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Hikmat Adhami
University of Ottawa

Mohammad Alja'afreh
Mohamed bin Zayed University of Artificial Intelligence & University of Ottawa

Mohamed Hoda
University of Ottawa

Jiaqi Zhao
China University of Mining and Technology

Yong Zhou
China University of Mining and Technology

See next page for additional authors

Authors

Hikmat Adhami, Mohammad Alja'afreh, Mohamed Hoda, Jiaqi Zhao, Yong Zhou, and Abdulmotaleb Elsaddik

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Hikmat Adhami [c], Mohammad Alja'afreh [a,c,*], Mohamed Hoda [c], Jiaqi Zhao [b], Yong Zhou [b], Abdulmotaleb El Saddik [a,c]

[a] Mohamed bin Zayed University of Artificial Intelligence, Masdar City, Abu Dhabi, United Arab Emirates
[b] School of Computer Science and Technology, China University of Mining and Technology, Xuzhou, 221116, China
[c] School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON, K1N 6N5, Canada

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ABSTRACT

Haptic is the modality that complements traditional multimedia, i.e., audiovisual, to evolve the next wave of innovation at which the Internet data stream can be exchanged to enable remote skills and control applications. This will require ultra-low latency and ultra-high reliability to evolve the mobile experience into the era of Digital Twin and Tactile Internet. While the 5th generation of mobile networks is not yet widely deployed, Long-Term Evolution (LTE-A) latency remains much higher than the 1 ms requirement for the Tactile Internet and therefore the Digital Twin. This work investigates an interesting solution based on the incorporation of Software-defined networking (SDN) and Multi-access Mobile Edge Computing (MEC) technologies in an LTE-A network, to deliver future multimedia applications over the Tactile Internet while overcoming the QoS challenges. Several network scenarios were designed and simulated using Riverbed modeler and the performance was evaluated using several time-related Key Performance Indicators (KPIs) such as throughput, End-2-End (E2E) delay, and jitter. The best scenario possible is clearly the one integrating MEC and SDN approaches, where the overall delay, jitter, and throughput for haptics- attained 2 ms, 0.01 ms, and 1000 packets per second. The results obtained give clear evidence that the integration of, both SDN and MEC, in LTE-A indicates performance improvement, and fulfills the standard requirements in terms of the above KPIs, for realizing a Digital Twin/Tactile Internet-based system.

1. Introduction

With designs being driven to near perfection, the Internet age was thought to be the last, but the never-ending journey of discoveries and research forced humanity to adapt to the new era. Today, with the evolution of the Internet of Things (IoT), a thousand billion connected things will define a new mobile network generation. Meeting the specifications of the Tactile Internet is a major part of the current studies on the fifth generation of mobile networks (5G) [1,2]. Tactile Internet (TI) is the future and ultimate form of the internet that allows real-time communication of human touch and actuation. It will provide an essential pattern change from content-distribution networks to skillset/labour-distribution networks allowing the realization of a new class of Cyber-Physical Systems (CPSs) from which the Digital Twin (DT) surfaced. The most comprehensive definition of digital twin is a digital replica of a living or non-living physical entity [3]. Hence it refers to a digital replica of potential and actual physical assets (physical twin), processes, people, places, systems and devices that can be used for various purposes. A digital twin continuously learns and updates itself from multiple sources to represent its near real-time status, working condition or position. This learning system learns from itself, using sensor data that convey various aspects of its operating condition. Since it is filled with sensors, and is connected to wireless networks- and shares data and communicates with other devices, the digital twin relies on Cloud platforms driven by Machine-to-Machine communications (M2M) and Data Analytics. One of the main characteristics of digital twin technology is its connectivity. This connectivity is created by sensors on the physical product, which obtain data and integrate and communicate this data through various integration technologies. Moreover, we can build a digital twin of almost everything regardless of its size – from single components and assets (rotors, turbines, pipelines, etc.) to complex processes and environments (production lines, manufacturing

* Corresponding author at: School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON, K1N 6N5, Canada.
E-mail addresses: hadha068@uottawa.ca (H. Adhami), Jaafreh@uottawa.ca (M. Alja'afreh), mhoda053@uottawa.ca (M. Hoda), jiaqizhao@cumet.edu.cn (J. Zhao), yzhou@cumet.edu.cn (Y. Zhou), elsaddik@uottawa.ca (A. El Saddik).

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plants, wind farms, etc.). The level of sophistication and detail of the digital twin models depends on the availability and maturity of the information technology infrastructure. It is obvious that the success of DT technology is dependent on internet connectivity. Without the latter, DT technology would not exist. Hence, providing a bilateral communication channel with ultra-fast, low latency, highly reliable and secure connectivity, is a key condition for the realization of DT applications. Here comes the role of the Tactile Internet.

In addition, the key aspect of the DT is the usage of multi-modal digital tools to bridge the gap between the physical and virtual worlds, with haptic more special teleportation added to 3D, audiovisual, and Mixed Reality (MR) communication platforms. Consequently, different applications will be offered by the Tactile Internet, such as remote well-being monitoring and surgery (Health 4.0), Fig. 1 remote driving, remote education and training, wireless commanded exoskeletons, industrial remote maintenance, and manufacturing (Industry's 4.0) [4]. Since most of the previous applications are critical to society, the Tactile Internet must be ultra-reliable and have enough bandwidth to enable numerous devices to communicate at the same time. Moreover, it has to keep end-to-end latencies to the minimum, similar to the requirements of the 5G (i.e., 1 ms). In addition, the conveying of haptic information, in particular, places significant demands on the communication network because it closes a global control loop between the human (master) and the remote robot (slave). As a consequence, the system's stability is extremely vulnerable to network latency. Furthermore, high-fidelity teleoperation necessitates a high-level sampling rate for haptic signals of 1 kHz or greater in order to guarantee high-quality interaction and the stability of the system as a result, teleoperation systems necessitate the exchange of 1000 or even more data Packets Per Second (PPS) among the master and slave devices. Such high packet rates are difficult to sustain in Internet-based networking [1,2] [5,6]. This is, indeed, the main technical aspect of the challenge of the Tactile Internet. One suggested solution to tackle the low latency specification is to engage Software Defined Networking (SDN) and Network Function Virtualization (NFV) technologies in the existing network infrastructure (before the deployment of the 5G network) [7,8]. However, this solution was not investigated and implemented in the literature to empower the realization of the digital twin. The early generations of SDN technology were used with data centers, campus networks, and private networks. Data centers, campus networks, and private networks were among the early adopters of SDN technology. This approach brings a potent and very economical network design by physically separating the data forwarding plane from the control plane. The latter is the network segment defined by SDN controllers that grant adequate selection to organize traffic. The data plane is the other segment characterized by pure, or hybrid switches, that lead the traffic upon control plane response. This splitting allows the utilization of open protocols (e.g., OpenFlow) to ensure communication between these different planes. SDN architecture empowers the network to associate with applications through Application Programming Interfaces (APIs), supporting application execution and security. In addition, SDN makes a flexible and adaptable network design that can be configured remotely, enabling the third-party feature. Several studies highlight the advantage of integrating SDN with edge computing for traditional network and/or multimedia communication [9,10].

The 5G technology is only in its early stages and its cornerstone which makes its standardization and deployment not available anywhere. Further, it has been reported that more than 50 billion devices were already connected to the internet in the year of 2020 [11,12]. This certainly creates a huge burden on the current network infrastructures such as the 4G as it cannot meet tremendous bandwidth and low latency requirements with such a huge number of devices. Not to forget that the Covid-19 pandemic is not ending soon, so it puts another burden on the internet as most of the daily work is now taking place online. Fired by these motivations, to the best of the authors' knowledge, integrating SDN/NFV with Mobile Edge Computing (MEC) for future multimedia e.g., (haptic), has not been adequately addressed so far. The main contributions in this paper are as follows:

- Build a framework that takes advantage of the use of SDN with MEC, along with existing network mobile infrastructures (like LTE-A), to convey the DT data over existing IP networks.
- Benchmark the suitability of the framework to realize the digital twin architecture on a large scale over the core of existing mobile networks.

Consequently, instead of using the traditional Quality of Service (QoS) approach, such as IntServ and DiffServ, we have incorporated modern networking solutions such as SDN and MEC to achieve that goal. We have shown that the outcome of this study can pave the road to realize what is referred to as a Tactile bilateral communication channel (i.e., extremely low latency/high reliability, haptic, MR, and audiovisual availability of the internet) even before the deployment of 5G everywhere in the world. The modeling of the DT modalities and their simulations are performed using Riverbed modeler 18.8 [13] based on extracting the traffics from the three Tactile Internet applications that resemble the DT analogy: VoIP, haptic, and high-resolution video streaming. The remainder of the article is as the following. Section 2 introduces the conducted methodology for the simulation of the Software Defined Networks (SDN) to evaluate the Key Performance Indicators (KPIs) of the deployed LTE-A network. Section 3 describes the state-of-the-art of different technologies and designs. Then, in section 4, we present and analyze the results of the different maneuvered scenarios. In section 5 we use a concise conclusion to argue in section 5, with the necessity for the integration of SDN and MEC over the LTE-A network to gain better performance than traditional networks, to achieve the most challenging requirement for Tactile Internet and DT applications.

2. Methodology

Among the main key research challenges to be addressed for the realization of TI in future networks throughout several applicability domains of TI, is the connectivity issue that is extremely demanding: (1) low latency of less than 1 ms, (2) high reliability of greater than or equal to 99.99%, (3) high data-rate for certain TI applications in the range of Gbps to Tbps and (4) very high back-haul capacity [4,6].

Many research works have been conducted to tackle the connectivity in the main three domains of the TI system. Among them, are the works in [14], and [6], especially for the wireless connectivity in the network domain. In this work, we focus on the LTE-A radio network connectivity. In our previous work [15], we investigated the viability of the current IEEE 802.11 (Wi-Fi) and 802.16 (WiMAX) standards, for short-range, low-latency TI applications. The outcomes revealed a variety of attitudes of the aforementioned, and concluded consequently, that 5G is needed to perform Tactile Internet applications.

Multiple wireless access architectures, as well as backbone networks, are used in End-to-End (E2E) communications. As a result, maintaining the optimal latency for audio, visual, and haptic data transmission is a critical task. In LTE-A based cellular system, the total latency may be minimized in various network segments, such as the Radio Access Network (RAN), the backhaul, and the core network. According to [14], the total (E2E) latency in an LTE-A cellular network is

$$T_{\mathbf{E2E}} = 2\ (T_{RAN} + T_{Backhaul} + T_{Core} + T_{Transport}) \qquad (1)$$

where T_{RAN} denotes the transmission time over radio Access network, $T_{Backhaul}$, T_{Core}, and $T_{Transport}$ represents, (1) the time it takes for a packet to travel between the user equipment and the eNodeB, (2) the time it takes for the connections between the core network (EPC) and the eNodeB, (3) the time it takes to process data at the EPC, and (4) the time it takes to communicate data between the EPC network and the Internet/Cloud. While T_{RAN} depends on coding schemes, and

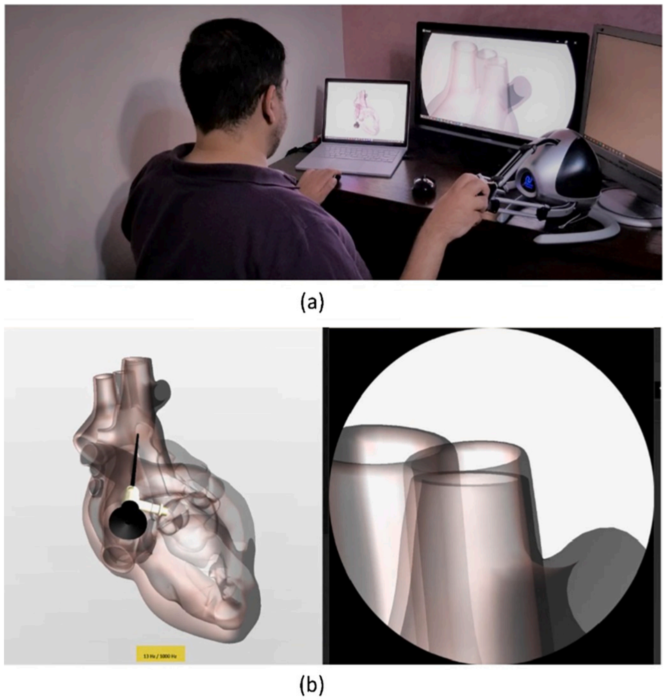

Fig. 1. (a) An example of Health 4.0 remote surgery using the DT architecture; (b) A proof of concept of Tele-heart-endoscope operation with 1 KHz haptic closed loop sampling rate.

$T_{Backhaul}$ depends on the medium used, our contribution emphasizes, as stated earlier, the latency minimization techniques to reduce T_{Core} and $T_{Transport}$. These techniques include innovative methods such as SDN/NFV for T_{Core} and MEC – enabled cloud/Internet for $T_{Transport}$ since it primarily relies on the server's distance from the core network.

In this work, all computer simulations are carried out by exploiting Riverbed modeler's new tools and features such as the LTE Advanced generation (LTE-A), SDN methodology, and System In The Loop (SITL) capability [16] as shown in Fig. 1. STIL allows the capture, and transfer of simulated data to physical and real network components through the host machine's network adapter. In addition, different models for LTE advanced networks were designed and, using the SITL feature, simulated data were sent to a real "OpenDaylight" SDN controller configured on a Linux virtual machine. Therefore, the network function virtualization is configured by default when using the SDN controller. Then the network performance regarding common KPIs such as throughput, jitters, and E-2-E delay were estimated in different networking scenarios.

3. Network model

To simulate the network performance, several scenarios were designed using the Riverbed modeler. The purpose is to investigate particular architectures and technologies that enable Tactile Internet applications before the massive deployment of the 5G mobile networks. Therefore, in this work, SDN as well other promising technologies such as mobile edge computing and network function virtualization are first integrated into the core network of LTE-A in different scenarios, and then the performance was evaluated and compared.

In the next subsections, we provide an overview of the aforementioned technologies.

3.1. LTE-A

LTE-A is a major enhancement of the 4th generation of mobile communication standards. It has evolved significantly to improve its radio and network performance since its launch by the 3GPP in Rel-10, reaching a latency performance of 10 ms in Rel-13 and 7 ms in Rel-14.

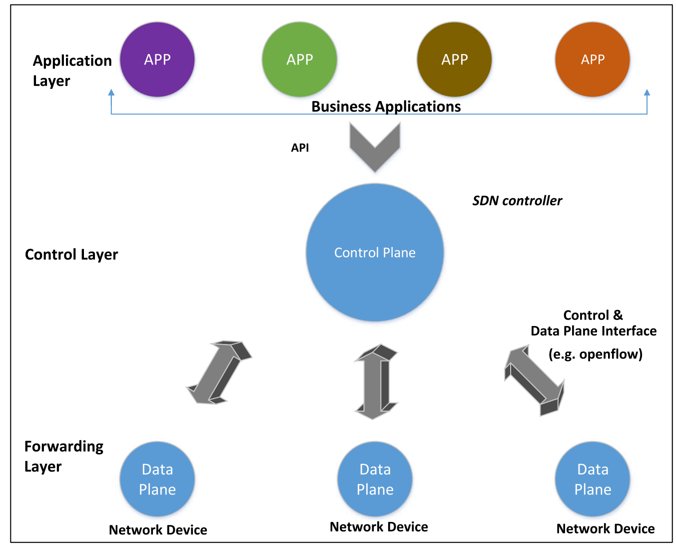

Fig. 2. SDN Architecture.

In this work, the LTE-A simulated by the Riverbed modeler is the release 14. The latter uses Orthogonal Frequency Division Multiple Access (OFDMA) with Multi Input Multi Output (MIMO): OFDMA is a multi-user variant of the famous Orthogonal Frequency Division Multiplexing (or OFDM) digital modulation technique. OFDMA is considered profoundly reasonable for broadband mobile communications because of its benefits which range from scalability, adaptability, and utilization of different user-friendly multiple antennas (MIMO), as well as its capacity to exploit channel frequency selectivity.

However, the aforementioned performance remains far from the target specification of 1 ms which is mandatory for smooth Tactile Internet applications. LTE-A evolution helped to realize many applications that require high QoS to provide smooth services to the users: virtual and augmented reality, holographic and 3D and video call, large file sharing, and ultra-high-definition video streaming and transmission.

3.2. Software defined networking (SDN)

SDN separates control and data planes inside the network and links them through the OpenFlow interface protocol. Fig. 2 presents a sketch of the SDN layered design. It is composed of three main planes: Data, Control, and Application planes.

The control layer is handled by SDN controllers that generate different configurations of the network based on the operator's policies. They reside between network devices and applications and relay information to switches and routers via interfaces (OpenFlow protocol) and APIs. A typical SDN controller (SDNC) incorporates topology management, statistics management, notification management, device management, shortest path forwarding, and security mechanisms. The data plane is the segment of the network characterized by switches that handle packet forwarding as a result of the control plane. Unlike traditional networks, however, these are now just simple forwarding components that have no intelligence. One or more network applications interact with controllers to define services and rules in the SDN application plane. They are able to create end-to-end features and vary the network behavior dynamically based on changes in the network topology, feature or policy requirements.

In this work, the $SDNC$, is a Java Virtual Machine (JVM) software. It is also recognized as the $OpenDaylight$ platform and can be run from any operating system or any hardware since it supports Java API. The OpenDaylight Controller features open northward APIs, used by the applications. These applications: (1) use the controller to gather information about the network, (2) run algorithms to operate analyt-

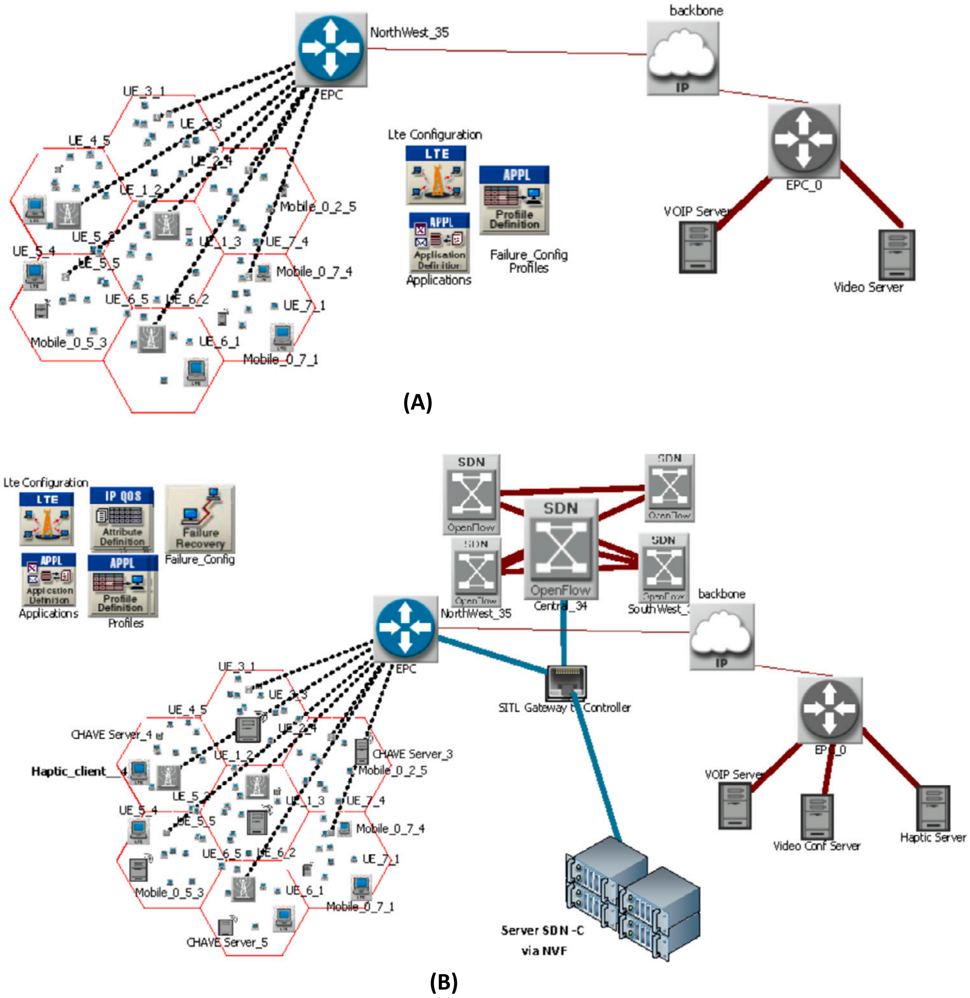

Fig. 3. Simulation scenarios: (A) LTE-A Baseline Network Scenario; (B) LTE-A Network Scenario with SDN and MEC Integration, for Haptic Audio/Video (HAV).

ics, and afterwards, and (3) exploit the Controller to build new rules all over the network.

3.3. Mobile edge computing (MEC)

Another approach to enhance the mobile network performance is to relocate its activities to fog entities located at the border (i.e., edge) of the network. Therefore, the concept of Mobile Edge Computing (MEC), is to bring computational and storage resources closer to the edge of the network. Thus, the end-to-end global latency will be reduced significantly. In addition, MEC supplies real-time data processing and message response. The implementation of MEC topology is based on multi-layer cloud concept. The first layer consists of Micro-clouds, that have limited processing, and storage capacities, and are linked to every $eNodeB$ base station. The second layer comprises extra potent units with greater storage and processing capacities. The final level at the core network has powerful storage and processing capabilities.

3.4. Network function virtualization (NFV)

NFV separates network operations from hardware equipments (i.e., routers, firewalls, load balancers) and other dedicated devices. Accordingly, network functions can be hosted on virtual machines. In this way, instead of dedicated hardware to provide a certain network function, software running on a computer or server is used. The main advantage provided by NFV (among others) is network scalability, which corresponds to the possibility of making functional additions without the need to install or acquire specialized equipment. In practice, the dynamic allocation of resources is one consequence of NFV [8]. Note that all the coming simulations concerning SDN deployment, include by default the NFV function thanks to the STIL Riverbed Modeler's feature.

4. Simulation infrastructure and results interpretations

Several network scenarios and topologies were designed on Riverbed modeler to evaluate and compare their performance. In addition, Video Conferencing, Streaming and VoIP applications were considered in the study. In the following subsections, details of these scenarios are given.

4.1. Description of the network scenarios

4.1.1. LTE-A network: baseline

Fig. 3.(a) represents the first scenario that corresponds to an LTE-A network only without SDN, NFV or MEC technologies. The scenario comprises the LTE-A core and access networks, and the gateway router. The Radio Access Network (RAN) topology is constructed for several numbers of cells.

Each cell consists of one eNodeB base station along with five randomly distributed devices (User Equipment) that can move on a defined vector-based trajectory. The devices that were used in this topology are described in Table 1. Note that this scenario has been simulated with Table 2 configuration parameters within Riverbed.

Table 1
Baseline scenario components.

Component	Riverbed Modeler Entity
Base Station	lte_enodeb_4ethernet_4atm_4slip_adv
IP Backhaul	router_slip64_dc
Gateway	lte_access_gw_atm8_ethernet8_slip8_adv
Application Server	ethernet_server
Workstation Application	lte_wkstn_adv
LTE Server	Lte_server_adv

Table 2
Baseline scenario parameters.

Simulation Parameter	Value
Simulation Area	Campus (X = Y = 10 km)
Simulation Time	10 minutes
Intermittence Period (Time for the network to get converged)	2 minutes
Number of eNodeB / Cells	7
Cell Radius	1 km
Nb of UEs per Cell	5
UE Speed in Movement	10 KMH
Standard	LTE-A Rel.13
Bandwidth	20 MHZ–FDD (Frequency Division Duplex)
Modulation Type	OFDM

4.1.2. LTE-A + MEC network

The second scenario corresponds to an LTE-A network with MEC integration. Similarly, the RAN consists of seven cells with the major difference of hosting the application servers. This illustrates the idea behind MEC technology wherein computational and storage capabilities are brought closer to the users. The devices that were used in this topology are the same as in the previous scenario with one additional component the Application Server, which is $lte - server - adv$ entity in Riverbed modeler.

4.1.3. LTE-A + SDN network

The third scenario corresponds to an LTE-A network with SDN integration. The proposed model consists of seven cells with randomly distributed devices that move within the cells. The SDN architecture is composed of Hybrid switches that support both OpenFlow and traditional Ethernet switching technology. They are connected to the Embedded Packet Capture (EPC) router that allows capturing packets that flow to, through or from it. Moreover, the Riverbed System-in-the-loop (SITL) element permits connections between genuine devices and the simulated network. The SITL module provides packet transmission between real and simulated packets (between the data plane and the control plane). SITL bridge serves as a foreign device whereby the simulation transfers the packets from the "OpenDayligh" SDN controller (which is installed on an external machine) to the simulation process on Riverbed. In such a simulation manner, physical hardware and simulation can interact as a unified system. The devices that were used in this topology are denoted in Table 3.

4.1.4. LTE-A + MEC + SDN network

The fourth scenario represents the integration of both MEC and SDN technologies over the LTE-A network, by bringing the clouds closer to the users and by enabling higher flexibility, has a synopsis of the total network and is in charge of the settlement to be taken, whereas the hardware (switches, routers, etc.) is merely in charge of expediting packets to the destination using a set of packet-handling rules. The controller is installed on an external machine connected to the SITL. The devices that were used in this topology are the same as in the previous scenario.

Table 3
SDN scenario parameters.

Component	Riverbed Modeler Entity
Base Station	lte_enodeb_4ethernet_4atm_4slip_adv
IP Backhaul	router_slip64_dc
Gateway	lte_access_gw_atm8_ethernet8_slip8_adv
Server	ethernet_server
Workstation Application	lte_wkstn_adv
LTE Server	Lte_server_adv
OpenFlow Switch	of_switch_eth16_adv
SDN Controller	OpenDaylight
System in the loop	sitl_virtual_gateway_to_real_world
Modulation Type	OFDM

4.1.5. LTE-A + MEC + SDN network for haptic audio/video

To assess the efficiency of the haptic transmission model, we used the network model in [16], in which the human-operator and teleoperator workstations are designed to send and receive haptic through the process model with a throughput of about 1000 packets per second using the "Task Configuration Utility". Each packet was configured to have a burst size of 74 bytes to represent the haptic (x, y, z) and their corresponding velocity and forces. The fifth scenario uses the same devices and topology that were used in the previous scenario, except for the operator (haptic client) and the teleoperator closed loop back hosted as $hapticSRV$.

4.2. Simulation results and analysis

In the following subsections, we show and interpret the most used KPI metrics in Riverbed, which are: throughput, e2e delay, and jitter (delay variation) for each of the above-mentioned network scenarios.

4.2.1. Comparison between LTE-A and LTE-A + MEC

The first and second scenarios were simulated in Riverbed modeler by evaluating the timing performance, in the case of a Video Conferencing application, concerning the following metrics: Downlink Delay and Uplink Delay. The network simulation time is fixed at 10 minutes for all cases and it corresponds to a runtime of approximately 1 h on a commercial PC with Intel core I7 3.0 GHz and 16 GB of RAM.

Fig. 4.(a) shows the Downlink Delay results in seconds where a peak value of 45 ms is achieved in the LTE-A scenario (blue curve) compared to 20 ms only in the LTE-A+MEC (red curve) scenario. Integrating MEC into LTE-A has clearly reduced the Downlink Delay in the network to below 45%. As for the Uplink Delay, the results are as follows: At the beginning of the simulation, the Uplink Delay in the LTE-A+MEC network was slightly below LTE-A scenario (118 ms and 125 ms), then it increases to 150 before saturating at a lower value of 130 ms. LTE-A network has an almost constant delay during the whole simulation time. The variation of the uplink delay for the LTE-A+MEC scenario is due to the presence of the own edge servers at each cell (besides the main servers) which contributes to the increase of the overall transmission delay at the beginning.

The first and second scenarios were simulated again by evaluating different performance metrics in the case of a Video Conferencing application: Packet End-To-End Delay, Packet Delay Variation. In this context, the Packet End-To-End Delay is defined as the time taken for a packet to be transmitted across a network from the source to its final destination. It represents a different quantity than Round-Trip Time (RTT), the latter takes into account the return path from the destination back to the source. Fig. 4.(b) shows that the End-To-End delays in the first and, second scenarios increase at the same rate and reach a peak value of $\approx$ 1.6 sec (at $\approx$ 2 minutes from simulation start). Then, in the case of LTE-A+MEC network, it decays exponentially down to $\approx$ 0.2 sec (the red curve, at 10 minutes from simulation start), while it slowly decreases to 1.24 sec only in the LTE-A network (blue curve). Fig. 4.(b) shows a clear improvement in the E2E delay (7 times lower delay) when integrating MEC in the LTE-A network.

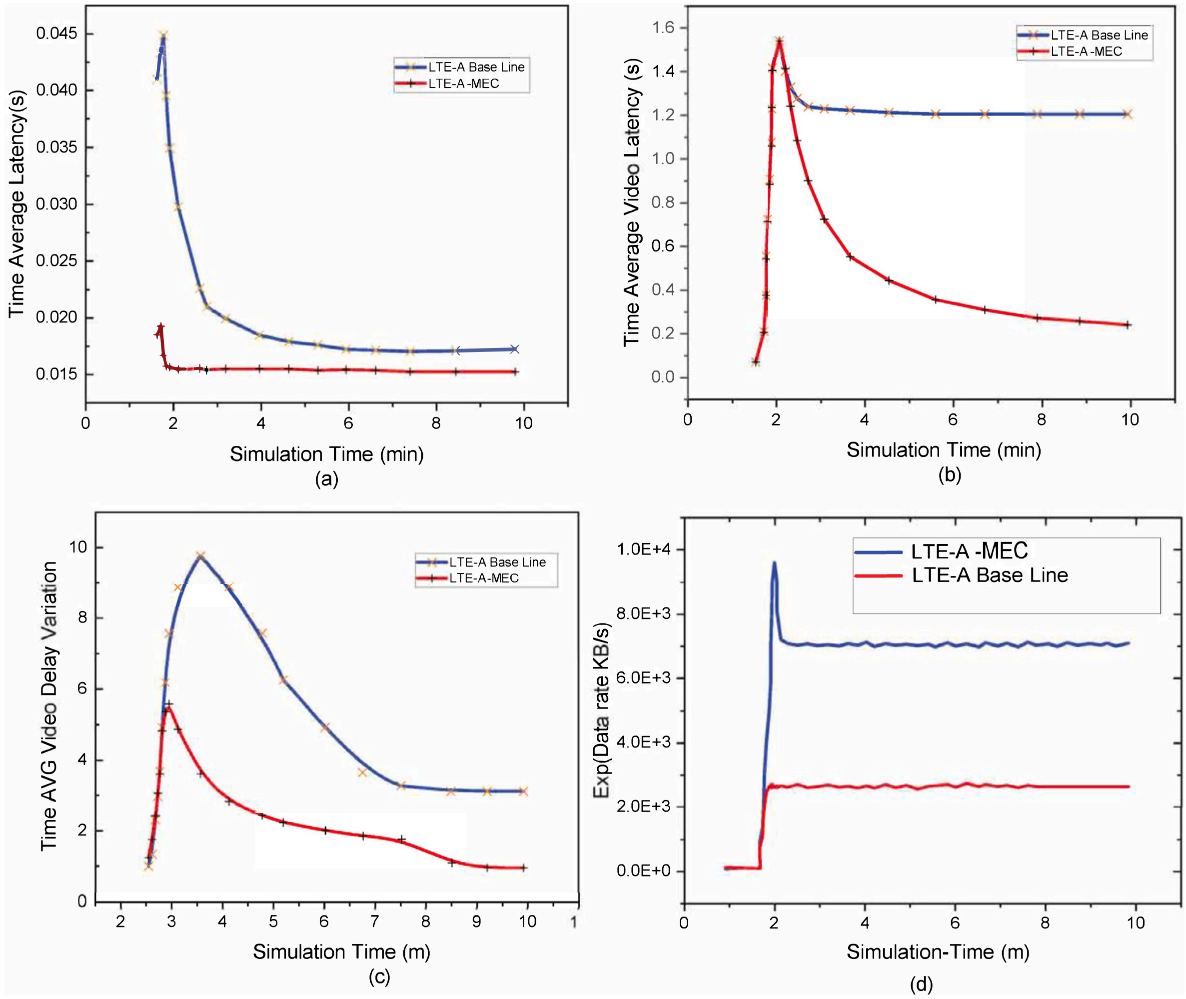

Fig. 4. Simulation Results: (a) Downlink Delay Results for LTE-A and LTE-A with MEC Integration Scenarios; (b) Packet End-to-End Delay Results for LTE-A and LTE-A with MEC Integration Scenarios (Video); (c) Packet Delay Variation Results for LTE-A and LTE-A with MEC Integration Scenarios; (d) Throughput for LTE-A and LTE-A with MEC Integration Scenarios.

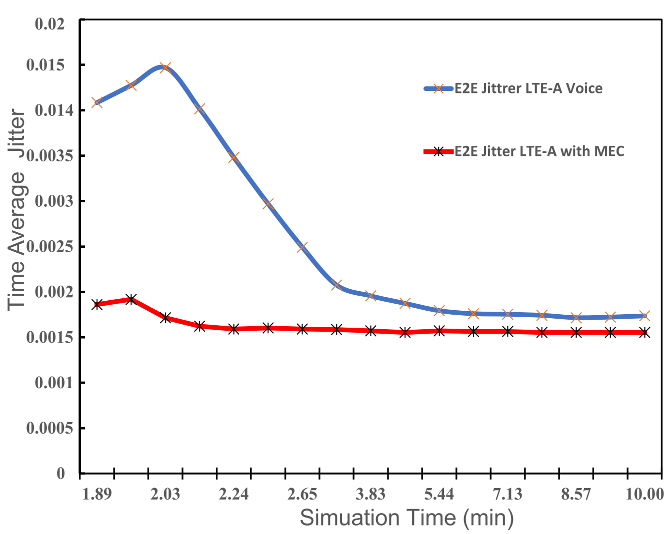

Fig. 5. Jitter KPI for DT Voice Modality.

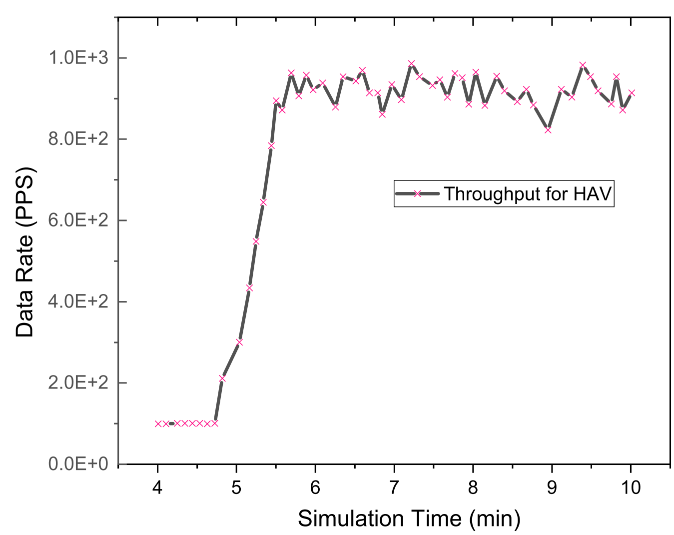

Fig. 6. Haptic Throughput Per Client.

Packet Delay variation is defined as the difference in End-To-End delays between the video packets. Illustrated in Fig. 4.(c) the maximum variation for the LTE-A+MEC scenario (5.5 s) is only half of the case for LTE-A network only (9.8 s).

The throughput is the successful data rate that is offered to a channel. The unit for the throughput is usually bits per second, but in this work, and since we are simulating video streams over a broadband network (LTE-A), we measure the throughput in packets per second. By

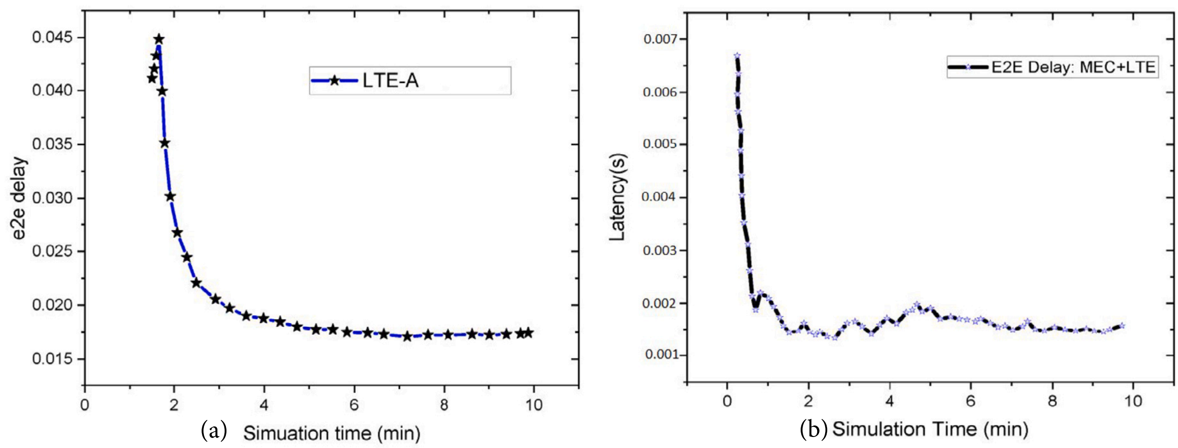

Fig. 7. Simulation Results for DT modalities; (a) Packet End-to-End Delay of LTE-A with MEC Integration Scenario for collaborative haptic AV; (b) Packet E2E Delay of LTE-A with MEC and SDN Integration Scenario for collaborative haptic AV.

Table 4
(Appendix) Simulations KPI compilation.

	End 2 End delay (msec)			Jitter (msec)			Throughput/node (PPS)		
	Voice	Video	Haptic	Voice	Video	Haptic	Voice	Video	Haptic
LTE-A	120	1400	19	15	100	60	50-60	24-60	1000
LTE-A+MEC	80	200	11	3	60	5	50-60	24-60	1000
LTE-A+MEC+SDN	40	100	3	~0.01	10	0.01	50-60	24-60	1000

comparing the throughput of each of the above two first scenarios, it is easy to notice from Fig. 4.(d), that the throughput with MEC integration (red curve) is much higher than the sole LTE-A scenario.

According to RFC 4689, jitter is defined as the latency fluctuation between two consecutive packets belonging to the same flow between two systems [17]. This usually occurs because some packets take longer time to travel from one point to another in the system mainly due to network congestion (which is totally random and time-variant), timing drift and route changes. Jitter can be estimated by the following formula:

$$Jitter = \left|\left(t_{i,r} - t_{i,s}\right) - \left(t_{[i-1],r} - t_{[i-1],s}\right)\right| \tag{2}$$

Where: $t_{[i-1],s}$, $t_{i,s}$, $t_{i,r}$, and $t_{[i-1]}$ denote the sending time of packet $(i-1)$, the sending time of packet i, the time of packet $(i-1)$, and the time of packet i respectively. In overall, the average or mean value of the jitter over a long period of observation is often the point of interest in terms of the average jitter results for the first and second scenarios, for the DT voice modality, the value in the case of LTE-A+MEC network, is smaller (= 3 ms) than the LTE-A case (=15 ms) as illustrated in Fig. 5.

4.2.2. LTE-A + SDN + MEC and haptic results

The fifth scenario is simulated in Riverbed modeler by evaluating the timing performance, in the case of a haptic application, in terms of E2E delay, jitter, and throughput. The detailed results for this scenario are explored in Fig. 7. Given that the haptic model was inspired from [16] at which each packet has a size of 74 bytes (28-byte payload and header + 8 bytes UDP header + 20 bytes IP header + 18 bytes Ethernet header), as such, the maximum throughput shown in Fig. 6 is 1184 Kbps (i.e., 2 times 592 Kbps for each bidirectional haptic workstation stream). Each haptic client was capable to perform the data exchange with the correspondent haptic server in each cell. Consequently, the end-end delay between a haptic master and slave setup was margined to 19 ms as of Fig. 7.(a). Generally speaking, introducing MEC in the LTE-A network achieves an E2E Delay of only 11 ms as shown in Fig. 7.(a). This performance is way above the required hypothetical specification of 1 ms for the Tactile Internet. Therefore, when both SDN and MEC were combined with the LTE-A network, the simulated E2E Delay is kept below 4 ms, as shown in Fig. 7.(b). The best scenario possible is clearly the one integrating MEC and SDN approaches. We believe that this is the best performance that can be achieved in this simulation topology as the tactile internet demands that the physical transmission must have very small packets to enable a one-way physical layer transmission of 100 μs. However, the duration for the one orthogonal frequency division multiplexing symbol alone is close to 70 μs long under current LTE-A cellular systems. In summary, the results in Table 4 showed that the integration of the MEC and SDN over the LTE-A networks had the best performance in general. For more detail about the result of each scenario, please note that Table 4 illustrates the QoS parameter of voice, video, and haptic achieved per each scenario.

5. Conclusion and prospective view

In this paper, we investigated the suitability of current network architectures for delivering future multimedia applications over the Tactile Internet with the 1 ms latency criteria. Performance assessment benchmarks for various types of networks (i.e., LTE-A, LTE-A+MEC, LTE-A+SDN, and LTE-A+MEC+SDN) were carried out for this purpose. To defeat the contests of realizing a Tactile Internet-based system, and to facilitate the realization of 1 ms round trip latency, SDN, MEC and NFV approaches are needed to achieve our goal. The deployment of a centralized SDN controller in the center of the mobile network, along with mobile edge computing (or MEC), efficiently improves the network performance and reduces the overheads such as end-end delay by managing and establishing a cost-effective and adaptable route between local and remote sides. In this way, the number of intermediate nodes is reduced. We conclude that the proposed structure results in a round trip latency of about only a few milliseconds, and this can lead us to the implementation of the Tactile Internet system.

From a future perspective, 5G wireless networks and beyond, are expected to be relied upon to handle a wide assortment of spurting TI applications, with different QoS needs. Therefore, non-ordinary challenges have to be addressed, especially, when conveying haptic data along with traditional sound and video streams.

CRediT authorship contribution statement

Each author declares substantial contributions through the following:

(1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data,

(2) drafting the article or revising it critically for important intellectual content.

Note: Mohammad Alja'Afreh did equally contribute to the article as the first author hence he is the correspondent author.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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