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IPv6 Transition Measurements in LTE and VHT Wi-Fi Mobile Networks

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ABSTRACT Full digital connectivity of the Internet of Things (IoT) devices demands several requirements including high-speed networks and a large number of IP addresses. The long term evolution (LTE) and very high throughput (VHT) 802.11ac networks are among the alternatives that can fulfill the speed requirements. To provide a large number of IP addresses, in addition to IPv4, LTE and 802.11ac also support IPv6. However, while the full digital connectivity cannot be fulfilled by IPv4 due to its limited address space and failure to support the scalability of the IoT applications, another major problem is that the potential benefits of IPv6 for LTE and 802.11ac mobile networks are completely ambiguous. The issue is further increased along with the design complexities inherent in LTE and 802.11ac infrastructures. Therefore, there are increasing concerns for cellular carriers and mobile service providers regarding migration to IPv6-only and whether the users in LTE-IPv6-only and 802.11ac-IPv6-only networks can achieve better performance than IPv4. To address the challenges associated with deploying IPv6-only in LTE and 802.11ac networks and quantify the performance, this work proposes a model. The model consists of a simulation environment with four distinct networks: LTE-IPv6-only, LTE-IPv4-only, 802.11ac-IPv6-only, and 802.11ac-IPv4-only. The model is further extended by setting up a real-world testbed environment to include four networks for replication of those simulations. To assure the most comprehensive environmental evaluation of the model, 128 distinct scenarios are developed and implemented, and the results are obtained in terms of quality of service parameters. The testbed results are compared to those of simulations to precisely assess the model.

INDEX TERMS LTE, VHT, IPv6, QoS, Internet-of-Things (IoT).

I. INTRODUCTION

Currently, long term evolution (LTE) and very high throughput (VHT) 802.11ac are the most worldwide used standards in mobile network technology. The standards with their high capabilities, are able to meet the demands for a wide range of services from simply sharing and interchanging data (video streaming and voice over IP) for the end-users to more complicated services for smartphones, sensors in remote areas, and other communications devices in context of the Internet of Things (IoT) [1]. Regardless of the type, providing these services as well as their functionality depend entirely on the availability of digital connectivity which allows network-connected devices to speak to each other. The future concerns for full digital connectivity of billions of new IoT devices along with enormous growth in demanding the mobile services lead to the exhaustion of internet protocol version 4 (IPv4) addresses and in turn to the development of internet protocol version 6 (IPv6). Initially, the Internet content providers tested the IPv6 for a single day on June 8, 2011, which is called World IPv6 Day. Later, on June 6, 2012, which is called World IPv6 Launch day, IPv6 was permanently enabled [2]. IPv4 address depletion was the main reason for the development of IPv6 in which the IP addresses are 128 bits compared to 32 bits in IPv4. This provides a total of 2^{128} addresses which is massive enough to fulfill the high demands of full digital connectivity [3], [4].

Because IPv4 and IPv6 are incompatible, several transition techniques including dual-stack, tunneling, and translation have been developed [5], [6], consequently. In the dual-stack method, both IPv4 and IPv6 coexist on the network at the same time. This method is useful when the destination network can receive both types of protocols. The second method is tunneling in which the IPv6 packets are encapsulated inside IPv4 before transmission [7]. This method is used when the destination network is not able to use IPv6 and only accepts IPv4 packets. The third method is the network address translation and protocol translation (NAT-PT) in which the

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IPv6 packets are translated into IPv4 packets before transmission [8]. Due to the complexity of the latter method, the first two methods are the most common today.

Although the transition methods facilitate the migration to IPv6, they are the primary problem that causes the adoption of IPv6 goes much slower than it is expected [9]. The second problem of the slow transition is the cost of equipment. Because IPv6 is not backward compatible with IPv4, the content providers need to replace and upgrade their network equipment, which results in extra charges. The third problem of the slow transition is the common use of network address translation (NAT) protocol. The main reason for IPv6 development was the exhaustion of IPv4 address space. However, NAT protocol, as a low-cost solution, works efficiently for small enterprise networks who neither need massive amounts of IPs nor require to grow as large as the big organizations. Thus, instead of the massive change of the IPv6 transition, they simply use NAT to fulfill all their requirements [9].

The fourth problem of the slow transition is that many websites and virtual private networks (VPNs) are not upgraded to support IPv6 protocol. Hence, to use these services, the users have no choice other than making the connections over IPv4. The fifth problem is that IPv6 header is 40 bytes, which is twice of IPv4 and also IPv6 address is 128 bits, which is four times larger than IPv4. The larger size involved with every single packet affects the performance of the constrained networks in which the applications need to send small packets such as IPv6 over low-power wireless personal area networks (6LoWPAN).

Given these problems will justify the slow adoption of IPv6. On the other hand, due to the lack of enough knowledge about the possible practical benefits of IPv6 in the mobile networks, there is an increasing concern for the content providers for migration to IPv6-only networks. Considering the growing interest in LTE cellular and 802.11ac networks, the issue is further increased along with the design complexity attached to these networks. The cellular carriers and mobile service providers are not certain about the changes experienced by the end-users in LTE-IPv6-only and 802.11ac-IPv6-only networks. However, future concerns and demands make IPv6 upgrade necessary by the service providers. This, on the other hand, only happens by clearing any doubt and determining all the uncertainties related to IPv6 deployment in mobile networks which, in turn, requires precise design, measurement, and analysis and this work contributes to this direction as follows:

1) It proposes a model to solve the uncertainties by characterizing the performance of IPv6 and IPv4 protocols in LTE and 802.11ac mobile networks.

2) The model establishes a simulation environment with four distinct networks: LTE-IPv6-only, LTE-IPv4-only, 802.11ac-IPv6-only, and 802.11ac-IPv4-only. Each network contributes to different purposes. The model is further extended to include a real-world testbed environment, which also comprises four distinct experimental networks with the same characteristics as those simulations.

3) The model takes into consideration two important factors that can affect the IPv6 performance, including the size of the transmitted packets (small and large) and the type of the transport protocol including transmission control protocol (TCP) and user datagram protocol (UDP).

4) To precisely assess the model, a comprehensive comparison between the simulation and testbed results is performed. By focusing on the quality of service (QoS) [10], [11], the model provides an extensive set of scenarios (128 distinct scenarios: 64 in the simulation environment and 64 in the testbed environment). The primary purpose is to validate the model and analyze the effects that IPv6-only protocol has on LTE and 802.11ac networks compared to IPv4-only. The comprehensive and detailed model can be used by the content providers, cellular carriers, and mobile network operators to have a practical understanding of the strengths and weaknesses of IPv6 in LTE and 802.11ac mobile networks and in what extend its deployment can affect the performance of these networks. This, on the other hand, has an important impact on speeding up the IPv6 transition.

The rest of the work is organized as follow. Section 2 gives a brief overview of the related works. Section 3 introduces the model and implementation details including the simulation environment, testbed setup and environment, scenarios, and QoS parameters. Section 4 presents the simulation and testbed results followed by a discussion of the findings. Finally, the conclusions are made in section 5.

II. RELATED WORKS

Few comparative studies have examined different aspects and functionality of IPv4 and IPv6 in different underlying networks. In [12], the authors provide an experimental setup to compare Web performance on IPv4 and IPv6 networks in four leading cellular carriers, including T-Mobile, Verizon, AT&T, and Sprint. Several webpages are loaded over IPv4 and IPv6 to compare round trip time, latency, and page load time parameters. The results show that in terms of web performance, IPv6 outperforms IPv4. However, the work only considers webpages and does not investigate other types of traffic, QoS parameters, or Wi-Fi networks. The LTE networks and QoS parameters in the presence of IPv6 are discussed in [13]. The authors provide recommendations about the QoS impacts and improvement by the IPv6 introduction in mobile networks. However, the work does not provide any implementation and measurements.

The authors in [14] focus on the impact of the size of IPv6 header on LTE networks. IPv4 is compared against IPv6 with and without header compression. They discuss that the header compression can improve the LTE performance while no implementation and measurements exist in work. In [15], the performance of IPv4 and IPv6 in LTE networks are compared through an experimental testbed. The round trip time of TCP connections to a web server is measured, which shows the connection time takes much longer for IPv6 than IPv4. The work does not investigate other types of traffic, QoS parameters, or Wi-Fi networks.

Through experimental setup, a comparison of 802.11ac with 802.11n and wired with Wi-Fi in the presence of IPv6 is provided in [16] and [17], [18], respectively. However, the works do not take into account cellular networks. Four transition technologies are investigated in [19] for Ethernet networks without Wi-Fi or cellular networks consideration. The authors in [20] investigate the impact of wired equivalent privacy (WEP), wireless protected access (WPA), and WPA2 security protocols on throughput and loss ratio of 802.11ac network with IPv4 and IPv6. The results show that for the same security protocol, IPv4 provides better throughput than IPv6 protocol while both have zero packet loss. However, other performance metrics and cellular networks are not investigated. The impact of security protocols on 802.11ac with and without IPv6 is also investigated in [21].

The LTE and Wi-Fi are compared against each other in [22] but without IPv6 protocol. The Qualnet simulator is used in [23] to compare IPv4 and IPv6 in older wireless networks, including 802.11a/g and 802.11b. By focusing on human shadowing and movement, the impact on 802.11ac with and without IPv6 is investigated in [24]. The CPU utilization, round trip time, and throughput are investigated in Windows 8.1 and Windows Server 2012. The results show that human movement has more effect on IPv6 than IPv4. The impact of IPv6 on jumbo frames in Ethernet networks is investigated in [25]. Windows server and Ubuntu are used in testbed to measure round trip time, CPU utilization, delay, and throughput. However, the IPv4 results are not measured to be compared against the IPv6 results.

Looking at the prior research studies on IPv6 reveals their limitations. The main limitation is the lack of an effective model for assessing the demands of LTE and 802.11ac mobile networks and the potential benefits of IPv6 for their end-users. This indicates a need to understand various perceptions of IPv6 in mobile networks. Another apparent limitation is much of uncertainty that still exists about the relation between IPv6 and QoS of the end-users in mobile networks. These have been left with complete ambiguity, identifying of which are the main contributions of this work.

III. DESIGN PRINCIPLES OF THE MODEL

This section presents the details of the proposed model, which as a solution-based approach, aims to provide the essential information to solve the uncertainties related to QoS behavior differences of IPv6 and IPv4 in LTE and 802.11ac networks.

A. SIMULATION ENVIRONMENT

The open-source network simulator (NS3) is used to build a simulation environment. The environment contains four distinct networks, each for different purposes. The simulated networks include LTE-IPv6-only, LTE-IPv4-only, 802.11ac-IPv6-only, and 802.11ac-IPv4-only with the following details.

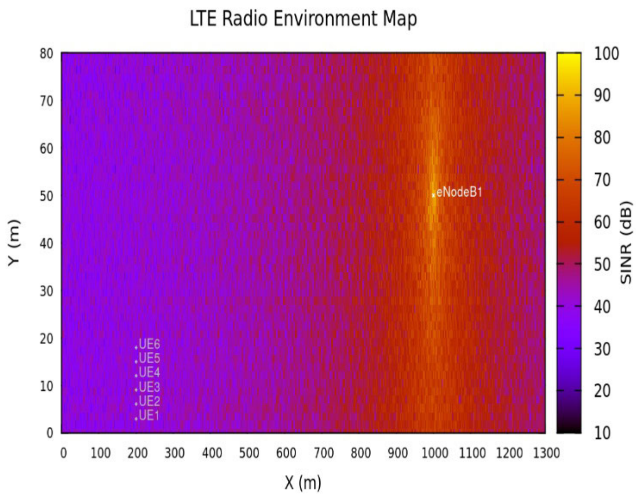

FIGURE 1. Radio Environment Map for UEs' position in LTE-IPv6-only.

1) LTE-IPV6-ONLY

The first network to simulate is LTE-IPv6-only for which a six-floor building is created. The height of each floor is 3m and six user equipment (UE) are placed individually on separate floors (each UE in one floor). Hence, the consecutive UEs are 3m apart vertically with the same 200m horizontal distance from x-axis. An eNodeB is created to which the UEs are attached and resides on the y-axis at 50m and the x-axis at 1000m. This means UEs are 800m horizontally far away from the eNodeB. The topology of the simulated network in the form of radio environment map (REM), which is a 2D heat map of the received signal strength for UEs and eNodeB, is presented in Figure 1.

In this network, the cell configuration is done as follows. The channel width is 20MHz by allocating 100 resource blocks. By considering the placement of the UEs, the Friis loss model is selected by the model which by analyzing the distance, will predict the received power level. The antenna configuration is chosen single input single output (SISO) because by default, wireless devices must comprise at least one antenna. The SISO is set by assigning zero to the transmission mode.

The direction of traffic is considered as downlink. Thus, a remote server is developed to transmit different types of data traffic to all six UEs simultaneously with the link bandwidth (LB) of 20Mbps. Moreover, here, the IPv6 stack is created on all the components, which enable the eNodeB, UEs, and server to communicate using only IPv6 protocol.

2) LTE-IPv4-ONLY

The second network to simulate is LTE-IPv4-only. It is designed with the exact same characteristics as LTE-IPv6-only network, but this time, the IPv4 stack is enabled on all the components to enable IPv4-only communications.

3) 802.11ac-IPv6-ONLY

The third network that the model includes is 802.11ac-IPv6-only. For the design purpose, six wireless stations (STA) with 802.11ac physical layer standard are created. Moreover, an 802.11ac access point is developed to which the STAs are connected. The STAs and access point are placed on the first floor of the building with 3m horizontal distance from each other. The IPv6 is the only stack that is created here on all devices including STAs, server, and access point. The configuration for loss model (Friis), channel number (40), channel width (20MHz), and the number of antennas (SISO) are done as well.

In order to transmission rate control, both LTE and 802.11ac networks select a modulation and coding scheme (MCS) index where a higher index means more data to transmit. While for LTE, the eNodeB selects MCS based on the current conditions of the channel, in 802.11ac we assign MCS index manually. From the existing ten indexes for MCS in 802.11ac network (0 to 9), we select 7 for backward compatibility of 802.11ac with the older devices and also because nine is forbidden when the channel width is 20MHz.

4) 802.11ac-IPv4-ONLY

The fourth network to simulate is 802.11ac-IPv4-only. It is created in the model with the same characteristics as 802.11ac-IPv6-only, but only the IPv4 stack is created on all the devices.

B. LABORATORY TESTBED SETUP

When designing a network model, the primary consideration is that it performs the intended functions in a correct, precise, and efficient manner. Simulations allow the researchers to explore different aspects of the network behaviors. However, due to model limitations and lack of real-world system devices, the simulation outcomes may not always reflect real-world results. On the other hand, testbeds, as alternatives to model the real-world scenarios, are solutions to complement the simulations. This does not mean testbeds are comprehensive because they also have their own practical limitations, particularly in wireless environments in which the results can be affected due to unpredictable environmental factors that are not controllable. With this in mind, we set up a lab testbed environment to experiment the scenarios in parallel to the simulation environment. The focus is mostly on the factors that are under control and common with our simulation environment. The lab in which we conduct the experiments is a 6-floor building (height of each floor is 3m) and that is why we also designed the same building in our simulation environment, as mentioned earlier. Similar to the simulation, the testbed environment contains four distinct networks, which are: LTE-IPv6-only, LTE-IPv4-only, 802.11ac-IPv6-only, and 802.11ac-IPv4-only with the following details:

1) LTE-IPv6-ONLY

In the first testbed network, to arrange our equipment in the lab building, we initially need to find the distance between the building and the eNodeB to which our LTE devices are connected. For this purpose, we use two Android applications called *Cell Tower v.1.2* and *Network Cell Info Lite v.4.19.5*. The distance shown by the two apps is about 1Km, and that is why the same distance was selected in the simulation environment, as mentioned earlier. There are six laptops (UEs) each placed in a floor of the lab building. The laptops all have LTE USB dongle attached, to provide cellular interfaces. The UEs all have *Kali Linux 2019* installed, and here IPv4 is disabled in the Kali network settings to have communications only based on IPv6. A *TP-Link Archer MR200* is placed on the second floor to attach all the six UEs to the eNodeB. The SIM card is inserted in the *MR200,* and its setting is configured similar to those simulation parameters. The channel width is also set on 20MHz. The traffic direction is downlink, hence, a new laptop with *Ubuntu 16.04*, is added to the network as the server. The server has LTE USB dongle interface to transmit different types of packets to the six UEs simultaneously with the link bandwidth of 20Mbps.

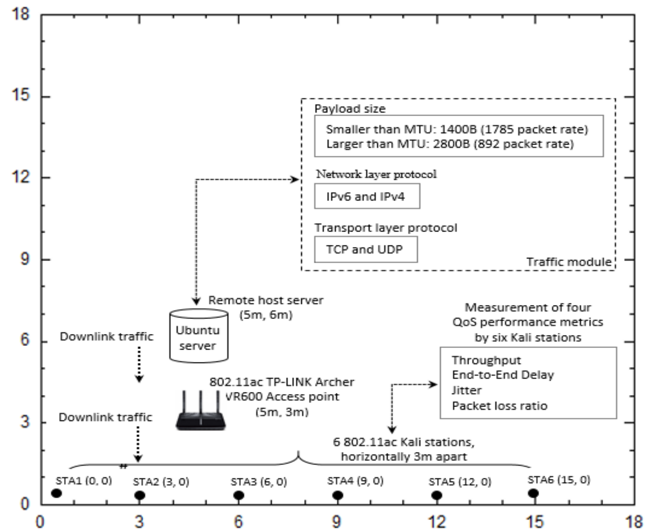

FIGURE 2. **802.11ac testbed setup.**

2) LTE-IPv4-ONLY

The second testbed network is LTE-IPv4-only network. It is designed with the same characteristics as LTE-IPv6-only testbed, but this time only IPv4 is enabled on the network settings.

3) 802.11ac-IPv6-ONLY

The third testbed network that the model includes is 802.11ac-IPv6-only. The *TP-LINK Archer VR600* access point is used to connect the six laptops (STAs) and Ubuntu laptop (server) using their built-in 802.11ac interfaces. Like the simulation environment, the STAs and access point are placed on the first floor of the laboratory building. The IPv6 is enabled in the network settings of the access point, server, and STAs. The arrangement of the components related to 802.11ac testbed along with the corresponding details is presented in Figure 2.

The testbed includes a remote host server (*Ubuntu 16.04*) on the second floor of the lab building residing on the y-axis at 6m and the x-axis at 5m. The Ubuntu server is used to transmit downlink traffic to the six 802.11ac STAs at the same time. For this purpose, the server comprises a traffic module by which different types of traffic flows with different specifications are generated. The module functionalities are done by the distributed internet traffic generator (D-ITG) tool. The downlink traffic of the server passes to the *TP-LINK Archer VR600* access point residing on the first floor on the y-axis at 3m and the x-axis at 5m. On this floor, there are also six 802.11ac STAs connected to the access point. The STAs (*Kali Linux 2019*) are located in a straight line so that the consecutive STAs are 3m apart from each other. Each STA is able to measure four performance metrics upon receiving the traffic.

4) 802.11ac-IPv4-ONLY

The fourth testbed network in the model is 802.11ac-IPv4-only. It has the same underlying technical properties of 802.11ac-IPv6-only, but it differs as only IPv4 is enabled on all the devices.

C. SCENARIO PLANNING

The model includes a variety of scenarios to measure and hence, gain further insight into the impact of IPv6 on the performance of LTE and 802.11ac networks. For this purpose, scenario planning is performed as follows.

1) For each scenario executed in the testbed environment, a similar scenario is executed in the simulation environment. For this purpose, the simulation parameters are configured accordingly to represent the values applied in the real testbed environment. Throughout this work, the acronym EXP denotes the testbed scenarios, and SIM refers to simulation scenarios.

2) For downlink traffic characteristics, the scenarios take into account different factors affecting the performance of mobile networks. The traffic flows, transmitted from the server to the six mobile users, are characterized by three following parameters:

2.1) Payload size (PS): the maximum transmission unit (MTU) of IPv6 packets is at least 1280 bytes [5]. Thereby, we select two different sizes for the payload of each packet: smaller than MTU *(PS = 1400B)* and larger than MTU *(PS = 2800B)*. The overhead attached to each individual payload in terms of the header of the layers from which it passes through falls into two parts. First, the common headers that are related to TCP/IP protocol suite, including physical (L1), data link (L2), network (L3), and transport (L4) layers. Second, the headers that are specific to the type of networks. Focusing on the common headers, the size of overhead caused by all the four layers (LO_{1to4}) is calculated by Eq. (1):

$$LO_{1to4} = L_1(Physical)+L_2(Ethernet) + L_3(Network)+L_4(Transport) \quad (1)$$

TABLE 1. The size of overhead caused by all the four layers (LO_{1to4}).

Layer overhead	$L_{3(Network)}$	$L_{4(Transport)}$	LO_{1to4}
$LO_{1TO4,\ TCP/IPv4}$	20	20	78 Bytes
$LO_{1TO4,\ TCP/IPv6}$	40	20	98 Bytes
$LO_{1TO4,\ UDP/IPv4}$	20	8	66 Bytes
$LO_{1TO4,\ UDP/IPv6}$	40	8	86 Bytes

TABLE 2. The size of total overhead caused by all the four layers (tO_{1to4}).

Packet size (PS)	Layers total overhead (TO_{1to4})	Size of total overhead (TO_{1to4})
1400B	$TO_{1TO4,\ TCP/IPv4}$	5.57%
	$TO_{1TO4,\ TCP/IPv6}$	7.00%
	$TO_{1TO4,\ UDP/IPv4}$	4.71%
	$TO_{1TO4,\ UDP/IPv6}$	6.14%
2800B	$TO_{1TO4,\ TCP/IPv4}$	2.78%
	$TO_{1TO4,\ TCP/IPv6}$	3.50%
	$TO_{1TO4,\ UDP/IPv4}$	2.35%
	$TO_{1TO4,\ UDP/IPv6}$	3.07%

By considering that the L1 (Physical) overhead is 20 bytes and L2 (Ethernet) is 18 bytes, the size of overhead caused by all the four layers (LO_{1to4}) is provided in Table 1.

Now given the *PS*, the total overhead (TO_{1to4}) attached to each payload sent over the network, is calculated by Eq. (2) and the calculated values are presented in Table 2.

$$TO_{1to4} = \frac{LO_{1to4}}{Payload\_size} \times 100 \quad (2)$$

2.2) Inter departure time (IDT) between consecutive packet transmission: is the rate at which the server transmits the packets for the users in LTE and 802.11ac networks. In all the scenarios, the IDT is selected constant. For each receiver *i,* the packets are transmitted at the rate of link bandwidth (LB_i) in bits per second with the payload size of PS_i in bits. Thus, the total number of payloads transmitted in the network per second (PPS_{tot}) and the total number of payloads transmitted by each user per second with 1400B and 2800B sizes (PPS_{tot1} and PPS_{tot2}, respectively) will be:

$$PPS_{tot} = \sum_{i=1}^{i=6} \left(\frac{LB}{PS}\right)_i = 6 \times \left(\frac{LB}{PS}\right) = \begin{cases} 6 \times PPS_{tot1} \\ 6 \times PPS_{tot2} \end{cases} \quad (3)$$

$$where:$$

$$PPS_{tot1} = \frac{20\times10^6(bps)}{1400\times8(b)} = 1785$$

$$PPS_{tot2} = \frac{20\times10^6(bps)}{2800\times8(b)} = 892$$

2.3) Type of transport protocol: LTE and 802.11ac networks are able to provide many different types of services such as VoIP, video, Internet access, and streaming each with different requirements. Some of these services are

TABLE 3. AAT limited by the layers' overheads.

Packet size (PS)	AAT's layer overheads	AAT (Mbps)
1400B	$AAT_{TCP/IPv4}$	113.66
	$AAT_{TCP/IPv6}$	112.15
	$AAT_{UDP/IPv4}$	114.60
	$AAT_{UDP/IPv6}$	113.06
2800B	$AAT_{TCP/IPv4}$	116.75
	$AAT_{TCP/IPv6}$	115.94
	$AAT_{UDP/IPv4}$	117.24
	$AAT_{UDP/IPv6}$	116.42

UDP-based and some are TCP-based. The structural difference between TCP and UDP as the two main types of transport protocols can directly affect the performance of the networks, and that is why their evaluation is essential. Keeping this in mind and with the aim of the model to be comprehensive, it takes into account both types of transport protocols.

3) For the performance evaluation purpose, the scenarios mainly focus on QoS parameters including throughput, end-to-end delay, jitter, and packet loss [4]. The per-flow (network flow over time) traffic are measured continuously as each data packet is received by the UEs and 802.11ac STAs to precisely monitor any QoS variation over the time for the mobile users. Moreover, while the per-flow measurements are important to specify the exact performance of the users, the average value of QoS parameters is also measured. On the other hands, since in all scenarios multiple data-flows arrive at the same destination, significant differences in the throughput values can be achieved. In such situations, the aggregate measurements are important to determine the entire network performance as a whole. For this purpose, we additionally measure the aggregated throughput in both LTE and 802.11ac networks to compare with the maximum achievable aggregated throughput (AAT) limited by the overheads mentioned in Eq. (1). The AAT is calculated by Eq. (4) and the calculated values are presented in Table 3.

$$AAT(Mbps) = \sum_{i=1}^{i=6} \frac{Payload\_size_i(B)}{Packet\_size_i(B)} \times LB_i(Mbps) \quad (4)$$

$$where:$$

$$Packet\_size_i = payload\_size_i + LO_{1to4}$$

As a summarizing, the scenario planning includes the following combinations: payload size (1400 and 2800 bytes with 1785 and 892 packet rates, respectively), type of transport protocol (TCP and UDP), type of network layer (IPv6 and IPv4), network standard (LTE and 802.11ac), four QoS performance metrics (throughput, delay, jitter, packet loss), and two environments (simulation and testbed). Consequently, the full design provided by the model includes 128 distinct scenarios to be conducted. The main details regarding the scenarios are summarized in Table 4 and Table 5.

TABLE 4. Testbed's parameters.

Hardware and Software Description (for testbed)	
LTE router	T-PLINK Archer MR200
802.11ac access point	T-PLINK Archer VR600
Sender (Server)	OS: Ubuntu 16.04 64-bit CPU: Intel® Core™ i7 @ 2.5 GHz RAM: 8GB Interfaces1: Intel ® Dual Band Wireless-AC Interface2: Huawei LTE USB dongle
Receivers (six UEs and six 802.11ac STAs)	OS: Kali 2019 64-bit CPU: Intel® Core™ i7 @ 2.5 GHz RAM: 8GB Interfaces1: Intel ® Dual Band Wireless-AC Interfaces2: Huawei LTE USB dongle
Cellular monitoring tool	Network Cell Info Lite v.4.19.5 and Cell Tower v.1.2
Traffic generator tool	D-ITG

TABLE 5. Scenarios' parameters.

Parameters Description (for both testbed and simulation)	
Payload size	1400B and 2800B
Transport layer protocol	TCP and UDP
Network layer protocol	IPv6 and IPv4
Network standard	LTE and VHT 802.11ac
MTU	1500B
Traffic profile	Constant bit rate (CBR)
Link bandwidth (LB)	20Mbps
Time duration	9s
Per device antennas	1
Channel number	40
Channel bandwidth	20MHz
Propagation Loss Model	FriisPropagationLossModel

IV. RESULTS AND DISCUSSIONS

This section presents the findings from the implementation of the simulation and testbed scenarios. The simulation results are compared to the results of the real testbed to provide a clear assessment of the reliability and validity of the model. Moreover, the results present the key points to answer the essential challenges and uncertainties of mobile service providers concerning the performance of IPv6-only LTE and 802.11ac networks.

A. LTE AND 802.11ac TCP THROUGHPUT

In order to identify the TCP throughput changes when deploying IPv6 in LTE and 802.11ac networks, we run the corresponding testbed (EXP) and simulation (SIM) scenarios. The throughput results for TCP flows with 1400 bytes' payload size (PS = 1400B) are presented in Figure 3.

Based on the results, the simulation and testbed show different throughput values. In the context of the LTE network, the throughput values are higher in the simulation

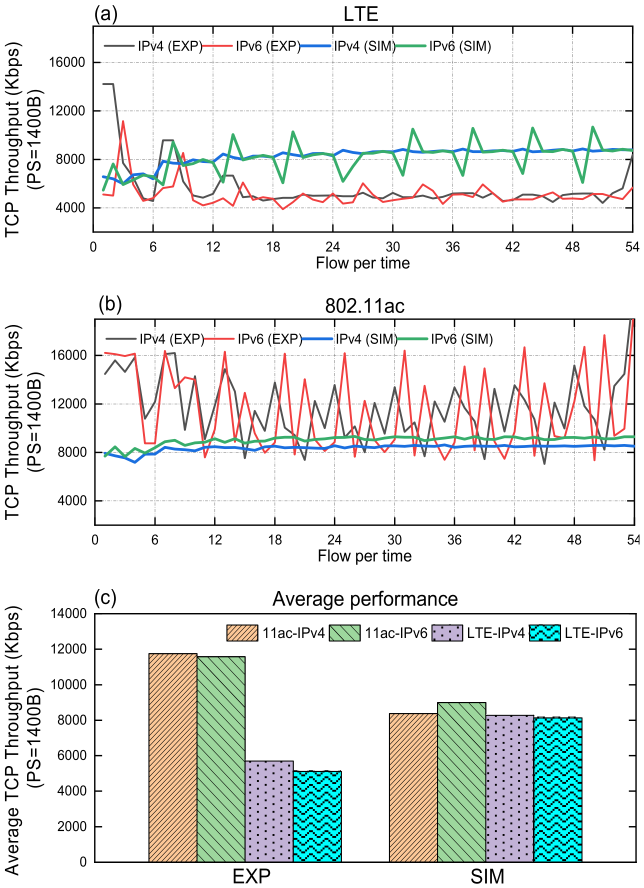

FIGURE 3. **TCP Throughput comparison with PS = 1400B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.**

environment than the testbed. In the LTE testbed, we observe that the throughput is higher at the beginning but it decreases as the time passes and then it increases at the end of the run time. This behavior is normal because as the number of packets increases in the network, they enter the queue to process by TCP. The average of simulated throughput for IPv6 and IPv4 in LTE network is 8127.089 Kbps and 8272.861 Kbps, respectively, compared to 5118.193 Kbps and 5703.496 Kbps in the testbed. Regarding the 802.11ac network, quite different results are observed as higher throughput is achieved in the testbed. The average of simulated throughput for IPv6 and IPv4 in the 802.11ac network is 8998.184 Kbps and 8374.475926 Kbps, respectively, compared to 11586.60741 Kbps and 11756.05926 Kbps in the testbed. As a result, the simulation and testbed results show no significant difference between the throughput of IPv6 and IPv4 in mobile networks.

In order to further analyze the IPv6 performance when the transmitted packets are larger than MTU, we change the TCP payload size to 2800 bytes. The per-flow throughputs obtained by the LTE and 802.11ac users are provided in Figure 4.

These results are consistent with those of smaller packets and show the close performance of IPv6 and IPv4. The results

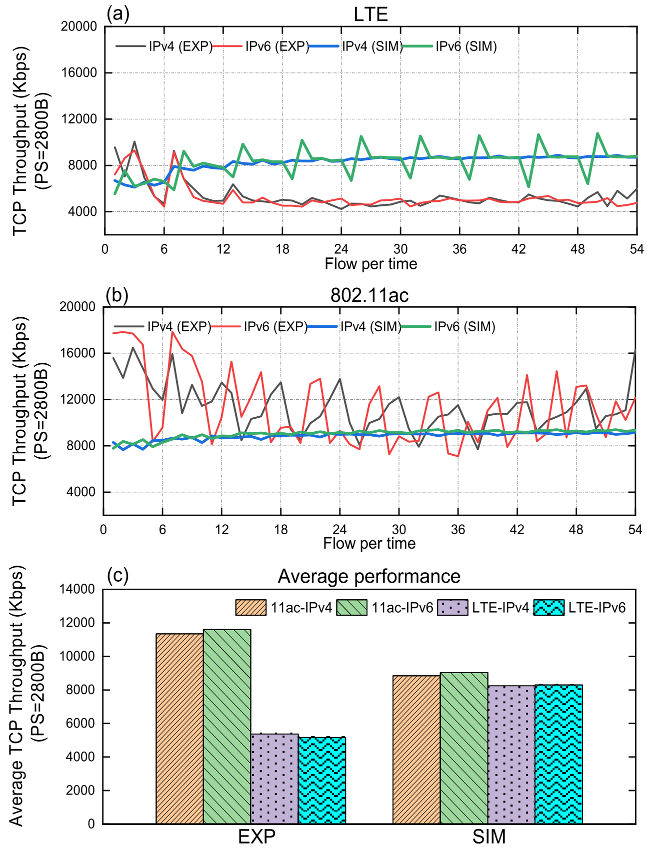

FIGURE 4. **TCP Throughput comparison with PS = 2800B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.**

suggest that increasing the packet size to double of what it was before, does not show remarkable throughput difference. Both the LTE and 802.11ac networks provide a similar amount of throughput as when the payload size is 1400B. The average of simulated throughput for IPv6 and IPv4 in the LTE network is 8293.891 Kbps and 8252.849 Kbps, respectively, compared to 5161.956 Kbps and 5368.119 Kbps in the testbed. In the case of the 802.11ac network, the average of simulated throughput for IPv6 and IPv4 is 9038.402 Kbps and 8845.084 Kbps, respectively, compared to 11597.808 Kbps and 11350.581 Kbps in the testbed.

The above scenarios are on a per-flow basis and identify the specific performance of each mobile user. Now, we extend the IPv6 analysis to the case in which the network performance is identified. For this purpose, we measure the aggregated throughputs in the testbed and simulation environments and then compare them with the achievable aggregated throughputs (AAT) calculated by Eq. (4). The TCP aggregated throughputs are shown in Figure 5.

Therefore, on the basis of all the findings, it is concluded that deploying IPv6 provides a similar amount of throughputs in LTE and 802.11ac mobile networks as IPv4. This assures the mobile service providers that IPv6 does not degrade the throughput performance of LTE and 802.11ac networks and they can fulfill the demands of delivering high bandwidth applications.

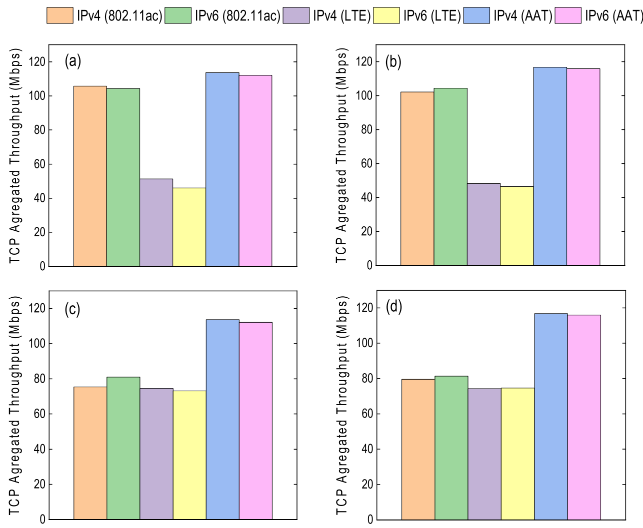

FIGURE 5. **TCP Aggregated Throughput: (a) testbed results vs. Analytical results for PS = 1400B, (b) testbed results vs. Analytical results for PS = 2800B, (c) simulation results vs. Analytical results for PS = 1400B, (d) simulation results vs. Analytical results for PS = 2800B.**

B. LTE and 802.11ac TCP PACKET LOSS RATIO

The scenarios in this section determine the IPv6 performance with a particular focus on the packet loss ratio (PLR). The 1400B TCP packets are transmitted in the LTE and 802.11ac networks with and without the presence of IPv6. The PLR results in the testbed and simulation environments are presented in Figure 6.

The findings of the above scenarios support the previous results. The testbed results show that IPv6 like IPv4 does not impose any packet loss to the LTE and 802.11ac networks. The PLR in both networks remains zero during the entire transmission time. In contrast, and contrary to expectations, the simulation results show a high number of lost packets just at the beginning of the time, which gradually decreases close to zero. The TCP is a reliable protocol and retransmits every lost packet. Moreover, the packet loss is mostly considered as a sign of a congested network. In all simulation scenarios, we consider 20Mbps link bandwidth in both LTE and 802.11ac, which is not that high to congest the networks. Given all these, the significant packet loss obtained at the start of the simulation results (about 12%) is not an acceptable value [26].

The difference between PLR values in the LTE and 802.11ac is not substantial and they are quite close. Measuring the average of simulated PLR caused by IPv6 in both LTE and 802.11ac networks shows 2% compared to 3% for IPv4. Generally, depending on the type of applications and networks, the acceptable rate of PLR will vary. However, it is a general agreement that the PLR lower than 3% is acceptable [26] and can go unnoticed while the rates above that cause the ill effects to be evident on the QoS performance of the corresponding applications [26]. Given this show that the average of simulated PLR in the LTE and 802.11ac networks for both IPv6 and IPv4 fall into an acceptable range.

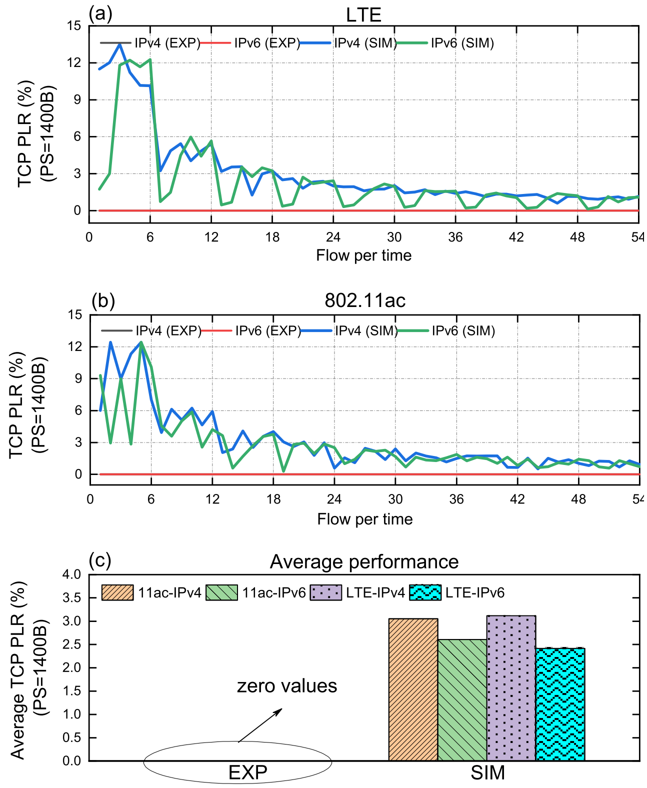

FIGURE 6. **TCP Packet loss ratio comparison with PS = 1400B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.**

The LTE and 802.11ac both are reliable high-speed networks. In our model, the focus is mainly on the IPv6 performance. Therefore, extra factors affecting the speed, including large number of users in high-density environments have been eliminated. The model for both simulation and testbed considers six users with 20Mbps speed, which both LTE and 802.11ac networks can perfectly handle with no load stress. Thereby, testbed results show no packet loss for TCP compared to 3% in simulation, which is also a low number.

In an attempt to further investigate the PLR of LTE and 802.11ac in the presence of IPv6, the size of payload increases to 2800B and the results are presented in Figure 7.

The present findings are consistent with the previous PLR results and show zero interruption for packet transmission in the testbed environment for both LTE and 802.11ac networks. However, like before, the simulated results show noticeable PLR when the simulation starts and then after one second, a remarkable reduction occurs, which in the middle of simulation time reaches to the lowest rate, about 1%. The highest PLR at the beginning of the simulation is due to the fact that because of the complexity of LTE and 802.11ac mobile networks, the simulator cannot include all the factors that exist and affect the real-world scenarios.

Measuring the average of simulated PLR caused by IPv6 in the LTE network shows 2% compared to 3% for IPv4 and it is 2% in the 802.11ac network. Taken together, these results suggest that the average of PLR falls into an acceptable

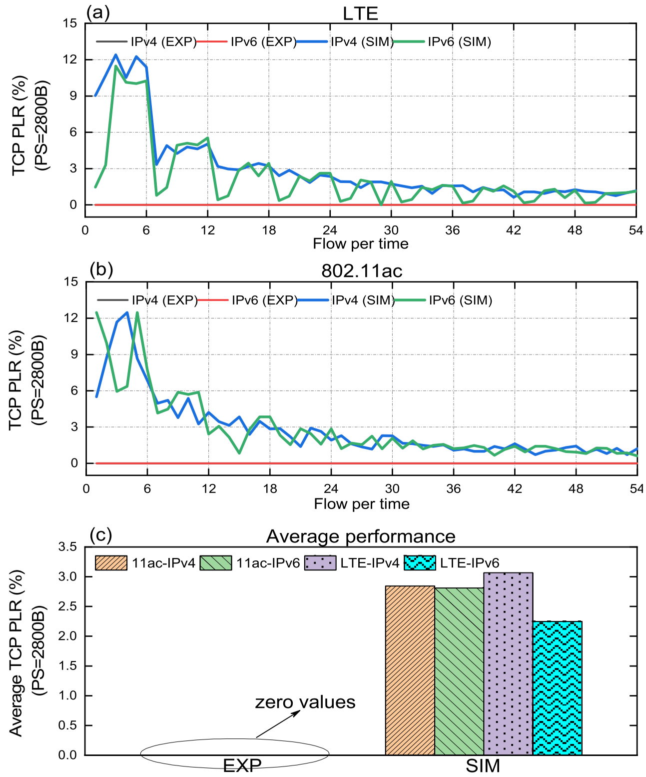

FIGURE 7. TCP Packet loss ratio comparison with PS = 2800B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.

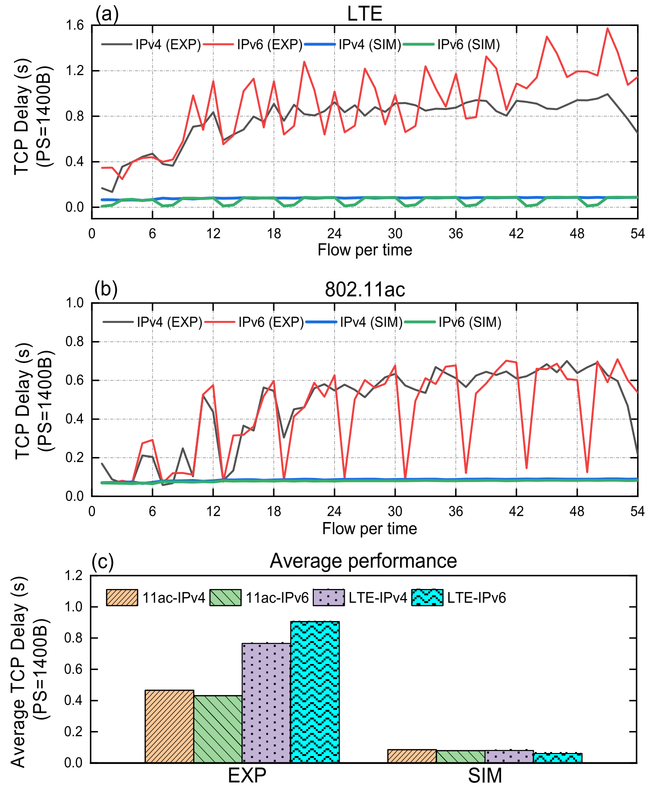

FIGURE 8. TCP Delay comparison with PS = 1400B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.

range [26] with no noticeable impact on the QoS in LTE and 802.11ac networks.

C. LTE and 802.11ac TCP DELAY

With respect to QoS parameters, particularly the delay, the present scenarios demonstrate findings of the delay that LTE and 802.11ac users experience with and without IPv6. The testbed and simulation delay results for a payload size of 1400 bytes are presented in Figure 8.

The results from performing the testbed scenarios indicate that UEs in the LTE network experience higher delay when IPv6 packets are transmitted compared to IPv4. In this case, the average delay of IPv6 packets is 0.905s, which is higher than 0.766s for IPv4 packets. On the contrary, a slight improvement in the performance of 802.11ac STAs in terms of less delay is identified when the IPv6 protocol is used. The average delay of IPv6 packets is 0.431s compared to 0.466s for IPv4.

Further analysis of the corresponding simulation scenarios is significant in two major aspects. The first is that the differences in the performance in terms of delay are statistically significant. The delay calculated in the simulation scenarios is much less than the delay measured in the testbed scenarios. The average of simulated delay for IPv6 and IPv4 in the LTE network is 0.061s and 0.080s, respectively, compared to 0.079s and 0.085s in the 802.11ac network. Comparing these delay values with the delays measured in the testbed show substantial differences. The inter-flow interference can result in performance reduction, which is not a problem for simulators and cannot be captured properly by them. The second major finding is that while the testbed results denote significant delay differences between the LTE and 802.11ac networks, the simulation results imply no substantial difference between them.

Building on these results, we proceed to further analysis of larger IPv6 packets (PS = 2800B). The testbed and simulation delay results are presented in Figure 9.

The results are in line with the delay results of the smaller packets and show that apart from the differences between the simulation and testbed results, the results are confirmation of a higher delay in LTE network than 802.11ac. The results also confirm that increasing the packet size to twice its original size does not induce noticeable changes in the amount of delay. The average delay of IPv6 measured in the LTE testbed is 0.832s compared to 0.766s IPv4 delay.

Regarding the 802.11ac network, the IPv6 and IPv4 packets in the testbed have an average delay of 0.531s and 0.557s, respectively. With respect to the simulation results, the IPv6 packets in the LTE networks have less delay than IPv4 packets. In this case, IPv6 has an average delay of 0.058s compared to 0.079s delay of IPv4 packets.

The same conclusion is also confirmed in the 802.11ac simulation environment as having less delay for IPv6 than IPv4. In this case, the average delay of IPv6 is 0.079s compared to 0.083s for IPv4 packets. Given all these results, it is concluded that the differences between the delay of IPv6 and IPv4 are not significant in LTE and 802.11ac networks.

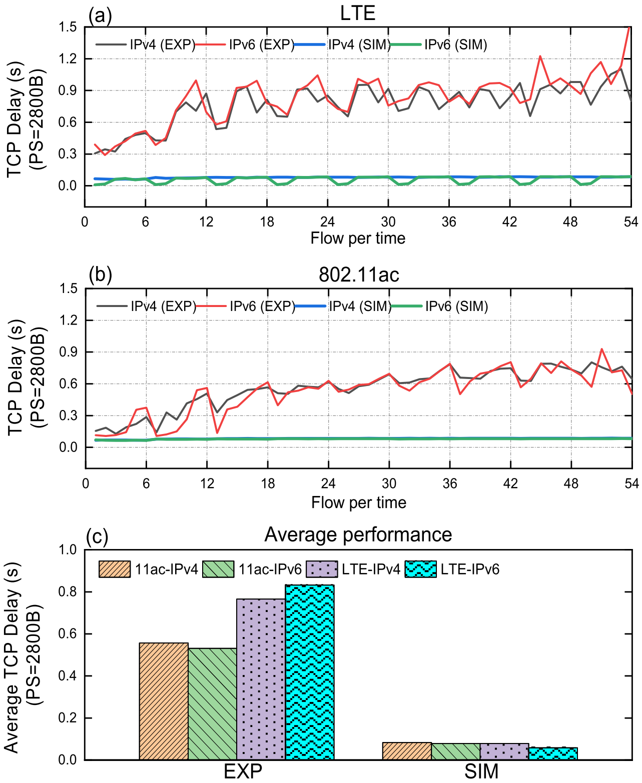

FIGURE 9. **TCP Delay comparison with PS = 2800B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.**

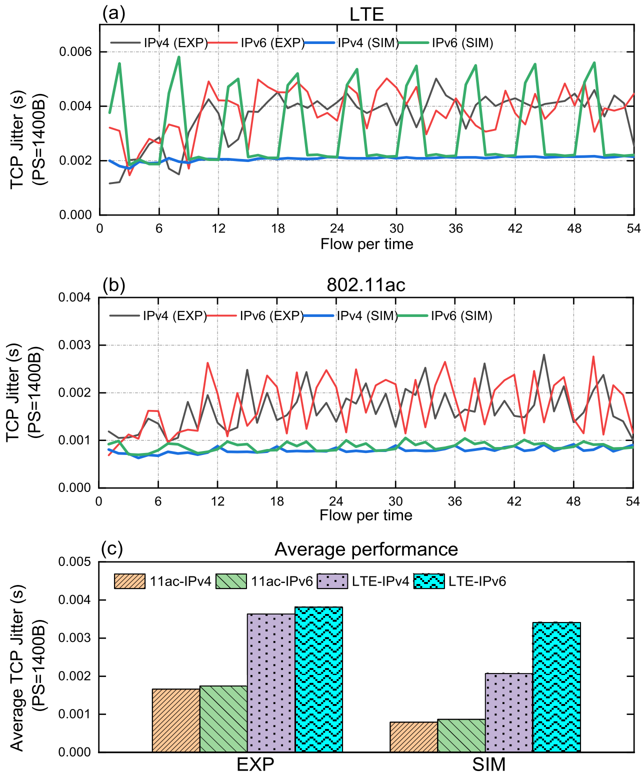

FIGURE 10. **TCP Jitter comparison with PS = 1400B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.**

D. LTE AND 802.11ac TCP JITTER

The scenarios in this section are prepared in accordance with the jitter parameter. First, we implement the testbed scenarios to determine the correlation between the IPv6 protocol and jitter in LTE and 802.11ac networks. Subsequently, the simulation scenarios are carried out and jitter results are obtained to further be compared against the testbed results. The jitter results with regard to 1400 bytes TCP payloads are presented in Figure 10.

It can be seen that the LTE testbed results match well with the simulation results, while in the 802.11ac network, there is a slight difference. The general recommendation is that the upper limit for acceptable jitter value is 0.03s. The jitter shows variation in the delay of the received packet and in essence, it is a measure of the quality of the connections in the networks. The high jitter values can lead to significant degradation of quality. The higher the jitter values, the more inconsistent the response times are, which damage the reliability of the networks and the performance of the real-time applications.

Looking at the graphs shows that the jitter values in both the testbed and simulation environments fall within the acceptable range. The average jitter of IPv6 and IPv4 in the LTE testbed is 0.0038s and 0.0036s, respectively compared to 0.0034s and 0.0021s in the simulation. These findings show a higher jitter for IPv6 packets than IPv4 in the LTE network. As regards the 802.11ac network, the average jitter of IPv6 and IPv4 in the testbed is equal to 0.0017s compared to 0.0009s and 0.0008s in the simulation. These results prove that the jitter difference between IPv6 and IPv4 is negligible, and thus IPv6 does not have an ill effect on the jitter in LTE and 802.11ac mobile networks [26].

To proceed with further testing, we extend the IPv6 performance evaluation by increasing the payload to twice its original size as 2800 bytes. The jitter values measured in the testbed and simulation environments are demonstrated in Figure 11.

The analysis reveals the correlation between the jitter value and the size of packets and clearly confirms that increasing the size of packets leads to increasing the jitter values. The average jitter of IPv6 and IPv4 in LTE testbed is 0.0072s and 0.0068s, respectively. These findings are in contrast with the simulation jitter, which for IPv6 and IPv4 is 0.0033s and 0.0021s, respectively. Despite the inconsistency, both the simulation and testbed results confirm a higher jitter for IPv6 compared to IPv4 in the LTE network.

Extending the assessment to the 802.11ac network provides two major findings. First, the jitter of IPv6 in the 802.11ac network is lower than in the LTE network. The second finding is that the difference between the jitter of IPv6 and IPv4 is less in the LTE network compared to the 802.11ac. The average jitter of IPv6 and IPv4 in the 802.11ac testbed is 0.0031s and 0.0030s, respectively. With regard to the simulation environment, the jitter values are equal to 0.001s. By considering all the jitter results together, it is concluded that while IPv6 protocol increases the jitter value

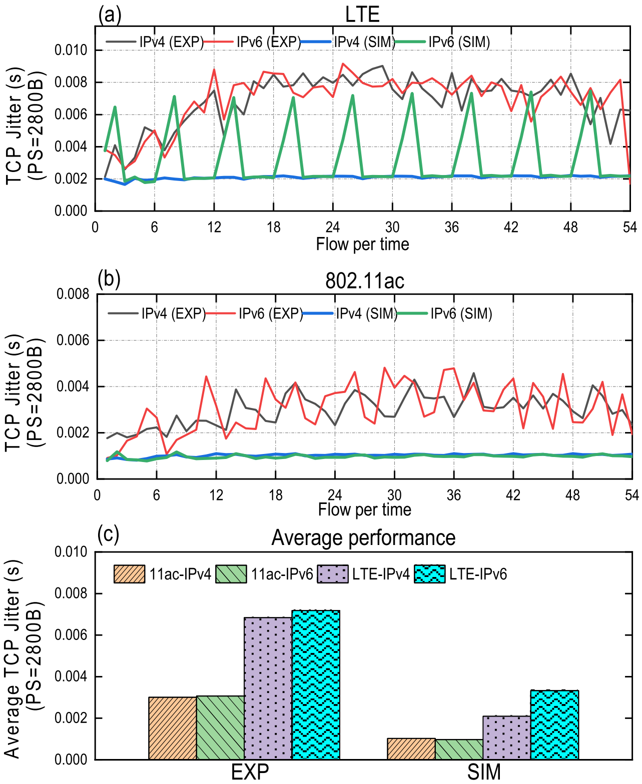

FIGURE 11. **TCP Jitter comparison with PS = 2800B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.**

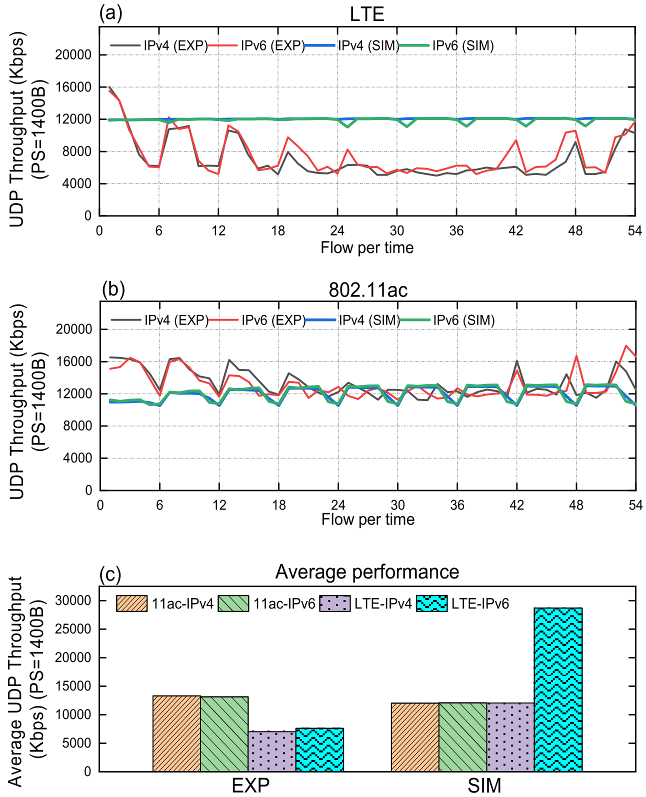

FIGURE 12. **UDP Throughput with PS = 1400B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.**

compared to IPv4 in LTE and 802.11ac networks, the values are still inside the acceptable range [26], which means IPv6 will not harm the performance of real-time applications in terms of jitter.

E. LTE AND 802.11ac UDP THROUGHPUT

The testbed and simulation scenarios in the previous sections widen our knowledge of IPv6 performance for TCP packets in LTE and 802.11ac networks. On one hand, TCP as a reliable protocol includes various techniques such as acknowledgment, retransmission, and large header to provide this reliability, and on the other hand, these induce extra overheads to the networks. To mitigate these extra overheads, the UDP protocol is used instead. Thus, further data collection is required to determine exactly how IPv6 affects UDP applications. For this purpose, the model includes the second group of scenarios. In contrast to the first group, the second group of scenarios is related to the generation of UDP connections instead of TCP. The UDP scenarios make a benchmark of IPv6 and IPv4 between testbed and simulation to determine in what extent IPv6 affects the performance of mobile users in LTE and 802.11ac networks. This section states the findings with respect to the IPv6 throughput for UDP packets in LTE and 802.11ac networks. The UDP throughput results for the payload size of 1400 bytes are presented in Figure 12.

The present findings have two important implications. First, there is a substantial difference between the testbed and simulation results in the LTE network, which is in contrast to the perfect match in the 802.11ac network. Second, regardless of the environment, IPv6 results outperform the IPv4. In respect to the LTE network and despite having different results, both the testbed and simulation confirm a better performance of IPv6 than IPv4 in terms of higher throughput. In the LTE testbed environment, the IPv6 users experience the average throughput of 7603.14 Kbps compared to 7030.69 Kbps for the IPv4 users. The average throughput of IPv6 in the LTE simulation is 28681.07 Kbps while IPv4 achieves 12051.29 Kbps. When it comes to the 802.11ac network, the testbed results tie well with the simulation results wherein a complete match is identified. Regards to the 802.11ac testbed, the measurement of IPv6 throughput shows 13145.69 Kbps compared to 13325.30 Kbps for IPv4. Relevant to the 802.11ac simulation results, the average IPv6 throughput is 12079.58 Kbps compared to 12023.95 Kbps for IPv4 protocol.

In view of these findings, it can be concluded that when small UDP packets are transmitted in LTE and 802.11ac networks, IPv6 performs better than IPv4. In order to determine if the same conclusion can be applied for the larger UDP packets, further data collection is required. Therefore, we carry out another set of scenarios to provide additional insight into the performance of IPv6 when 2800 bytes UDP packets (PS = 2800B) are transmitted in the LTE and 802.11ac networks. The results are presented in Figure 13.

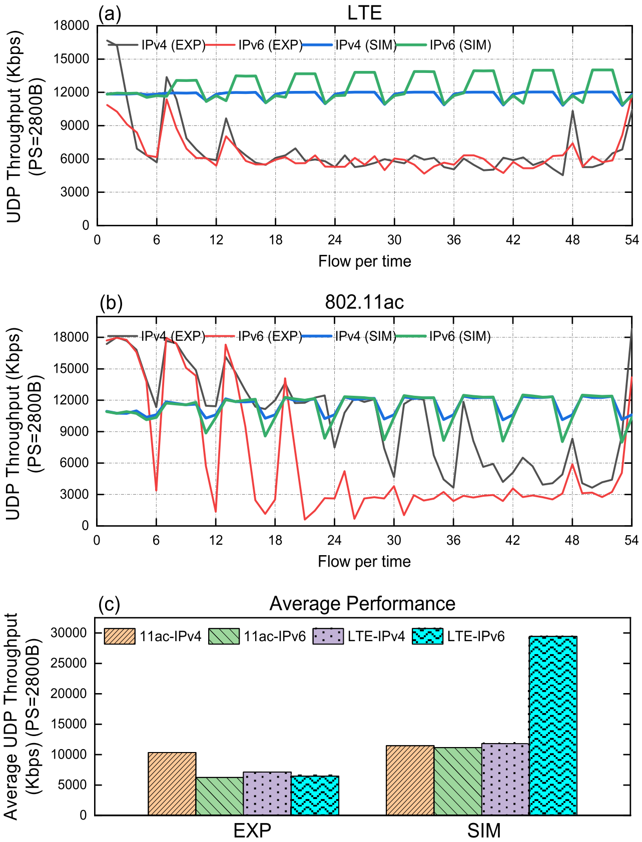

FIGURE 13. UDP Throughput with PS = 2800B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.

The testbed results show a negative impact of the large packets on the UDP throughput of 802.11ac users so that as the size increases, the throughput decreases. Moreover, the reduction is more significant for IPv6 than IPv4. The IPv6 average throughput in the 802.11ac testbed is 6225.96 Kbps compared to 10358.76 Kbps for IPv4. Comparing these results with results of the smaller UDP packets show 52% and 22% throughput reduction for IPv6 and IPv4, respectively. This proves susceptibility of IPv6 to the larger packets in 802.11ac networks. In the context of the LTE network, the testbed results show that the larger packets cause little to no harm to the UDP throughput for both IPv6 and IPv4. The IPv6 throughput in the LTE testbed is 6443.73 Kbps, which is very close to 7136.89 Kbps as IPv4 throughput.

In relation to the simulation results, we can see that even though some results differ from the testbed, a similar pattern is obtained, which is a reduction of throughput as the size of UDP packets grow. With regards to the 802.11ac network, the average of the simulated throughput is 11168.94 Kbps for IPv6, which is close to 11462.02 Kbps throughput for IPv4. In contrast, the LTE simulation results show two important findings. First, there is a significant difference between IPv6 and IPv4 throughput of the larger packets, second, increasing the size of packets does not have a substantial impact on the UDP throughput. In this case, the LTE simulated throughput is 29442.33 Kbps for IPv6, which is

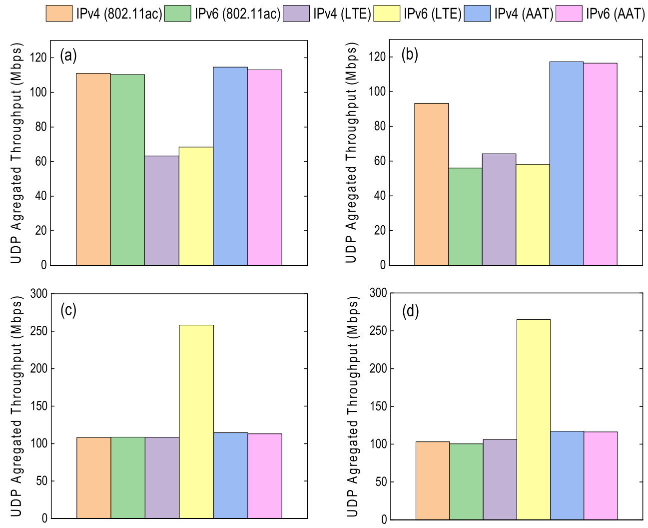

FIGURE 14. UDP Aggregated Throughput: (a) testbed results vs. Analytical results for PS = 1400B, (b) testbed results vs. Analytical results for PS = 2800B, (c) simulation results vs. Analytical results for PS = 1400B, (d) simulation results vs. Analytical results for PS = 2800B.

significantly higher than 11802.18 Kbps throughput for IPv4. The conclusion drawn on the basis of both the testbed and simulation findings implies that UDP throughput is considerably higher than TCP for both IPv6 and IPv4 in LTE and 802.11ac networks. Moreover, larger packets cause more throughput reduction for IPv6 compared to IPv4 while the reduction is higher for UDP than TCP. A comparison between the aggregated throughputs and achievable aggregated throughputs (AAT) is also provided in Figure 14.

F. LTE AND 802.11ac UDP PACKET LOSS RATIO

The scenarios in this section aim to assess the PLR rate of IPv6 experienced by the mobile users in LTE and 802.11ac networks during transmission of UDP packets. The PLR results for 1400 bytes UDP payloads are provided in Figure 15.

This graph is quite revealing in several ways. Initially, we can see that, like TCP results, the PLR is significantly higher in the simulation than the testbed networks. Moreover, while the TCP protocol in the testbed environment provides zero PLR for both IPv6 and IPv4 in the LTE and 802.11ac networks, we find the higher PLR rates for the UDP packets. In this case, IPv6 has smaller PLR than IPv4 in both networks. With respect to those results reported by the LTE, the PLR of IPv6 is 0.015% compared to 0.153% for IPv4. Meanwhile, in the 802.11ac testbed, the IPv6 PLR rate is 0.961%, which is lower than 1.2% for IPv4. Following the simulation results also confirms the testbed results show lower PLR for IPv6 than IPv4. The LTE mobile users experience 41.968% PLR using IPv6, which is in contrast to 46.663% PLR of IPv4. Similarly, the 802.11ac simulation results show having 46.886% PLR for IPv6 users, which is slightly lower than 46.184% for IPv4. Despite their difference, as mentioned before, the PLR obtained in both the testbed and simulation

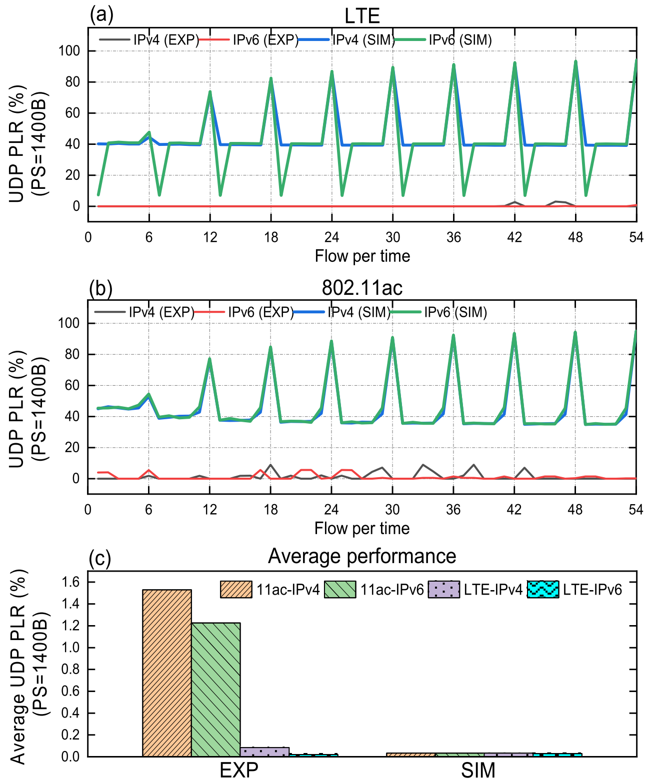

FIGURE 15. **UDP Packet loss ratio with PS = 1400B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.**

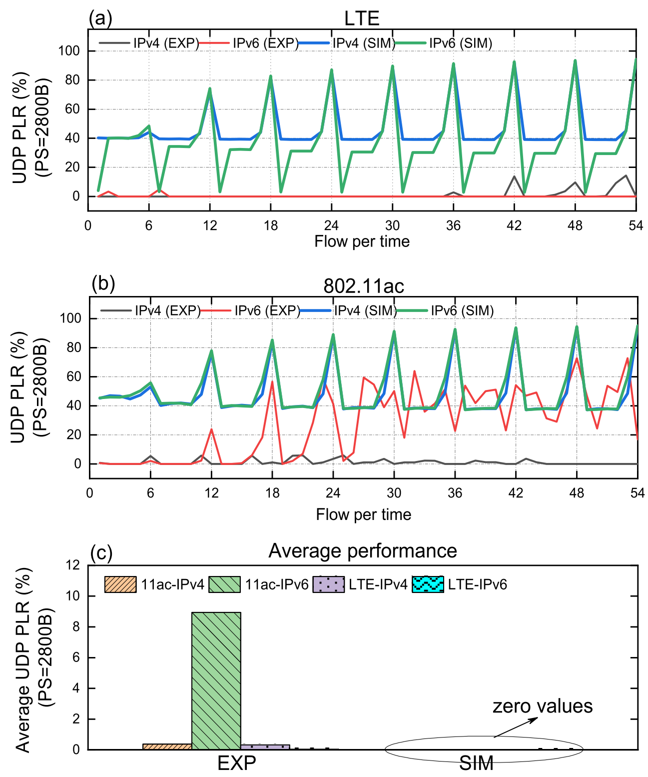

FIGURE 16. **UDP Packet loss ratio with PS = 2800B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.**

results are falling in the acceptable recommendation range. This proves IPv6 with smaller UDP packets has substantial lower PLR than IPv4 in both LTE and 802.11ac networks and hence, does not degrade the performance of LTE and 802.11ac networks.

The above results provide important insights into the PLR performance of IPv6 with UDP packets smaller than MTU. However, still, the PLR performance of IPv6 for the UDP packets with a size larger than MTU is uncertain. Is there any PLR increases or decrease associated with IPv6 for larger packets? Are the larger size of packets affect the IPv6 PLR performance differently than the smaller packets? To answer these questions, further analysis is prepared in accordance with the larger size of packets (PS = 2800B). The results are presented in Figure 16.

The testbed findings support the notion that while the PLR significantly increases as the packet size increases in both the LTE and 802.11ac testbeds, the impact is higher on IPv6 compared to IPv4. Further analysis shows that the larger size of UDP packets has more influence on the 802.11ac than LTE. From this data, we can see that in the LTE testbed results, the average PLR of IPv6 is 0.151% compared to 1.016% for IPv4. This is in comparison with the much higher PLR of 1.171% and 28.024% for the 802.11ac IPv6 and IPv4, respectively. On the contrary, the simulation results of the larger packets show that there is no remarkable change of the PLR associated with the LTE and 802.11ac networks. The simulated PLR in the LTE network shows an average of 47.285% and 37.853% for IPv6 and IPv4, respectively. Additionally, according to the simulated PLR in 802.11ac networks, the average PLR of IPv6 is 50.335% and is 48.587% for IPv4. None of these results significantly differ from the results of the smaller packets.

In line with the results, the present findings have three important implications. First, the UDP PLR for IPv6 is higher than TCP in both LTE and 802.11ac networks. Secondly, as the size of packets increases in both networks, the mobile users that exchange IPv6 packets experience more performance reduction in terms of higher PLR than when they exchange IPv4. Thirdly, LTE network in the presence of IPv6 performs better than 802.11ac network.

G. LTE AND 802.11ac UDP DELAY

This section covers the concerns about the end-to-end delay of IPv6 mobile users. In this regard, we implement the corresponding testbed and simulation scenarios to measure the delay caused by IPv6 in LTE and 802.11ac networks to compare against IPv4 delay when UDP packets are exchanged between the mobile users. The results for 1400 bytes UDP payloads are presented in Figure 17.

Although the testbed and simulation results differ slightly to some extent, they suggest that there is a close association between them. With respect to the 802.11ac network, the results demonstrate similar delay behavior in the testbed and simulation. A comparison of the 0.280s delay for both IPv6 and IPv4 in the simulation along with the 0.152s and

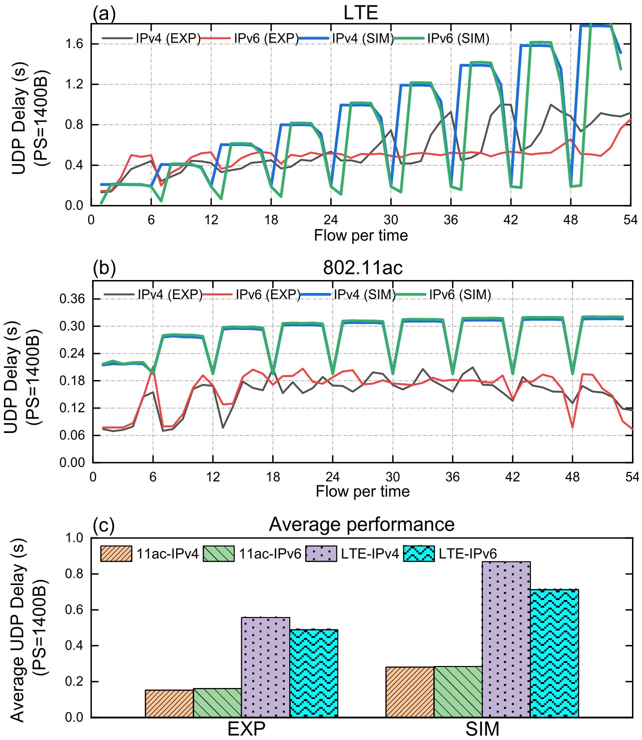

FIGURE 17. UDP Delay with PS = 1400B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.

0.160s testbed delays for IPv6 and IPv4, respectively reveals this similarity. Turning now to the LTE testbed shows that the 0.557s and 0.489s delay values are measured for IPv4 and IPv6, respectively. In this analysis, 0.868s for IPv4 and 0.712s for IPv6 are delay values attained from the simulation scenarios. Taken together with the results of delay, a clear benefit of IPv6 over IPv4 in terms of lower delay is identified for LTE in the testbed and simulation results. In this regard, we additionally need to determine the influence of larger IPv6 transmissions and whether they cause improving the performance of mobile users or vice versa. Thus, we further set out more scenarios with the aim of assessing the importance of IPv6 size of packets. The results on analyzing the delay of UDP packets with a size larger than MTU (PS = 2800B) in the presence of IPv6 compared to IPv4 are demonstrated in Figure 18.

Once again, the findings confirm that the testbed results are consistent with the simulation results. Frm the LTE testbed results, we can see that the larger IPv6 packets do not have a considerable impact on the delay values and in this case, only a slight reduction is observed. This is in contrast to increasing the delay for IPv4 in line with increasing the size of packets. Having these statistics show 0.466s average delay for IPv6 compared to 0.659s for IPv4. On the other hand, when it comes to the 802.11ac testbed, increasing the size of packets results in increasing the delay. In this case, the average delay value is 0.658s for IPv6 and 0.248s for IPv4 while both are higher than when the smaller packets (PS = 1400B) are transmitted in the 802.11ac network.

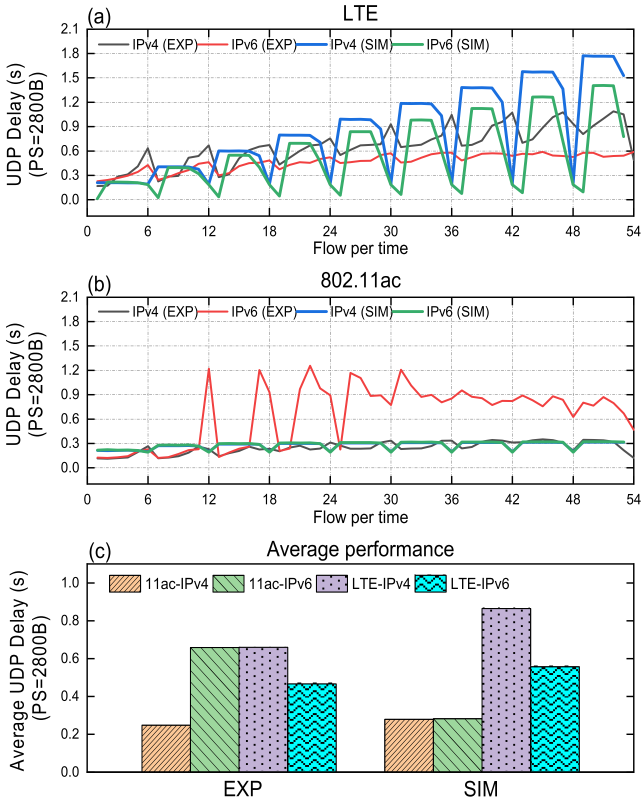

FIGURE 18. UDP Delay with PS = 2800B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.

On the other side, the LTE simulation results also confirm less delay for IPv6 packets, 0.557s, compared to IPv4, 0.868s. Regarding the 802.11ac simulation results, the findings show close delay values for IPv6 and IPv4. In this case, 0.282s delay value for IPv6 and 0.278s for IPv4 are observed, which prove no performance differences. From the results, it is concluded that mobile users in LTE networks regardless of the size of packets experience better performance in terms of less delay when IPv6 is used in the communications. However, this performance improvement by IPv6 is not obtained for mobile users in 802.11ac networks. In this case, when IPv6 is used as the transmission protocol, the delay significantly increases, particularly for larger UDP packets.

H. LTE AND 802.11ac UDP JITTER

Experiments on IPv6 jitter values are conducted in this section. The aim is to present the assessment of the performance and effectiveness of IPv6 with UDP packets in terms of jitter in LTE and 802.11ac networks. The results for 1400 bytes UDP payloads are presented in Figure 19.

By comparing the testbed and simulation results of the 802.11ac network, no evidence for significant differences between them is found. The data gathered in the 802.11ac testbed indicates the exact same jitter values for IPv6 and IPv4 with the average of 0.0012s. Likewise, in the case of 802.11ac simulation, the IPv6 and IPv4 result in the same jitter values with the average of 0.0013s. Meanwhile, the LTE testbed shows the same jitter values for IPv6 and IPv4 with

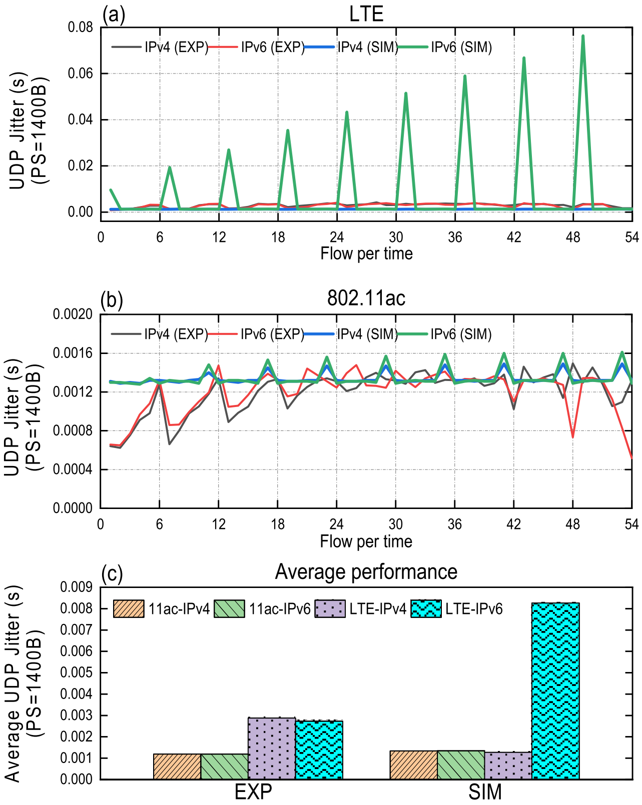

FIGURE 19. UDP Jitter with PS = 1400B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.

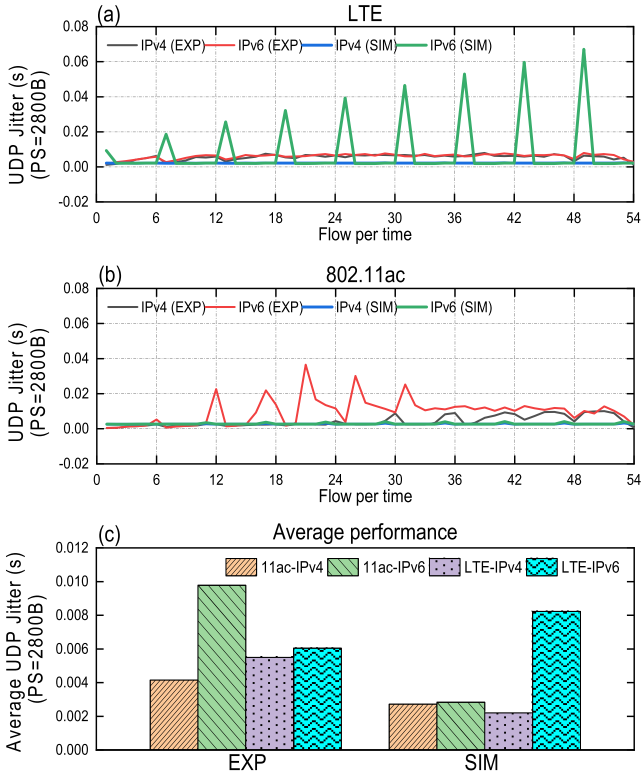

FIGURE 20. UDP Jitter with PS = 2800B: (a) LTE per-flow, (b) 802.11ac per-flow, (c) LTE and 802.11ac average values.

the average of 0.0028s. The LTE simulation results, on the other hand, show that IPv4 achieves a statistically significant improvement compared to IPv4. In this case, while the average value of IPv4 jitter is 0.001s, the IPv6 jitter is 0.008s, which is much higher than IPv4. These results suggest no advantage of IPv6 and IPv4 over each other as they both perform equally in terms of jitter.

The effects of IPv6 on the jitter of LTE and 802.11ac with smaller UDP packets are similar to those of IPv4. However, to take the analysis further, we implement the scenarios involving UDP packets with larger size (PS = 2800B) to illustrate the performance of IPv6 in LTE and 802.11ac networks. The results are provided in Figure 20.

Taking the LTE testbed results into consideration indicates a significant increase in the jitter values of both IPv6 and IPv4 as the size of UDP packets grow. By comparison, the analysis finds evidence for slightly better performance of IPv4 over IPv6. In this case, the average jitter value of IPv6 is 0.006s compared to 0.005s for IPv4. However, in the LTE simulation, while like the testbed using IPv4 is advantageous over IPv6, unlike the testbed, the difference between the values is higher. In this case, IPv6 provides 0.008s average jitter, which shows a significant difference with the IPv4 jitter with the average of 0.002s. The 802.11ac testbed results, on one hand, similar to LTE testbed, indicate that IPv4 outperforms IPv6 and on the other hands, show apparent differences between the performance of IPv6 and IPv4. The average of jitter for IPv6 is 0.009s that is much higher than IPv4 with 0.004s average jitter. On the contrary, looking at the 802.11ac simulation results shows the equal performance of IPv6 and IPv4 with the same average jitter of 0.003s.

By considering the jitter results together, it is concluded that IPv4 performs better in both LTE and 802.11ac networks when large UDP packets are exchanged between the mobile users. The main advantage of IPv4, in this case, is that it provides less jitter than IPv6. Otherwise, with smaller UDP packets, they perform equally in both networks.

V. CONCLUSION

With the emergence of IoT, a digital connected world is not a distant dream. This, on the other hand, demands to fulfill the large IP address requirements of the IoT devices with no limitation by the Internet service providers. However, IPv6, as an alternative solution has to successfully confront and resolve the key issues associated with its performance in high-speed mobile networks. Toward this direction, this work proposes a model to provide a sophisticated comprehensive approach to quantify the performance of IPv6 in LTE and 802.11ac mobile networks and at the same time determines the uncertainties related to the QoS requirements of the mobile users owning the IPv6-based devices. In an attempt to be comprehensive and accurate, the model includes both testbed and simulation environments. The assessment of the model is based on performing a wide range of distinct scenarios in both environments side by side.

Taken together, the findings implicate that for the connection-oriented services, which are based on TCP protocol, the IPv6 achieves equal performance as IPv4. This is consistent in both LTE and 802.11ac networks regardless of the size of the payloads. A further important implication is that compared to the LTE, the 802.11ac mobile users experience better performance in terms of higher throughput, less delay, and less jitter values. As far as the connectionless services are concerned, the performance of IPv6 is not equal to IPv4 for UDP packets. In this case, the performance of IPv6 varies depending on different network parameters. This performance can be explained by the fact that, unlike TCP, which is a reliable protocol, the UDP as a best-effort protocol does not guarantee data reliability. Although IPv6 provides less throughput, it also imposes less PLR to the LTE and 802.11ac networks. In this case, while IPv6 provides better delay and jitter values for the LTE users, the 802.11ac users experience those values better in the presence of IPv4. The findings add substantially to our understanding of IPv6 performance and have important implications for identifying the corresponding influences on QoS experienced by the mobile end-users in LTE and 802.11ac mobile networks.

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