and New Reno based on Scalability of the Network:

Three matrices have been considered to analyze the performance Throughput, Average End-to-End delay and Packet-Delivery-Ratio (PDR).

The simulation results are shown in this chapter. Figure 12, 13 and 14 shows the throughput, End-to-End delay and PDR respectively of IEEE 802.3 Wired LAN IoT cluster with one switch for TCP Variants Tahoe, Reno and New Reno.

Figure 15, 16 and 17 shows the throughput, End-to-End delay and PDR respectively of IEEE 802.11 Wireless LAN IoT cluster with one Access point for TCP Variants Tahoe, Reno and New Reno based on Scalability of the Network.

A.1. IEEE 802.3 Wired LAN IoT cluster with one switch:

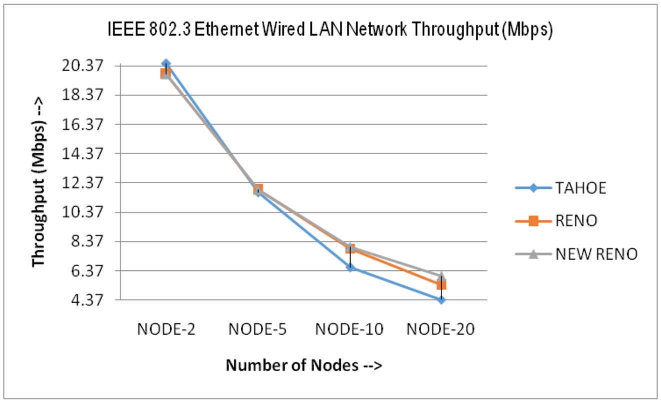


Figure 12. Throughput vs Node density in wired IoT cluster of IEEE 802.3 LAN (Bus topology) with one switch for different variants of TCP Tahoe, Reno and New-Reno

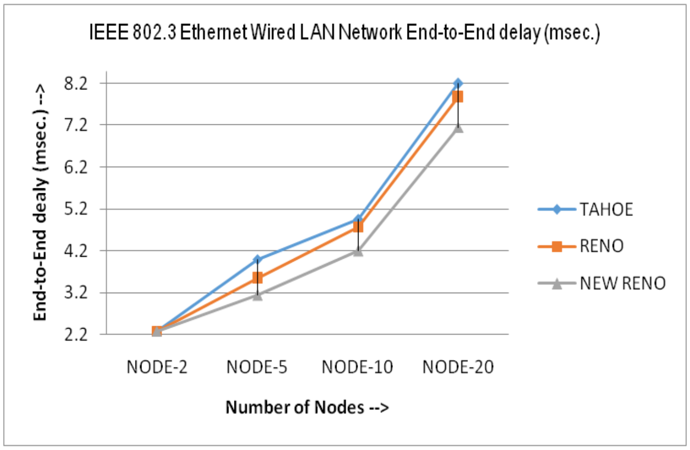


Figure 13. End-to-End delay vs Node density in wired IoT cluster of IEEE 802.3 LAN (Bus topology) with one switch for different variants of TCP Tahoe, Reno and New-Reno

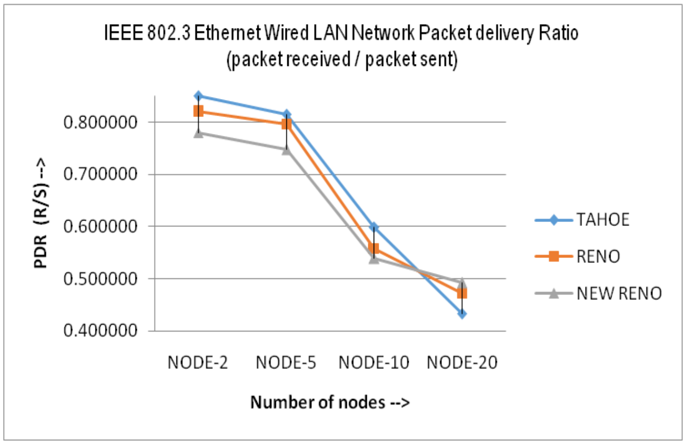


Figure 14. Packet delivery ratio vs Node density in wired IoT cluster of IEEE 802.3 LAN (Bus topology) with one switch for different variants of TCP Tahoe, Reno and New-Reno

A.2. IEEE 802.11 Wireless LAN IoT cluster with one access point as point coordinator:

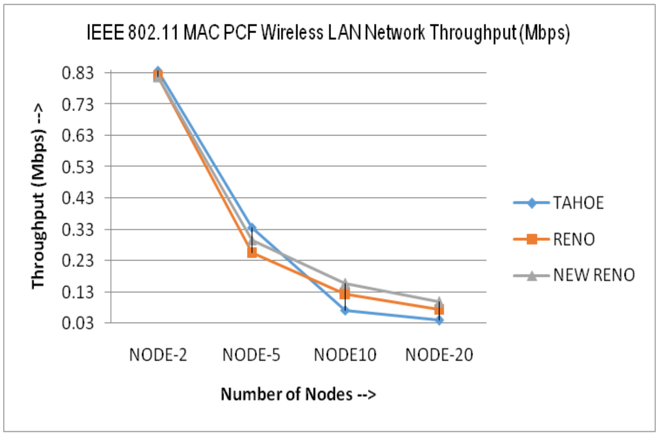


Figure 15. Throughput vs Node density in wireless IoT cluster of IEEE 802.11 WLAN (star topology) with one access point as a point coordinator for different variants of TCP Tahoe, Reno and New-Reno

Throughput calculation is given in the equation (3) below:

$$Throughput = \frac{Amount\ of\ data\ received\ \ (Mbits)}{Total\ simulation\ time} \qquad (3)$$

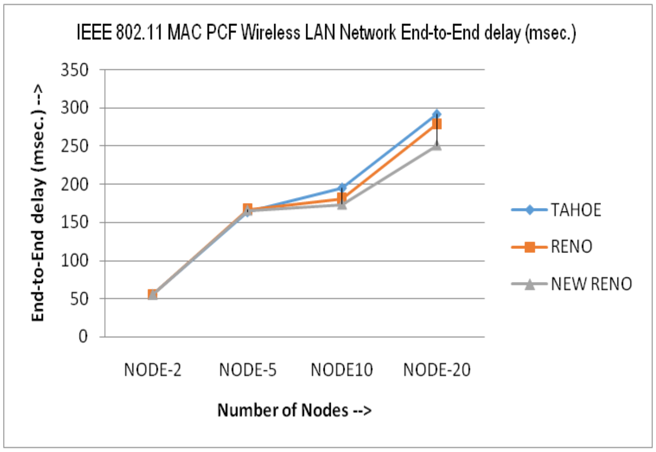


Figure 16. End-to-End delay vs Node density in wireless IoT cluster of IEEE 802.11 WLAN (star topology) with one access point as a point coordinator for different variants of TCP Tahoe, Reno and New-Reno

Average End-to-End delay calculation is given in the equation (4) below:

$$Average\ End-to-End\ delay = \frac{Total\ End-to-End\ delay\ by\ received\ packets}{Total\ Number\ of\ packets} \qquad (4)$$

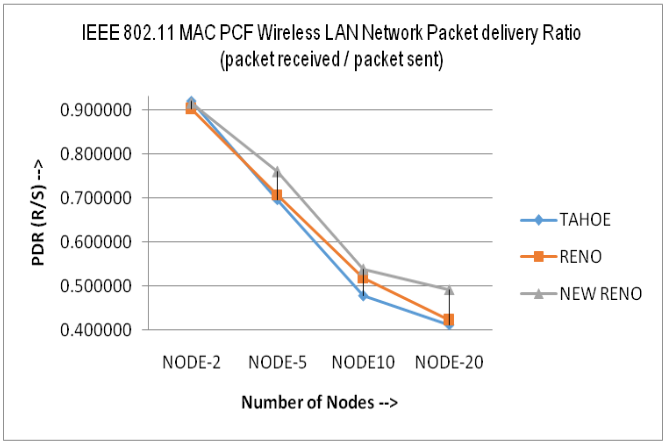


Figure 17. Packet delivery ratio vs Node density in wireless IoT cluster of IEEE 802.11 WLAN (star topology) with one access point as a point coordinator for different variants of TCP Tahoe, Reno and New-Reno

Packet Delivery Ratio (PDR) calculation is given by equation (5) as below:

$$PDR = \frac{Total\ number\ of\ packet\ received}{Total\ number\ of\ packets\ sent} \qquad (5)$$

B. Performance results TCP Variants Tahoe, Reno and New Reno Network based on Segment Size:

Figure 18, 19 and 20 shows the throughput, End-to-End delay and PDR respectively of IEEE 802.3 Wired LAN IoT cluster with one switch for TCP Variants Tahoe, Reno and New Reno with varying Maximum Segment Size of 512 , 2048 and 4096 bytes. .

B.1. IEEE 802.3 Wired LAN IoT cluster with one switch:

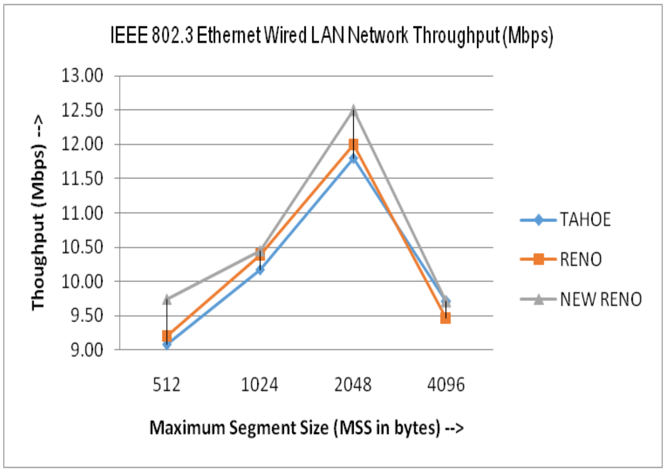


Figure 18. Throughput vs Maximum Segment Size (bytes) in wired IoT cluster of IEEE 802.3 LAN (Bus topology) with one switch for different variants of TCP Tahoe, Reno and New-Reno

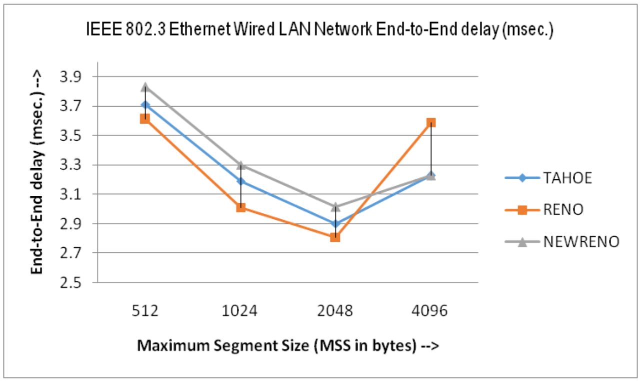


Figure 19. End-to-End delay vs Maximum Segment Size (bytes) in wired IoT cluster of IEEE 802.3 LAN (Bus topology) with one switch for different variants of TCP Tahoe, Reno and New-Reno

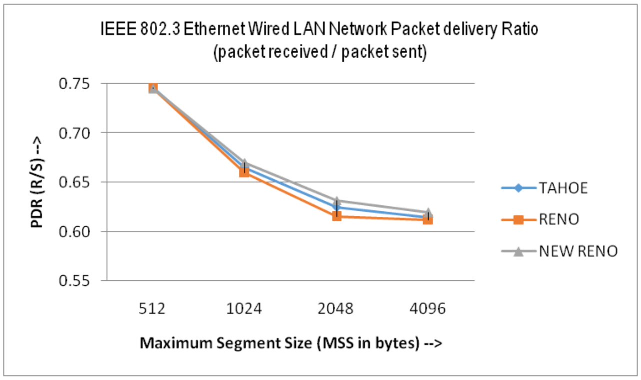


Figure 20. Packet delivery ratio vs Maximum Segment Size (bytes) in wired IoT cluster of IEEE 802.3 LAN (Bus topology) with one switch for different variants of TCP Tahoe, Reno and New-Reno

B.2. IEEE 802.11 Wireless LAN IoT cluster with one access point as point coordinator:

Figure 21, 22 and 23 shows the throughput, End-to-End delay and PDR respectively of IEEE 802.11 Wireless LAN IoT cluster with one Access point for TCP Variants Tahoe, Reno and New Reno based on Maximum Segment Size.

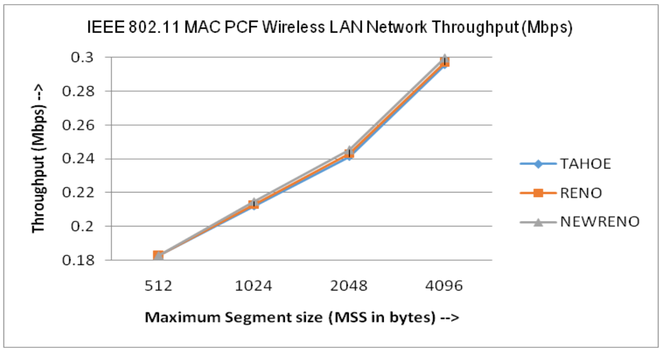


Figure 21. Throughput vs Maximum Segment Size (bytes) in wireless IoT cluster of IEEE 802.11 WLAN (star topology) with one access point as a point coordinator for different variants of TCP Tahoe, Reno and New-Reno

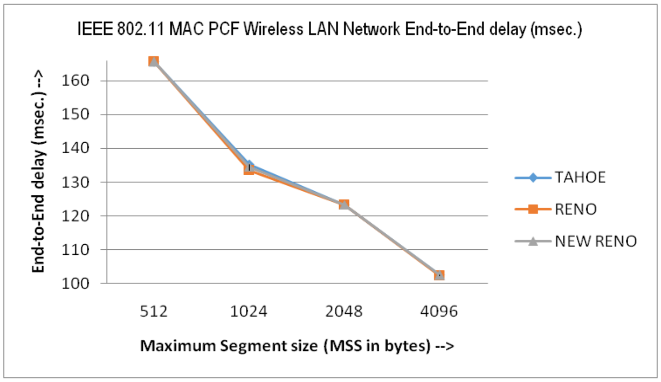


Figure 22. End-to-End delay vs Maximum Segment Size (bytes) in wireless IoT cluster of IEEE 802.11 WLAN (star topology) with one access point as a point coordinator for different variants of TCP Tahoe, Reno and New-Reno

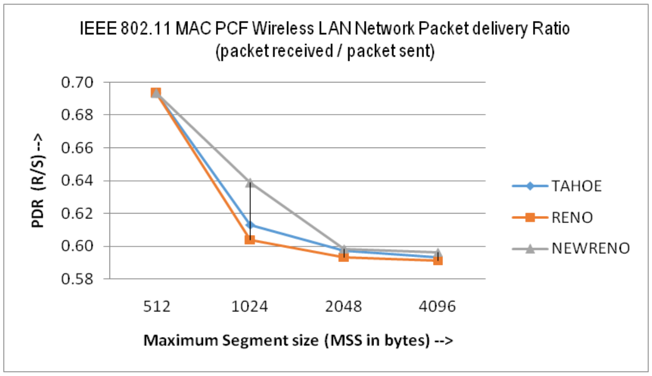


Figure 23. Packet delivery ratio vs Maximum Segment Size (bytes) in wireless IoT cluster of IEEE 802.11 WLAN (star topology) with one access point as a point coordinator for different variants of TCP Tahoe, Reno and New-Reno

V. RESULT ANALYSIS

A. Performance Analysis TCP Variants Tahoe, Reno and New Reno based on Scalability of the Network:

A.1. IEEE 802.3 Wired LAN IoT cluster with one switch:

The simulation result shows in IEEE 802.3 Ethernet IoT cluster scenario in Figure 12, TCP New-Reno is showing overall better throughput over Tahoe and Reno variants especially when the node densities increases. However, when the node density is very low i.e 2 nodes, only the Tahoe is slightly outperforming the Reno and New-Reno. This result proves the algorithm modification of Reno and New-Reno to deal with multiple packet loss. When the node density increases the traffic in the cluster increases hence it is more likely to have congestion in the network or eventually multiple packet loss. Under this circumstances, Reno with *fast-retransmit* and the New-Reno with *fast-recovery* algorithm are able to handle congestion and most particularly the *cwnd* size remain optimum to give better throughput. Whereas in End-to-End delay as shown in Figure 13, the New-Reno is showing overall less delay because of *fast-*

recovery algorithm. The Reno performs the second best with *fast-retransmit* and as predicted the Tahoe showing the maximum delay because it waits for time out in the pipeline.

The Packet-delivery-Ratio (PDR) as shown in Figure 14, the TCP Tahoe is showing better packet deliver ratio over Reno and New-Reno except when the node density increases above 10 nodes, the Tahoe shows sudden drop in PDR which can be justified by the packet drop for more congested scenario.

A.2. IEEE 802.11 Wireless LAN IoT cluster with one access point as point coordinator:

In wireless scenario, IEEE 802.11 MAC PCF WLAN IoT cluster as shown in Figure 15, when the node density increases and the network become more congested the New-Reno definitely outperforms the Tahoe and even Reno. For End-to-End delay as shown in Figure 16, after the node density increases beyond 5 nodes the New-Reno starts to dominate by showing minimum delay especially under high node density condition over Tahoe and Reno. Tahoe shows maximum delay for Node density 10 & 20, whereas Reno shows medium delay for these cases. Whereas in PDR as shown in Figure 17, all the TCP variants are showing poor results at higher node density. However TCP New-Reno is showing better PDR over Tahoe and Reno. We can see the congestion is more severe in case of wireless in comparison with wired scenario. Based on these 1st experiment results an optimum network size with node density 7 is selected to perform the 2nd experiment for analyzing the performance of TCP variants for varying Maximum Segment Size (MSS).

B. Performance Analysis TCP Variants Tahoe, Reno and New Reno Network based on Segment Size:

B.1. IEEE 802.3 Wired LAN IoT cluster with one switch:

In wired scenario an IEEE 802.3 Ethernet LAN IoT cluster with 7 nodes in bus topology is simulated with variable MSS. As shown in Figure 18, overall throughput of TCP Tahoe is least and TCP New-Reno performs the best in throughput. However all the variant shows optimum throughput at MSS of 2048 bytes. In case of End-to-End delay as shown in Figure 19, Optimum segment size is 2048 bytes showing least delay for all the variants. Tahoe outperforms New-Reno in delay marginally. However in case if PDR as shown in Figure 20, all the curves are mostly parallel to each other. Among all TCP variants New-Reno shows the best PDR followed by Tahoe and least being the Reno.

B.2. IEEE 802.11 Wireless LAN IoT cluster with one access point as point coordinator:

In wireless LAN scenario with IEEE 802.11 MAC PCF IoT cluster comprising of 7 nodes, firstly the throughput as shown in Figure 21 shows a gradual increment for all the TCP variant respectively. However in wireless scenario the TCP variants are not showing any significant difference in throughput over varying MSS. On the contrary the optimum Segment Size for maximum throughput has changed to 4096 bytes from that of the 2048 bytes in wired scenario and almost linear trend is observed. As shown in Figure 22, the End-to-End delay is least at MSS = 4096 bytes. Optimum Segment Size for minimum End-to-End delay has changed to 4096 bytes from 2048 bytes as that of wired scenario and almost linear and a negative slope curve is observed. As shown in Figure 23, the PDR of TCP New-Reno is showing comparatively best performance of PDR from MSS range of 512 to 2048 bytes. From 2048 to 4096 bytes all the TCP variants are showing almost similar results of least PDR as the MSS increases.

VI. CONCLUSION

As far the IoT reliable connection oriented End-to-End application is concerned like MQTT or RFC8323 for CoAP the TCP Tahoe performs the best for a smaller IoT cluster having less than 5 nodes in overall all performance matrices. However when the node density increases the Reno and New-Reno is more promising as it has better algorithms to handle multiple packet loss by implementing *fast-retransmit* and *fast-recovery* algorithms respectively. Particularly the wireless IoT network clusters the packet loss scenario is evident due the fact that wireless channel is noisier than wired having more BER. Further the IEEE 802.11 MAC is contention based and with increased node density the contention increases yielding more packet loss. Thus the simulation results shows the TCP Reno and New-Reno are outperforming the TCP Tahoe in case of more node density particularly in wireless scenario where there are more probability of packet loss. On the maximum Segment size case it is evident that the simulation results show 2048 bytes to be the best selectable case for such scenario. The simulation results are showing remarkable corroboration of theoretical concept and would be of great help in resource planning and deployment of network clusters for reliable applications such as MQTT, CoAP (RFC8323) based on TCP for different application specific requirements especially for IoT application networks.

ACKNOWLEDGEMENT

The simulation is done using scalable network’s QualNet® 6.1 in Wireless Communication & Networking Laboratory, School of Electronics Engineering, KIIT Deemed to be University, Bhubaneswar, India. The preparatory and statutory legal license belongs to the software owner. QualNet® software is used strictly for educational use in this paper.

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