Proactive Forwarding of High Data Rate in Smart Virtualization Networks for High-Speed Trains

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***Abstract*—The Internet and mobile services provided by high-speed train (HST) communication networks are affected by high occurrences of interruptions due to high-speed movement. Rapid connection and disconnection with the access points (APs) impact the performance of quality-of-service to indoor train communication. To ensure a high-data-rate delivery and highly reliable connection to the Internet for end-users, we propose a novel method of handling packet flows in HST communication networks based on software-defined networking (SDN) and network function virtualization. Our proposed combination of technologies is called smart virtualization. The approach in this paper is based on making decisions to change the paths of packet flows between the APs, depending on the use of a triggering signal to initiate layer 2 handover. This packet path switching is controlled by an SDN controller. Our proposed approach operates by sending train information via a train head triggering signal for proactive registration in advance when the train enters an overlap area of AP signals. The suggested software-defined network has been emulated and performed by using the Mininet simulator and the MATLAB platform. After extensive testing, the obtained results that were supported by the triggering signal have an efficient reduction in delay and packet loss than the obtained results without using triggering signal. The average control delay time was reduced by nearly 45%, and the retrieved data were roughly 90% of packet loss when adopting the triggering signal system.**

***Index Terms*—High-speed train, packet forwarding, proactive forwarding, SDN, virtualization.**

I. Introduction

ALWAYS being available and connected anytime and anywhere on the Internet by mobile or fixed devices is a feature of present-day existence. Increasingly, the development of application services is leading to need to deliver large amounts of data without delay or interruption through online connection during user movement. To achieve this, an efficient network is required to handle the transferred data. When associating moving targets to a network, this is more difficult than for stationary, because of their changing position and location for both geographic and topology of accessing attachment points of that network. Since packet forwarding among network devices depends on IP addresses, several protocols have been proposed to tackle packet loss and long handover latency through rapidly acquiring the IP address of a mobile node. Such protocols include the Mobile IPv6 (MIPv6) [1], Fast Mobile IPv6 (FMIPv6) [2], Hierarchical Mobile IPv6 (HMIPv6) [3], Proxy Mobile IPv6 (PMIPv6) [4], and Fast Proxy Mobile IPv6 (FPMIPv6) [5]. Despite these protocols having been developed and provided significant advances in mobility management, they suffer from many obstacles such as long handover delay time, signaling overhead, and a high rate of packet loss [6]. These protocols serve as mobility management ones with the ability to handle such management through the IP layer. Moreover, they have provided significant features for mobility management at low and medium speeds of moving targets [7]. However, the mobility management issue for high-speed moving targets is too difficult for the existing protocols and needs creative solutions to tackle this context. As a high-speed train (HST) moves from one access point (AP) to another, it requires disconnecting from the current AP (APc) and connecting to the next AP (APn) to sustain its session connectivity to the Internet, a process known as handover. The handover delay time is known as the timespan that is required by network devices to complete handover handling. Within the handover process, the HST is separated from the network for a while. Hence, transmitted data packets addressed to the HST according to its IP address may be dropped if the handover processing time is too long. HSTs suffer from the weak achievement of wireless connection services as trains run at high speed. Hence, this poor performance is reflected in the provided Internet services to the passengers in the compartments of those trains. The HSTs have witnessed a fast evolution in traveling at high speed up to 98 m/s and greater [8]. The provided Internet services to HSTs are far from adequate due to too much repeated handover during their rapid movement. This frequent handover means the Internet services and connectivity have become critical. A new mechanism for routing and delivering data must be implemented to ensure high data rates and continuous Internet connectivity for end-users [9].

Emerging virtualization of networking technologies, such as software-defined networking (SDN) and network function virtualization (NFV), has been helping to make mobile and Internet networks more flexible and agile. A network architecture based on SDN technology depends on the separation of the data layer (also known as the data plane) which is the bottom plane, and consists of network devices such as switches, routers, and APs; regardless of whether they are real or virtual devices, they are separated from the control layer (known as the control

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plane, CP) which administers the control functionalities of the software-defined network. The data layer involves physical or virtual switches with high performance to deliver the data to their destination, while the control layer is represented by the SDN controller (SDNc), which is centralized in the logical software substance [10]. On the other hand, NFV runs network functions like load balancing, cipher/decipher, firewall, etc. By using SDN and NFV together, the network infrastructure can be reduced by more than 30% for a new installation of physical infrastructure [11], [12]. The OpenFlow is a well-known protocol that links the SDNc and forwarding devices. The Open Networking Foundation (ONF), which is a non-profit consortium, it defined the SDN architecture as a separation of the control plane and data plane. Furthermore, the ONF standardized the OpenFlow protocol to be the significant southbound application programming interface (API), which could be an open standard or user proprietary. Switches and routers should support the OpenFlow protocol in the transfer of controlling information with SDNc. The southbound APIs can be customized by the user to achieve an appropriate task and approach [12]–[14].

Our contribution concerns the fixed or wired part of wireless network systems (i.e., neglecting RF or wireless matter). In other words, we are interested in the APs and the stationary infrastructure devices of the wireless network (routers and switches). We consider our proposal for designing a virtualized domain as a part of a wireless network, a domain that consists of SDNcs, enabled OpenFlow switches (OFSs), and wireless APs. The main contributions in this paper are as follows.

1) Using an SDN technique to administer the handling of packet flows during HST mobility. In software-defined networks, the most important feature is to relieve the overhead control messages or signals that direct the flows of packets.
2) Drawing on the excellent feature of the SDN of its the capability of dealing with per packet or per flow independently from the IP address to destine data packets, we put forward a technique for picking specific fields from the IP address fields to be fragmented and consolidated with other fields by utilizing SDNc to steer packet flows.
3) Utilizing a triggering signal to direct packet streams proactively. The SDNc uses the information that is included in the triggering signal to initiate redirection processing to change the packet flow paths from APc to APn. This proactive processing leads to reduced packet loss and decreased handling delay time, while keeping the continuity of connection during HST mobility.

The rest of this paper is organized as follows. Section II provides a brief overview of the wireless technologies that can deliver a high data rate, which are proposed to be employed in this paper for network systems, with related works being presented at the end of this section. Section III illustrates the structure of the proposed system, while Section IV explicates the distance estimation that has been used in our paper. The obtained numerical measurements from the experiments have been analyzed in detail in Section V. Section VI explains the setup of the testbed and its implementation with Mininet simulation. Finally, the conclusions are drawn in Section VII.

II. Preliminaries

In this section, a brief outline of some technologies that can be used in the proposed network to facilitate the understanding of the main idea, including object speed calculations, millimeter-wave (mmW) AP, massive multiple-input multiple-output (MIMO) antennas, wireless gigabit (WiGig) AP, identifiers of network and host, as well as IP address and mobility. In addition, a review of important related studies is provided.

A. Technologies May Be Used

1) Target Speed and Wireless Registration: High-speed moving targets (trains or cars) suffer from interrupted wireless services when they cross from the attached AP to a new one. That is, this happens due to breaking of the connection from the APc and connecting to the APn, i.e., the wireless reregistration process. Suppose that the speed of a moving target is 350 km/h, the delay time of the layer 2 wireless registration CP is 50–250 ms [15], and the separation distance between any two adjacent APs is 200–1000 m.

With a simple calculation via (1), we can estimate the delay time that is required by a moving target to move from one AP to another as flows, such that

$$t = d/\nu \tag{1}$$

where t is the time required to cross the distance d with target speed ν.

1) Separation distance between APs is 200 m:
350 km/h = 97.222 m/s
so 200 m/97.222 m/s = 2.057 s.
2) Separation distance between APs is 1000 m:
350 km/h = 97.222 m/s
so 1000 m/97.222 m/s = 10.286 s.

It is clear that layer 2 wireless registration time delay of the CP is much smaller than that required by a moving target to move between the adjacent APs. Consequently, there is enough time to complete RF registration when the moving target travels between any pair of adjacent APs. In other words, there is enough time to handle data packets between any pair of adjacent APs.

2) Millimeter Wave AP: The most important feature of an mmW is its frequency band ability to carry multigigabit throughput data rates at a range from 1 m to a few thousand meters [16], [17]. The frequency band (30–300 GHz) of the mmW can give 200 folds more than the usage of current wireless bandwidth. This wide bandwidth has encouraged the wireless industry to utilize mmW APs for use in outdoor and indoor small cells ranging from a few meters to a few kilometers [18], [19]. By using mmW, a multi-Gb/s rate can be delivered to the users by the beamforming technique, which overcomes short and loss of channel propagation of the mmW [20], [21].

3) Massive MIMO Antennas: Massive MIMO antenna schemes can be employed to enhance the data rate, improve fidelity, boost radiated energy efficiency, reduce latency on the wireless interface, and simplify the multiple access of the media access control layer. Massive MIMO impacts the performance of wireless communication systems when the sender and the

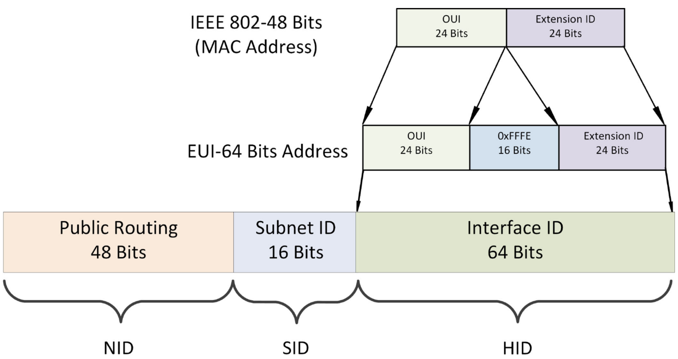

Fig. 1. IPv6 structure.

recipient support utilizing many antennas to receive and transmit multiple streams of data concurrently [22], [23]. By using physical layer characteristics, the massive MIMO technology can directly be combined with that of the mmW to provide the throughput of Gb/s traffic for wireless APs. Moreover, massive MIMO with the mmW can improve link reliability [24].

4) WiGig Attachment Point: One of the most important characteristics of the 5G network is its ability to perform high data rate ranging from 1 to 7 Gb/s. This means that the last distribution point of a wireless LAN should be able to provide a capacity of data rate of more than 1 Gb/s to users. WiGig is the standard of IEEE 802.11ad works as indoor mmW AP at 60 GHz [25], being able to achieve the multigigabit transmission rate. The beamforming technique has been found to overcome the issues of non-line-of-sight, while improving energy efficiency [26]. WiGig APs are suitable for being used inside the compartments of the HST.

5) IP Address and Mobility: We have focused on IPv6, because of its capability to provide a vast number of IP addresses. Moreover, it has the significant attribute IP address autoconfiguration. Also, the IPv6 address is a combination of physical and logical IDs, which represent host and network interface IDs, respectively. Fig. 1 illustrates the IPv6 structure, which shows how the device can identify itself through its IPv6 address. In other words, IPv6 is not utilized by the communication networks for routing purposes only, for it can also be worked as an indicator of the location of a mobile device in the network. Fig. 1 shows the three parts of the identifier elements of the IPv6 [27], [28] given as follows.

1) Network identifier (NID), which represents the public topology (public routing) and consists of 48 bits. Moreover, it can be considered as the parent of the SID.
2) Subnetwork identifier (SID), which pertains to the site topology (local routing) and consists of 16 bits. As alluded to above, the SID is viewed as the child of the NID, which can involve a vast number of SIDs. The NID and SID together represent the global routing prefix of an IPv6. Also, they can be used as an indicator of the location.
3) Host identifier (HID), which represents the interface attachment port of a device that can connect to a network through it, being 64 bits long. The combination of the NID, SID, and HID creates a single IPv6 address that is used by a device to be an end-to-end identifier for it. Furthermore, the HID can work as an indicator of the mobile device's position.

The network operator who provides services to a mobile device should have information about geographic locations of all the subnetworks that belong to his/her network. That position of a mobile device can be determined by its IP address, due to the previous location knowledge of the subnet that serves the device [29].

B. Related Works

The world has witnessed a significant development in the maximum moving speed of HSTs. With this development, several issues have faced HSTs like a train running safety, high rate of handover repetition, and maintaining continuous Internet services. This paper concerns handling and routing packets in a software-defined network. Especially, managing and controlling of data packets that have been proactively destined by an SDNc through pre-exchange controlling messages are the objectives.

The authors in [30] explored the evolution of wireless heterogeneous networks toward mobile 5G networks for high-speed moving vehicles. They used narrowband RF channels for the control data, while for the user traffic wideband, high-frequency wireless channels were deployed. However, the drawback of this research was the utilization of different RF technologies, because forwarding of packets would need more processing, thus resulting in long handover latency. In [31], the authors presented various scenarios for high-density transportation moving targets at high or low speed over heterogeneous networks and dense cells. They aimed to estimate the performance of a proposed vehicular networks architecture based on a multiaccess router. The shortcoming of this paper is dependence on the multiaccess router, consisting of several antennas that could physically connect many types of wireless network technologies. Hence, a long handover process problem remained. Based on the logical design for network slicing and mobility management among many kinds of APs, a study was presented in [32]. This work was founded on the separation of the logical network into various layers based on an edge cloud and core cloud. Lei *et al.* [33] presented a study of the causes of random delay of control services of high-speed railways and their influence on the speed profile and the path of the HST. These authors formulated the movement of trains as a part of the Markov approach to analyze fading channels for HSTs.

Several protocols have been proposed and implemented to resolve the handover latency and data loss dilemmas. Some of them have used a reactive approach, while others have adopted a proactive one in relation to handling data packets. MIPv6, PMIPv6, and HMIPv6 were designed as reactive protocols to address mobility management problems during handover within subnetworks [4], [34], [35]. These protocols have been used by communication networks to optimize the handover procedure, decrease overhead signaling, and realize layer 3 handover. While enhancements have been made in handover procedures, they still suffer from high rates of packet loss and long delay times [36]. Those protocols did not use layer 2 information to estimate

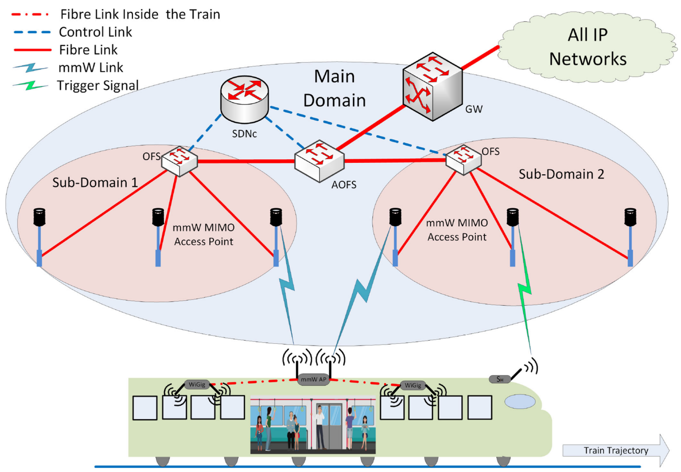

Fig. 2. System architecture.

the direction of a moving target to discover its destination. The FMIPv6 and FPMIPv6 protocols are expanded and improved versions of the MIPv6 and PMIPv6 respectively [6]. A proactive scheme was used by these protocols, which were created principally to cope with the handover delay time and data packet loss problems. By employing a predictive scheme, the network starts layer 2 handover over using the received signal strength (RSS) of the moving target [36]. All of these protocols still have considerable problems in terms of long handover latency and high rates of data loss. Moreover, they were designed to manage the mobility of low-speed moving targets up to a maximum 70 km/h [36]. Designs of 5G-crosshaul based on SDN and NFV have been presented in [37], with this study considering the principal parameters of application elements and their interactions with the control layer. In addition, the mmWave communication network and HST scenarios were investigated by the authors. The authors in [38] put an expectation–maximization algorithm depending on the historical information basis; also, they provided an estimator of a blind channel model for the uplink of an RF transmission scheme on the HST.

III. Proposed System Description

The structure of the proposed system, as shown in Fig. 2, consists of three principal parts. The first represents the main domain (operator network), the second, represents the subdomains (subnetworks or subnets), and the third pertains to the train (its AP and triggering signal). The following subsections explain these parts.

A. Main Domain

The main domain comprises the SDNc, gateway (GW), aggregator OpenFlow switch (AOFS), and other OFSs in each domain. The SDNc regulates and supervises the AOFS and other OFSs. Based on the saved information in the SDNc's lookup table about the links that connect all devices associated with the system, the SDNc dictates its rules to the AOFS and OFSs for governing traffic flow from/to the main domain and subdomains. According to this information, the SDNc creates and maintains its lookup

TABLE I
SDNc Entries in the Lookup Table

Main Domain Prefix (NID)	Sub-domain (SID)	VLAN	Train ID (HID)
2001:0DB8:ACAD/48	:0001/16	AP1	T_{11}, T_{12}, ..., T_{1n}
		AP2	T_{21}, T_{22}, ..., T_{2n}
		AP3	T_{31}, T_{32}, ..., T_{3n}
	:0002/16	AP4	T_{41}, T_{42}, ..., T_{4n}
		AP5	T_{51}, T_{52}, ..., T_{5n}
		AP6	T_{61}, T_{62}, ..., T_{6n}

table and makes the rules and actions, which are sent to the AOFS and other OFSs as flow tables. The SDNc is considered as the brain of the main domain because it determines the packet routes. It sends the decisions and actions to the AOFS and OFSs to forward the data to a specific interface that links the AP to deliver the data to the destination target. That is, the decisions are taken based on the lookup tables and saved in SDNc. The lookup table of the SDNc consists of the main domain prefix (network operator prefix NID), subdomain identifier (SID), virtual local area networks (VLANs), which serve as APs, and the train identifier, which is equivalent to HID. Table I illustrates the entries of the lookup table and the field entries that should be processed to make decisions and rules. In our paper, the VLAN ID represents the local network topology of an AP that serves trains under its coverage area.

The AOFS receives the data from the GW to forward that data to its destination based on the SDNc rules and actions. The AOFS's responsibility is to direct packet flow among the subdomains as the train traverses from one subdomain to another. That is, when the train moves from one domain to another, the AOFS changes the path of packet flow from the previous domain to the new one. However, when the train moves from one AP to another within one subdomain, the AOFS keeps the path of packet flow unchanged. Fig. 3 illustrates the entries of the flow table and the fields that the packets have to subject to it. The GW represents the gate to all IP networks that are installed outside the main domain. This is a traditional device that connects the main domain (operator network) to the Internet backbone and other IP networks. It works according to rules and policies that are applied to the traditional network devices, which means that the GW is not subject to the rules and actions of the SDNc.

B. Subdomains

Every subdomain consists of at least one OFS and several APs. For simple understanding, we provided a single OFS in each subdomain, as shown in Fig. 2. The OFS and AOFS communicate with each other through the forwarding layer (data plane) to send and receive the data. The OFS forwards the received packets according to rules and actions that have been made by the SDNc. However, these are not the same as those the SDNc has made for the AOFS. The OFS steers packet flow between APs as the train moves from the APc to the APn during its passage on the trajectory. The NID is still the same for the main domain even when the train moves among the subdomains, whereas the SID is changed by the SDNc when the train does

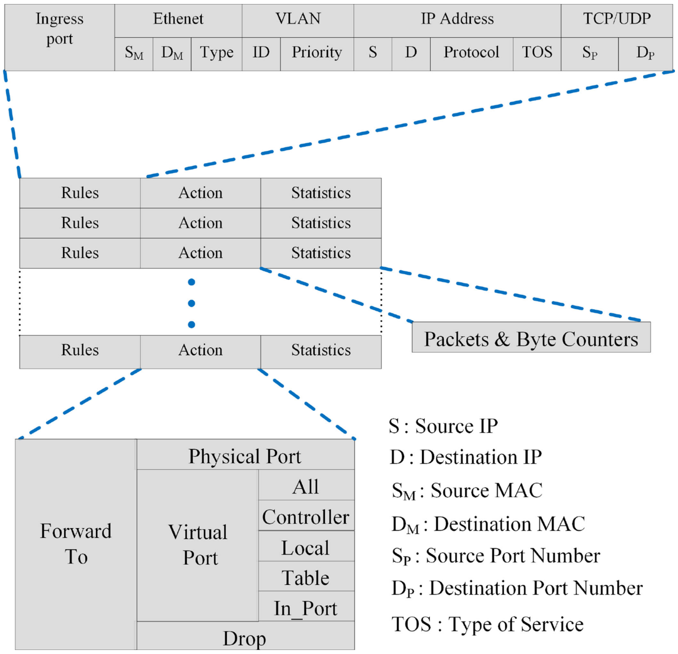

Fig. 3. Generated SDN OpenFlow table.

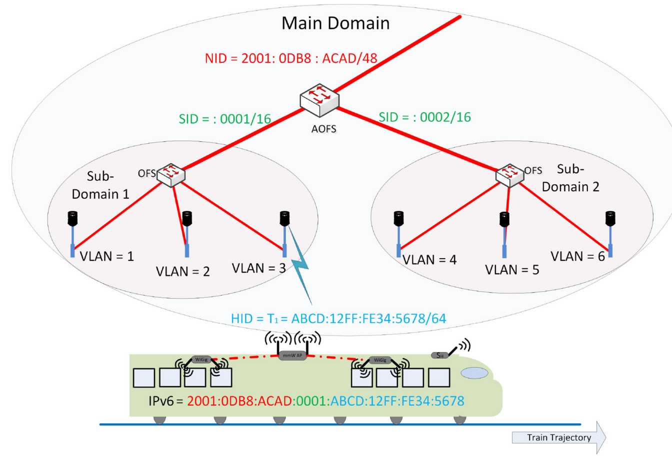

Fig. 4. Proposed SDN IPv6 hierarchy structure.

so. APs work as VLANs, which means each AP can provide an independent virtual network that can afford many virtual IP addresses based on one real IP address. To put it simply, a single SID can provide many virtual networks, each being able to provide several IP addresses. As we mentioned above, the train AP represents HID, and hence, the stateless autoconfiguration of the train's IPv6 address involves NID, SID, and HID. This IPv6 address indeed is used as the train identifier in a specific network. Furthermore, it can be used by the network operator as a pointer to the location of the train.

C. Trigger Signal and Train AP

We proposed an innovative mechanism to manage the forwarding of packets according to an independent triggering signal that is sent by the train. This signal is received by the APn, which, in turn, sends the triggering signal to inform the SDNc about the train location. We called this signal the handover triggering signal (S_H). The S_H is sent by an antenna positioned at the front of the train. The S_H is sent by the train in one direction to be received by the APn before the train reaches the APn so as to prepare the flows path switching of packets by the SDNc. S_H involves information such as HID, which pertains to the AP ID of the train, the destination of the train, the APc attached to the train, and the train speed T_s. The APn forwards this information to the SDNc to switch the flow direction of the OFS only or the OFSs and the AOFS if the train moves from one AP to another within one subdomain or from one subdomain to another, respectively. The primary purpose of S_H is to notify the SDNc to dictate to the OFSs and AOFS to change the flow direction. When the SDNc receives the triggering signal, it starts to modify the flow path direction from the APc to the APn. The modifications are sent to AOFS and OFSs to achieve packet flow handover to the appropriate AP. Fig. 4 shows the hierarchical architecture of the proposed scheme for forwarding packets inside the main domain. Also, Fig. 4 points to the NID (red), SID (green), and HID (blue) parts of the IPv6 address for the train. Receiving S_H urges the APn to start layer 2 handover by notifying the SDNc to make decisions and actions to direct the flow session of the train between the APs seamlessly. This proactive procedure enables the APn to be ready to host the connection with the train, while it is still associated with the APc. The handover begins based on changing the quality parameters of the links. We rely on the received signal strength indicator (RSSI) parameter in our proposal, which can be used by the AP to predict the distance between it and the train. So, the handover procedure is started by the AP to deliver the data to the train.

D. Packet Flow Forwarding Scenario

When a mobile device changes its attachment point from one AP to another, it is required to register to the new AP at the layer 2 level. This means this registration can be made without changing the prefix (64 bits) of the IPv6 address. This process decreases the handover latency and helps to keep on-going connection without any lapse as the train moves between APs. This scenario has proposed as the train traverses between APs within one subdomain. Fig. 5 represents forwarding of packet flow between the train and the APc, which is controlled by the OFS flow table created by the SDNc. This means that the AOFS flow table entries are not modified when the train transits between the APs of one subdomain. Fig. 6 shows the path switching of the packet flow when the train moves from the APc to the APn in the same subdomain. We can recognize from Figs. 5 and 6 that the responsibility of OFS is to manage this flow within one subdomain, according to its flow table made by the SDNc. At the same time, S_H is received by the APn to provide information to commence a layer 2 handover between it and the train's AP.

Fig. 7 shows the last AP of a subdomain that is providing services to the train as the APn of another subdomain receives S_H. In the meantime, the flow table entries of the OFS and AOFS do not change until the SDNc decides the right time to send

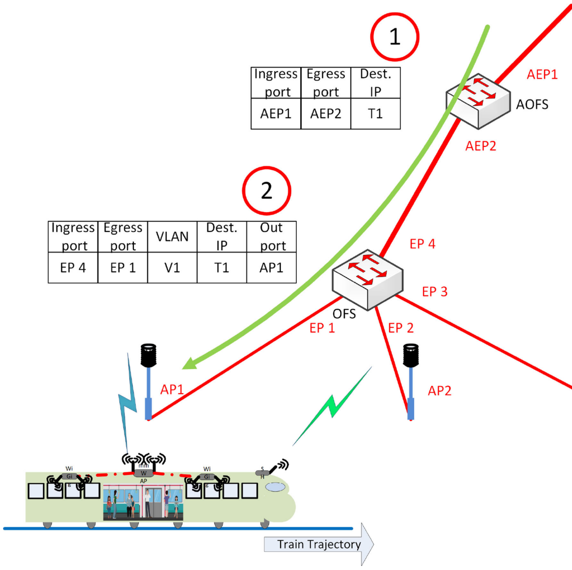

Fig. 5. Packet forwarding based on the flow table within one subdomain.

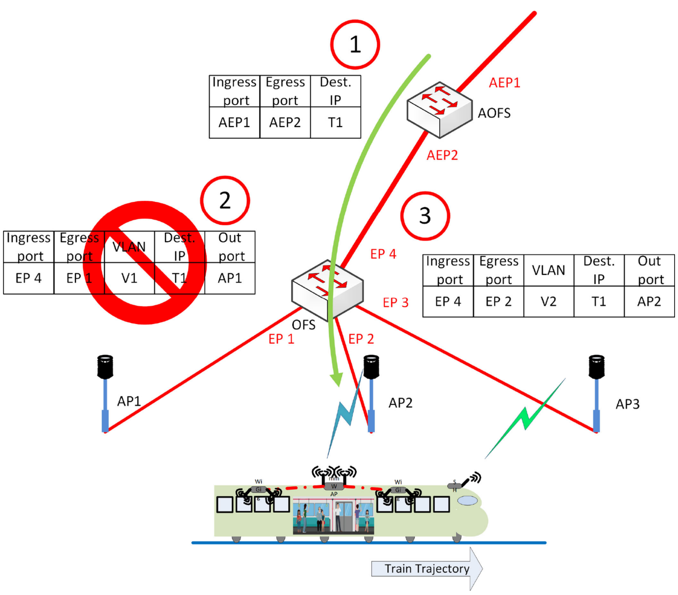

Fig. 6. Packet forwarding based on the modified flow table within one subdomain.

modifications to the AOFS and the OFSs of the new subdomain. Fig. 8 explains the events of packet handover between adjacent subdomains. After the SDNc finishes processing the incoming information from the APn as a result of the train's movement, the SDNc sends amended flow tables to the AOFS and OFS to handle the packet flow.

IV. Distance Estimation and RSSI

The SDNc has a holistic view of the software-defined network topology and knows about the global positioning system (GPS) coordinates of the APs, the train speed and the train destination, HID, and quality-of-service provision of all the software-defined network's APs. The SDNc can estimate the suitable time to be

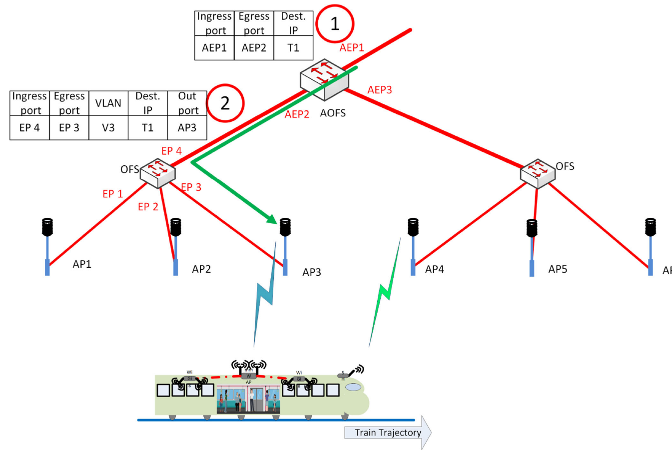

Fig. 7. Packet forwarding based on the flow table between adjacent subdomains.

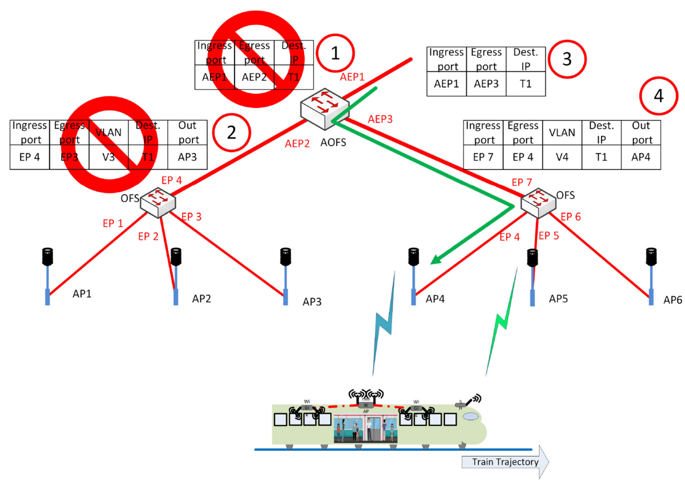

Fig. 8. Packet forwarding based on the modified flow table between adjacent subdomains.

associated with the coverage range of the APn through measurements that are executed by the SDNc. These measurements are based on the information that is sent by S_H as well as that programmed and saved in the applications layer and the control layer of the software-defined network.

Fig. 9 illustrates the essential time sequence of the proposed procedure. The procedure begins when the APn receives S_H and then forwards this information to the OFS, which forwards to the SDNc to change the path of that session based on modifying the OFS flow table. This procedure occurs when the train moves between two APs within one subdomain. And, when the train crosses from one subdomain to another, the SDNc dictates its rules and actions to the AOFS and OFS to alter the session flow path based on the modified flow tables on the AOFS and OFS.

The SDNc measures the distance between the train and the APn by using the GPS coordinates of the two. The two-dimensional space distance separating two positions can be calculated by the famous Pythagoras theorem and can be expressed as

$$D_{T_i}^{\mathrm{APn}} = \sqrt{(x_1 - x_{Ti})^2 + (y_1 - y_{Ti})^2} \tag{2}$$

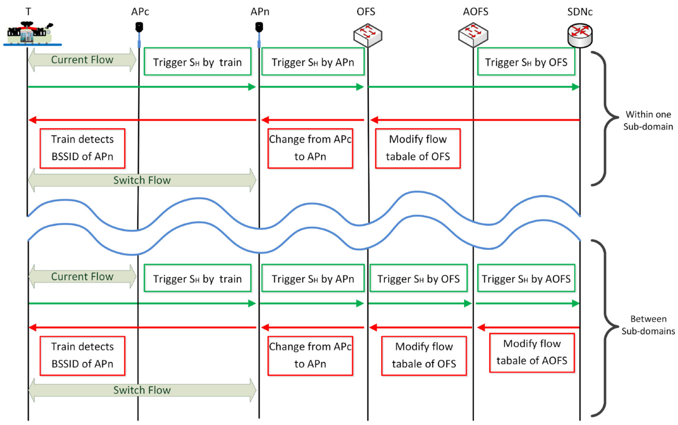

Fig. 9. Association with the APn: with and without the support of S_H.

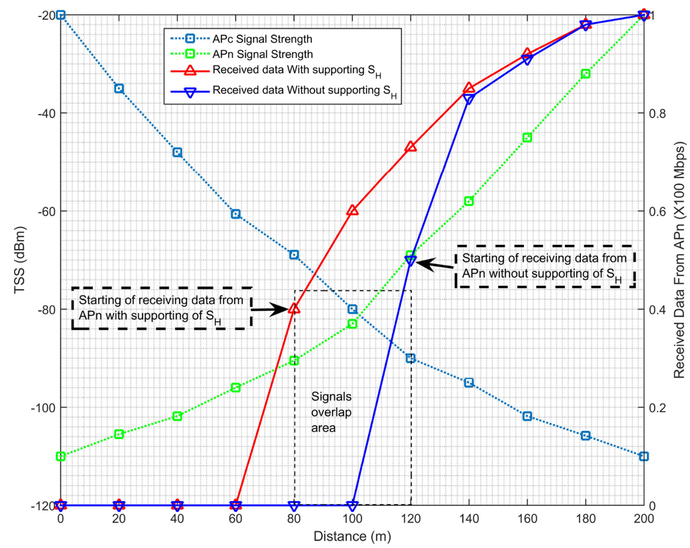

Fig. 10. Association with the APn: with and without the support of S_H.

where $D_{T_i}^{\text{APn}}$ is the distance between the train i and the APn, x_1 and y_1 are the coordinates of the APn, while x_{Ti} and y_{Ti} are the GPS coordinates of the train i.

Measuring the RSSI does not refer directly to determining the position of the train. However, it can be used to form an equation in terms of changing the distance between the train and the APn. Suppose the train sent S_H with power $P_{Re D_{T_i}^{\text{APn}}}$ at the distance $D_{T_i}^{\text{APn}}$, $P_{Re_{D_0}}$ is the RSS at a specific known distance D_0, and the wireless wave propagation in free path loss γ equals 2 [39]. We can get (3) as follows:

$$P_{Re_{D_{T_i}^{\text{APn}}}} = P_{Re_{D_0}} - 10 \times \gamma \times \log\left(\frac{D_{T_i}^{\text{APn}}}{D_0}\right). \tag{3}$$

The conversion from mW to dBm, or from dBm to mW, can be done by (4), or (5), as

$$P_{Re_{D_{T_i}^{\text{APn}}}}(\text{dBm}) = 10 \times \log[P_{Re_{D_{T_i}^{\text{APn}}}}(\text{mW})] \tag{4}$$

$$P_{Re_{D_{T_i}^{\text{APn}}}}(\text{mW}) = 10^{\frac{P_{Re_{D_{T_i}^{\text{APn}}}}(\text{dBm})}{10}}. \tag{5}$$

When γ equals 2, (3) can be written as follows:

$$\frac{P_{Re_{D_{T_i}^{\text{APn}}}}}{P_{Re_{D_0}}} = \left(\frac{D_{T_i}^{\text{APn}}}{D_0}\right)^2. \tag{6}$$

Thus, the distance between the train and the APn can be found by the RSS (S_H) at the distance $D_{T_i}^{\text{APn}}$ and the RSS ($S_{H_{D_0}}$) at the reference distance D_0, as

$$D_{T_i}^{\text{APn}} = D_0 \times \sqrt{\frac{S_H}{S_{H_{D_0}}}}. \tag{7}$$

Equation (7) can be used to determine the distance between the train and the APn ($D_{T_i}^{\text{APn}}$). Also, it is utilized to discover the position of the train for making the handover decision. $D_{T_i}^{\text{APn}}$ calculated by (7) is based on the geographic points of the X as well as Y-axis and the RSS of the S_H received by the APn with the help of GPS. All the locations of APs are known and at fixed positions in advance, being saved by the SDNc, which can use this information to steer packet flows in the software-defined network.

From the predicted $D_{T_i}^{nA}$ and the known T_s, the SDNc can decide the appropriate time to change the packet flow between APs. Fig. 10 shows the impact of utilizing S_H on link switching when the train enters a signals overlap area (it is 40 m where the lowest transmitted signals of APs can be received by the HST) of the APc and the APn. By using S_H, the link switch starts at an earlier time than when not deploying it. In other words, the start of the link switch is prepared and executed by the SDNc as the APn receives S_H even the signal strength of APc is larger than APn. Using S_H improves the seamlessness handover due to the proactive preparation of layer 2 handover in software-defined network. Consequently, regarding packet loss, throughput data rate, session interruption, and handover delay all these terms are enhanced.

Also, Fig. 10 shows the impact of using S_H on receiving data from the APn when the HST enters the overlap area. By utilizing it, the HST can receive data at almost -80 dBm, which represents the minimum value of the transmitted signal strength (TSS), i.e., the transmitted power by the APn to be obtained by the data from the APn by the HST. This TSS value can practically be detected, and the data can be extracted by the HST. Also, from the figure, we can observe that the support of S_H enables the HST to receive data from the APn at a distance of 20 m before the crossing point of the APc and APn signals at mid-distance between them. The amount of data the HST has obtained are almost 40 MB of the overall data of 40.8 MB that have been injected by the simulated scenario along the overlap area, while the HST could not obtain any data from the APn when not supported by S_H until the TSS of the APn hit the value of -70 dBm. This improvement in receiving the data has been achieved through proactive triggering of the SDNc to change packet flow direction from the APc to the APn. Without using S_H, the link switch (switch from APc to APn) only happens when the train was in the area where the TSS of the APn is

TABLE II
RESULTS OF MEASUREMENT CALCULATIONS

T_s	Bandwidth			Data amount within 40 m overlap area	Distance crossed within 50 ms	Data amount within RF registration delay 50
	100 Mbps	1 Gbps	10 Gbps			
98 m/s	1.02 Mb/m	10.2 Mb/m	102 Mb/m	40.8 Mb for (100 Mbps)	4.9 m	4.998 Mb for (100 Mbps)
				408 Mb for (1 Gbps)		49.98 Mb for (1 Gbps)
				4080 Mb for (10 Gbps)		499.8 Mb for (10 Gbps)
56 m/s	1.786 Mb/m	17.86 Mb/m	178.6 Mb/m	71.44 Mb for (100 Mbps)	2.8 m	5.0008 Mb for (100 Mbps)
				714.4 Mb for (1 Gbps)		50.008 Mb for (1 Gbps)
				7144 Mb for (10 Gbps)		500.08 Mb for (10 Gbps)
28 m/s	3.571 Mb/m	35.71 Mb/m	357.1 Mb/m	142.84 Mb for (100 Mbps)	1.4	4.9994 Mb for (100 Mbps)
				1428.4 Mb for (1 Gbps)		49.994 Mb for (1 Gbps)
				14284 Mb for (10 Gbps)		499.94 Mb for (10 Gbps)

larger than that of the APc. In this case, the SDNc receives delayed information about the train's position in preparation for changing the path of the packet flow from the APc to the APn.

V. NUMERICAL MEASUREMENT

To determine the amount of data that exist within 1 m for a specific throughput with respect to a specific T_s, the following equation can be used:

$$M_d(\text{Mb/m}) = \frac{Thr(\text{Mb/s})}{T_s(\text{m/s})} \tag{8}$$

where M_d is the amount of data per meter regarding a certain throughput Thr of a particular bandwidth. The AP signals' overlap area is 40 m and RF registration is 50 ms as a minimum value of layer 2 RF registration delay time. The maximum probability of packet loss within the overlap space (40 m) can be calculated by the following equation:

$$P_{\text{loss}} = \frac{\text{DM}_{\text{overlap}} \times \text{RF}_{50\text{ ms}}}{1518 \times 8} \times \frac{1}{\text{DR}_{\text{overlap}}} \tag{9}$$

where $\text{DM}_{\text{overlap}}$ is the amount data that can be transmitted by APs at a certain T_s and bandwidth, $\text{RF}_{50\text{ ms}}$ is the time delay of RF registration, and $\text{DR}_{\text{overlap}}$ is the average received data when the train is within the signals' overlap area. Table II shows the calculated numbers based on our proposal.

The amount of data per meter that should be transmitted by APc or by APn within the overlap area have been estimated by (9), according to different bandwidths and different train speeds (as shown in Table II). These calculations have been used to predict the packet loss and the average of received data.

Fig. 11 illustrates the percentage of the probable number of lost packets within the overlap distance. The figure shows that the rate of lost packets increases due to a rise in the capacity of the channel bandwidth and with the increase in the speed of the train. The increase in the percentage of lost packets is due to the increase in the data amount (MB) existing in the distance unit (m). This means the APc or APn transmit data rate per unit time per meter (Mb/s/m) depends on the channel bandwidth capacity; hence, every meter crossed by the HST not connected to APc or APn will increase the number of lost packets. Also, the number of lost packets increases with an increase in the speed of the HST, i.e., the traversed meters by the HST for 1 s will be higher when it moves quickly than it runs slowly. That is, the HST crossing a relatively long distance without it is associated with neither APc nor APn. By way of explanation, the number of lost

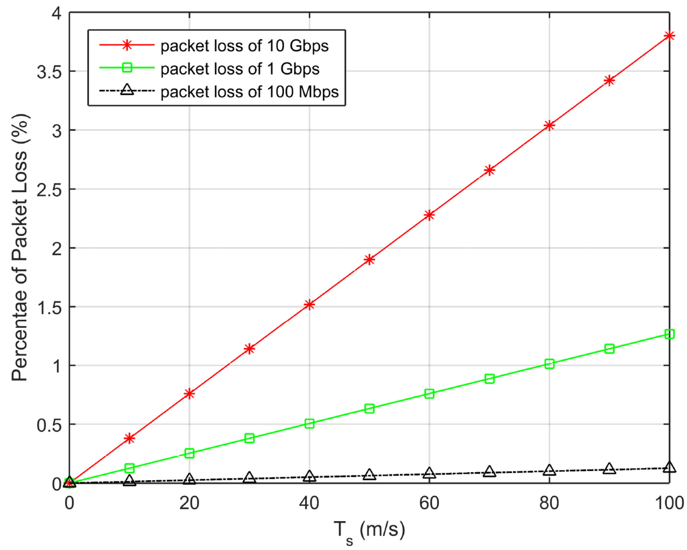

Fig. 11. Lost packets for different throughput versus T_s.

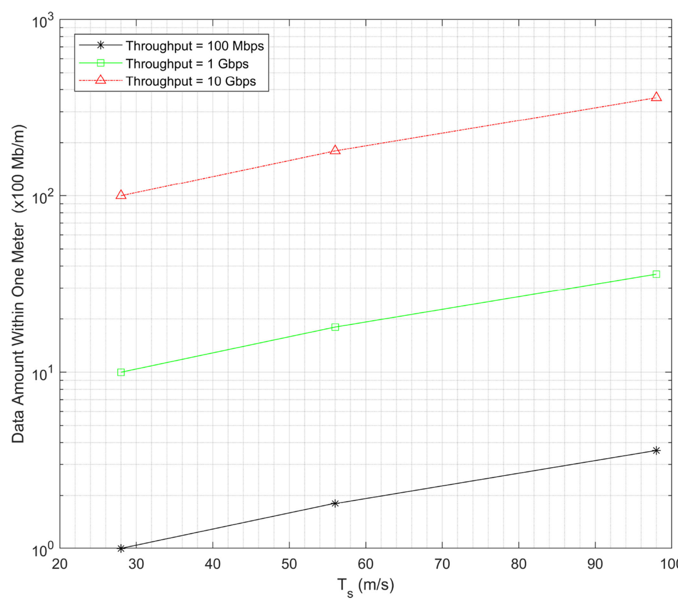

Fig. 12. Data amount per meter against different values of T_s.

packets depends on the layer 2 RF registration time that the train needs to connect with the APn. That is, a long RF registration time leads to a large number of packets being lost. Furthermore, when the train moves fast, it will move a longer distance than when it is slower, but the same amount of time is required to complete the RF registration (50 ms to associate with the APn).

Fig. 12 shows the data amount per meter with different values of a channel throughput versus different train speeds related to 50 ms. The data amount per meter increases exponentially with increasing channel throughput. In other words, the number of bits in each meter jumps to a high value due to the capacity of the transmission channel (100 Mb/s, 1 Gb/s, and 10 Gb/s). On the other hand, an increase in T_s (as proposed 28, 56, and 98 m/s) leads to an increase in the number of meters that are traversed by the HST within 50 ms.

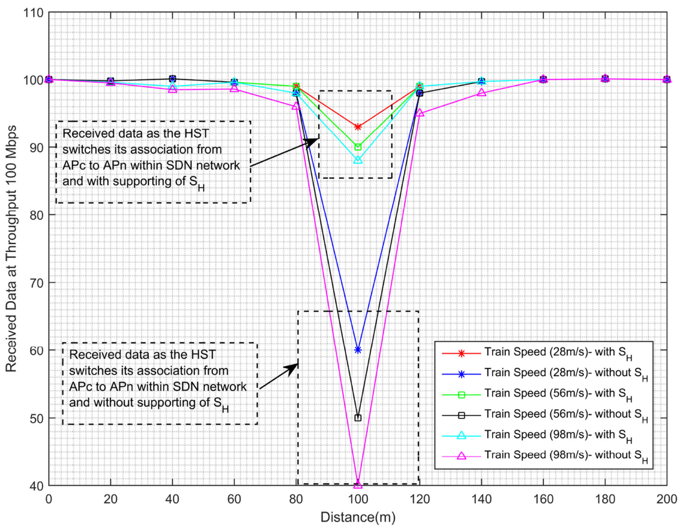

Fig. 13. Average amount of received data when the HST crosses signals' overlap area.

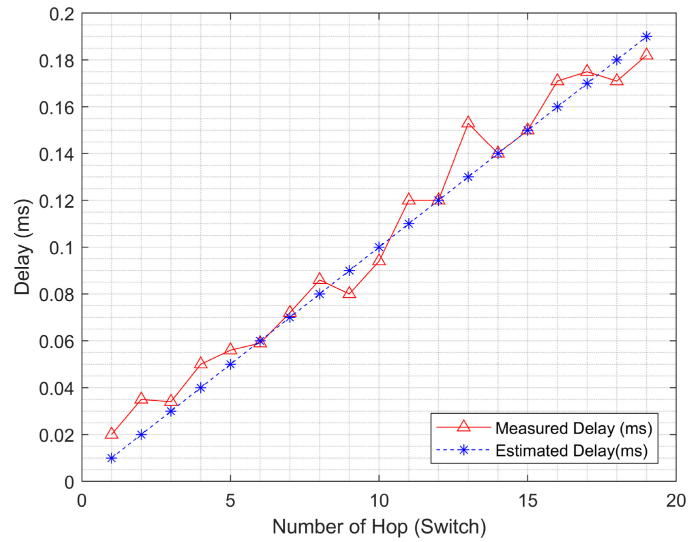

Fig. 14. Path delay of the control packets corresponding to the number of switches.

Fig. 13 shows the received data against T_s when the HST traverses between the APc and the APn within the proposed software-defined network. Suppose that the throughput of the channel capacity is 100 Mb/s. Then, the obtained results show that the received data with supporting S_H are higher than those reported without it as a proactive signal to start path modification by the SDNc. We considered an overlap distance of 40 m (between 80 and 120 m) for collecting the data. The line graph above represents the average data received by the HST from the APc and the APn together. It can be seen that the proactive scheme of layer 2 RF registration improved the software-defined network performance in handling the packet flow between the APs. This improved performance appeared in the received data at the signals overlap area. The HST received 93%, 90%, and 89% of the data existing in 40 m of the overlap distance at different values of T_s of 28, 56, and 98 m/s, respectively. In contrast, the received data percentages were 61%, 52%, and 40% before using S_H. This degradation in received data percentages is due to the reactive system of the SDNc to direct the packet flow between the APs without the support of S_H.

To build and manage a dynamic network in an SDN environment. The SDNc should exchange control messages (packets) with the other devices (OFSs) to handle the data flow within the network. We have considered the delay (transmission, process, and queue) in successive devices along the whole path instead of a delay in each device belonging to that path. By pinging the SDNc from any AP (host), we can notice the overall delay time of packets within the round trip time required to finish its journey. This constitutes three delay times making up the total (t_{tot}), namely, the RTT (the whole delay time that is required by a signal to be acknowledged by the destination includes the propagation delay for the paths between a sender and receiver) between the SDNc and the OSF (t_{OFS}), the RTT between the SDNc and the AOSF (t_{AOFS}) and the link delay (t_{link}). We represented the delay time by the following equation:

$$t_{\text{tot}} = t_{\text{link}} + t_{\text{OFS}} + t_{\text{AOFS}} + \text{Cal} \quad (10)$$

where Cal represents the SDNc calibration with a variable value and corresponds to the constraints of the SDNc. Fig. 14 shows that the estimated delay values increase with an increase in the number of hops. The measured values are obtained from the hop number multiplied by the offset value of the SDNc [40]. Moreover, we can see from Fig. 14 that the path delay is linear with increasing the number of the switches that are linked serially in the software-defined network.

VI. Testbed Setup and Implementation

A Mininet simulator, Python network programming, and MATLAB software have been used for the virtual realization and implementation of the proposed software-defined network with supporting physical AP devices.

1) *Mininet simulator:* This is a network emulator that can design and imitate a complete OpenFlow network locally on a desktop or laptop computer. It builds virtual network devices such as hosts, links, switches, and controllers. The hosts run on the Linux system software. The switches support OpenFlow for very flexible manner routing and subject to be controlled by the internal or external SDNc. Mininet supports research, learning, development, prototyping a network, testing, and performing a complete experimental network on a desktop or laptop. It affords a suitable and reasonable for network testbed, allows for complex topology testing without wiring up any physical devices, supports random system topologies, and provides an extensible Python API for experimental network production.
2) *Python network programming:* This is a comprehensive object-oriented programming method, which includes a standard library that covers everything demanded for quickly creating effectual network applications. Moreover, Python has a diverse of third-party libraries and combinations that expand Python to all field of network programming and topology creation.

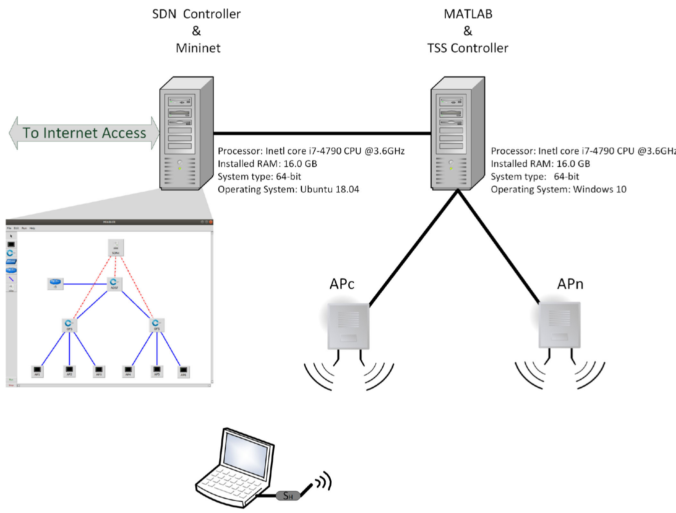

Fig. 15. Testbed setup block diagram.

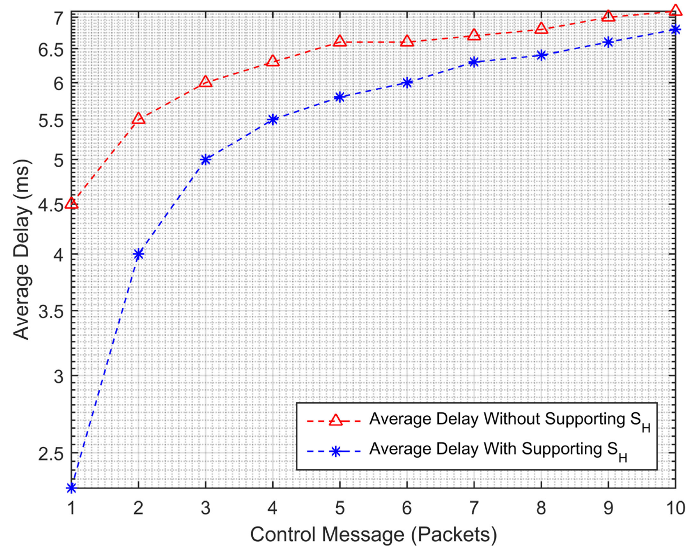

Fig. 16. Impact of S_H on the average delay of control packets.

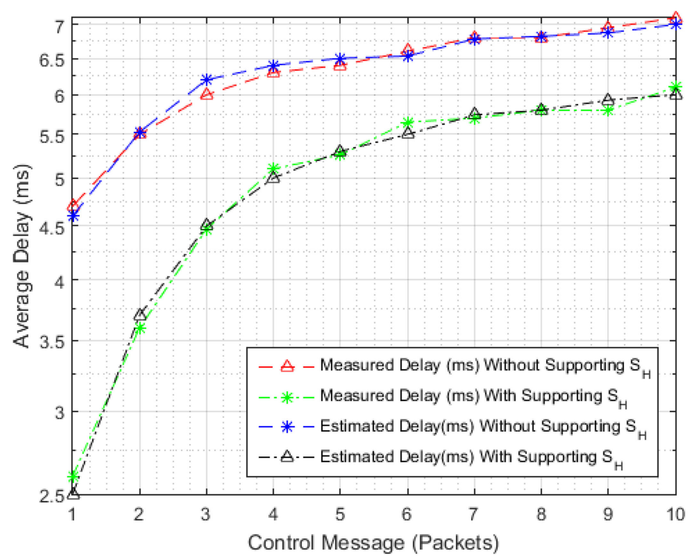

Fig. 17. Measured and estimated delay comparison for control packets.

3) *MATLAB platform:* This has been employed to assess the performance of the proposed software-defined network. In addition, it has been used to interface and control the physical AP devices.

To simulate the connection change between the train and APs (handover), we utilised two APs which represent (APc and APn). By regulating the TSS of both in which the TSS of APc decreases the TSS of APn increases at the same time and the same value simultaneously. This process represents and mimics the assumed movement of the HST that should move from the APc to the APn. The crossing point of the curves in Fig. 10 represents the threshold point of the TSS of the APs and at this point, the train can receive data packets from APc and APn. This process has been simulated and coded by the MATLAB platform. 400 packets have been injected by the programming code to the APs during the handover procedure. Handling the packets' path direction (switching from APc to APn) is based on the Mininet VM, which includes the SDNc, AOFS, and OFSs. We neglected the wireless registration procedure, i.e., the RF registration (authentication, authorization, and accounting).

Fig. 15 illustrates the testbed setup of the proposed network implemented to emulate the software-defined network. The Mininet network has been configured using the Python programming language. The experiment topology consists of three switches (two OFSs and one AOFS) linked by the SDNc, and six hosts represent the APs connected by the OFSs. For simplicity, we connected two physical APs that are controlled and interfaced by Python and MATLAB coding. In the first experiment scenario, we performed the measurements to see the control delay when the injected data change its path from the APc to the APn without the support of S_H. The second experiment scenario was carried out in the same way, but this time S_H was utilized.

The comparison of the effect of using S_H on the average delay values is presented in Fig. 16. From the results displayed in the figure, we find that the average delay values without using the proactive signal are higher than when S_H is deployed. In fact, the average delay almost is halved when using it. The software-defined network can be enhanced by using a creative idea to improve the performance of the software-defined network through reducing the delay of both the CP and the data plane. Fig. 17 shows the measured delay and estimated delay for the experimental scenarios, with the parameters for these being listed in Table III. The performance of the proposed software-defined network is improved by using the proactive scheme versus the reactive scheme for both the measured and the estimated controlling delay. The overall test period was 100 s. We configured and programmed the network based on the HST sending its S_H, which is received by the APc, and at that instant, the APc pings the SDNc to make the flow decision. This process is configured to happen after 20 s of beginning the test. To mimic the transferring of the HST from the APc to the APn, we controlled the TSS of the APc by attenuating its

TABLE III
TESTBED SETUP PARAMETERS

Item	PC1	PC2
Type	hp	hp
CPU Vendor	Intel(R)	Intel(R)
CPU Type	Core i7-4790 @ 3.60 GHz	Core i7-4790 @ 3.60 GHz
RAM	16 GB	16GB
Host Operating System	Windows 10	Ubuntu 14.4
Host Software	MATLAB R2017b	Python 3.7.0, Mininet 2.2.1

TABLE IV
HARDWARE AND SOFTWARE USED IN THE TESTBED

Parameters	Value
T_s	28, 56, 98 m/sec
Packet Size	1522 Byte
Control Messages	10 message
Overlap Distance	40 m
Delay Per Link	0.001 msec
Processing Delay	0.005 msec
OFS Modifying Delay	0.005 msec
AOFS Modifying Delay	0.005 msec
SDN Modifying Delay	0.010 msec
Layer 2 RF Registration	50 msec
Test Duration	100 sec
Test Repetition	10 Times

TSS; at the same time, the TSS of the APn increases according to the time increasing. By doing so, the handover between the APs has been mimicked. The injected data starting at TSS equal -80 dBm to represent the proposed data that should be in the signals' overlap area. The amount of data in this area are expressed as the throughput rate of the proposed channel capacities (40.8–14 284 MB for 100 Mb/s and 10 Gb/s). The experiment setup was constructed by using two *hp* computers as workstations for this paper, which have the specifications provided in Table IV.

In Fig. 17, a comparison between the measured and estimated delay values with the support of S_H and without S_H for both cases is depicted. The figure shows that the practical and predicted results scored higher delays when S_H was not utilized as a triggering signal than when it, with the corresponding estimation deviation varying from 0.02 to 0.27 ms. Also, from Fig. 17, it can be observed that for both cases of estimated and measured results, the proactive scheme of directing the flow of packets is developed by using S_H in the software-defined network. The control delay has experienced a noticeable reduction in the measured values by utilizing S_H. This reduction in the delay can be observed at the launch of making the decision by the SDNc to switch the packet flow path. This decrease in the delay is due to proactive processing of control messages that are exchanged by the SDNc, AOFS, and the OFSs to switch the packets stream from APc to APn. The same observation of control delay can be seen with the predicted values. That is, this decreases at the beginning of taking the decision to change the packet flow path between the APs.

VII. CONCLUSION

Virtualization has added exceptional features to communication networks, such as cloud computing, SDN, NFV, etc., which have led to improvements in performance. Despite these techniques having been applied, communication networks still need new creative ideas to meet the demands of the vital matters, such as reducing delay, dealing with high data rate throughput, enhancing reliability, guaranteeing session continuity, etc. Our proposal for an software-defined network environment was to serve HSTs and provide results in a low controlling delay and high data rate delivery. We obtained the advantages of our proactive scheme through the reduction of the number of controlling delay messages between the SDNc and the underlying OFSs. Moreover, our technique results in a decrease in the number of lost packets during the handover procedure in both the cases of increasing the channel bandwidth capacity and the train speed. Given the achieved results, we conclude that the obtained results indicate that there is a need to find innovative ideas to enhance and support the virtualization techniques, for forwarding and directing flows of packets and reducing packets loss, which is greatly influenced by the speed of HSTs and the capacity of the data transmission link.

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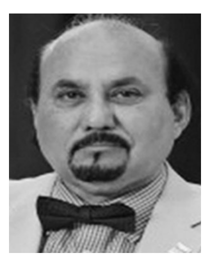

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