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Quality Management of Surveillance Multimedia Streams Via Federated SDN Controllers in Fiwi-Iot Integrated Deployment Environments

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ABSTRACT Traditionally, hybrid optical-wireless networks (Fiber-Wireless - FiWi domain) and last-mile Internet of Things edge networks (Edge IoT domain) have been considered independently, with no synergic management solutions. On the one hand, FiWi has primarily focused on high-bandwidth and low-latency access to cellular-equipped nodes. On the other hand, Edge IoT has mainly aimed at effective dispatching of sensor/actuator data among (possibly opportunistic) nodes, by using direct peer-to-peer and base station (BS)-assisted Internet communications. The paper originally proposes a model and an architecture that loosely federate FiWi and Edge IoT domains based on the interaction of FiWi and Edge IoT software defined networking controllers: the primary idea is that our federated controllers can seldom exchange monitoring data and control hints the one with the other, thus mutually enhancing their capability of end-to-end quality-aware packet management. To show the applicability and the effectiveness of the approach, our original proposal is applied to the notable example of multimedia stream provisioning from surveillance cameras deployed in the Edge IoT domain to both an infrastructure-side server and spontaneously interconnected mobile smartphones; our solution is able to tune the BS behavior of the FiWi domain and to reroute/prioritize traffic in the Edge IoT domain, with the final goal to reduce latency. In addition, the reported application case shows the capability of our solution of joint and coordinated exploitation of resources in FiWi and Edge IoT domains, with performance results that highlight its benefits in terms of efficiency and responsiveness.

INDEX TERMS Fiber wireless (FiWi), Internet of Things (IoT), software defined networking (SDN), quality management, federated SDN controllers.

I. INTRODUCTION

Software Defined Networking (SDN) is gaining more and more attention as a new model to overcome traditional issues of network management solutions, such as limited reconfigurability and complexity of managing traffic in a per-flow differentiated management [1]. The well-known main principle of SDN is the clear division between the control plane and the data plane. The former is in charge of i) achieving a logically centralized point of view of the network, ranging from overall topology to per-node capabilities and current loads, ii) gathering application-level requirements for currently supported services, e.g., distributing a multimedia stream to multiple destination nodes with possible awareness of their locations, iii) making control decisions based on the centralized point of view to improve overall Quality of Service (QoS), e.g., by reducing inter-flow traffic interferences of competing applications, and iv) dynamically reconfiguring nodes to ensure the achievement of targeted goals. The latter is in charge of dispatching packets from sources to destinations, by transparently taking advantage of the control plane, which properly configures the mechanisms that rule how nodes should manage incoming/outgoing traffic.

Traditionally, SDN has emerged in the communication research and industrial fields primarily to manage switches of closed environments such as datacenters and department networks via the OpenFlow protocol [2], the de facto standard supported by networking industrial-grade devices. However, we believe that the adoption of SDN techniques is crucial to efficiently manage QoS also in more open, distributed, and heterogeneous deployment environments. In particular, the paper specifically considers a multi-domain environment consisting of a) Edge Internet of Things (IoT) networks and b) Fiber-Wireless (FiWi) access networks. This FiWi-IoT integrated deployment environment is of central relevance for Smart Cities, where our goal is to efficiently and effectively support Smart City applications involving:

- vanilla sensors and actuators provided not only by the municipality infrastructure but also by participating citizens;
- mobile volunteer nodes extending the traditional network by supporting peer-to-peer ad-hoc packet dispatching as well as service provisioning in an impromptu way.

In particular, on the one hand, the Edge IoT domain consists of the network infrastructure (based on cable/wireless communication links) exploited by the Smart City to deploy sensors and actuators (ranging from temperature sensors and surveillance cameras to variable message signs to inform drivers) and provide services close to sensors and actuators themselves (such as surveillance applications in control rooms), together with management features to support the efficient dispatching of packets among devices and applications. On the other hand, the FiWi domain is composed of the hybrid optical-wireless network infrastructure aiming at providing high-bandwidth and low-latency access to cellular-equipped devices, including both smartphones and the fraction of Edge IoT nodes with cellular capabilities. The two domains are traditionally managed in a completely disjoint manner, with no possibility of influencing the behavior of one another or even sharing monitoring/management information. This silos-based approach has simplified the development and management of the associated networks. However, nowadays a sharp separation of the two does not allow to fully exploit the potential of novel scenarios, e.g., multimedia streaming in emergency situations in a Smart City, demanding for both performance and flexibility.

We claim that, to enable QoS management and improve the end-to-end Quality of Experience (QoE) in Smart City scenarios, it is recommendable to adopt a novel, inter-domain, and federated SDN approach. Nowadays the state-of-the-art in the field is to deploy "regularly" independent SDN controllers for each domain, as it is emerging with mature proposals for traffic engineering and management that exploit the specific characteristics and resource allocation properties of the targeted environments (e.g., SDN controllers specialized for the FiWi domain [3], [4]). However, we further push forward what is currently emerging in the recent literature by originally proposing that these "regularly" independent SDN controllers should federate to exchange critical and concise monitoring indicators together with control/re-configuration hints in order to manage the integrated Edge IoT and FiWi domains in a synergic way. The proposed solution is based on very loose integration (federation) of SDN controllers, so to maintain "regular autonomy" and minimum intrusiveness, with good overall performance and scalability.

To better clarify the objectives of our proposed integrated solution, Section III outlines the notable use case of an emergency situation requiring to provide multimedia streams generated by fixed surveillance cameras in the Edge IoT domain to mobile smartphones of dynamically identified emergency personnel. To serve the multimedia stream in an effective manner, there is the need for the cooperation of the Edge IoT and FiWi domains, the former to identify emergency personnel and reroute multimedia streams towards their smartphones, the latter to support the delivery of the traffic ensuring high priority, high-throughput, and low-latency packet dispatching.

In short, we claim that this paper provides the community of researchers in the field of integrated FiWi-Edge IoT deployment environments for Smart Cities with an original and innovative proposal that advances the state-of-the-art with the following contributions: i) a novel integrated architecture and model where federated SDN controllers collaborate synergically for QoS management, ii) innovative guidelines on how to make SDN controllers in different domains (FiWi and Edge IoT) exchange few critical monitoring information about relevant multimedia flows, iii) how to apply the proposed architecture and model to the notable case of quality management of surveillance multimedia streams in unexpected emergency situations, and iv) first quantitative performance results that demonstrate the feasibility and effectiveness of the proposed approach (to the best of our knowledge these are the first reported performance results about the joint usage of SDN controllers in FiWi-Edge IoT integrated domains).

The remainder of the paper is organized as follows. Section II provides the readers with the needed background about FiWi and Edge IoT domains, while the following Section III presents our original architecture while supporting the running example of an emergency situation with multimedia surveillance streams. Then, the paper presents design and implementation guidelines on how to federate our SDN controllers in a lazy and lightweight way. Performance results, primary open technical challenges in the field, and conclusive remarks end the paper.

II. FIWI AND EDGE IOT BACKGROUND

As better detailed in the following sections, the proposed solution based on the loosely integration of FiWi and Edge IoT domains allows to improve end-to-end QoS management in this area. This has the potential to leverage the spread of novel scenarios based on the dynamicity of spontaneous networking (where nodes share computing/networking resources and provide new services in a peer-to-peer way) but with the quality goals of the FiWi domain, with typically optimized latency, bandwidth, and number of supported mobile users.

Before presenting our proposed framework and to facilitate its full and easy understanding, the section outlines the needed background and the main characteristics of the two target FiWi and Edge IoT domains.

A. HYBRID OPTICAL-WIRELESS ACCESS NETWORKS

The integration of optical and wireless networks provides a cost-effective and flexible access network, which combines the huge bandwidth potential of the optical domain, in the backhaul, and the advantageous characteristics the wireless networks, in the fronthaul, such as mobility, reachability, roaming, and mobile service provisioning. In essence, the integration of optical and wireless domains in a single access network defines a FiWi access network, which is divided into two main categories based on the level of integration, namely Radio over Fiber (RoF) and Radio and Fiber (R&F). While the RoF concept has low practical value since it entails complex PHY operations such as converged modulation, coding, and transmission, R&F seems nowadays to be much more functional and applicable. R&F paradigms allow flexible architectures without imposing serious modifications in the radio and fiber domains. As a result, efficient and cost-effective topologies are feasible, thus allowing an effective way of converging multiple types of optical solutions with various wireless/cellular technologies [5].

The R&F architecture comes with two main paradigms in the literature: optical-wireless mesh networking and optical-wireless (broadband) access networking (or hybrid optical-wireless access networking). In the former case, several wireless routers and a number of gateways are connected to an optical device, e.g., to the Optical Network Unit (ONU) in the case that a Passive Optical Network (PON) is used as the main technology for the backhaul of the network, and thus to the network backbone and the Internet. It is worth mentioning that this kind of hybrid network introduces a routing sub-network at the edges, where multiple wireless nodes (smartphones, sensors, IoT devices, vehicles, and anything that is considered mobile and is identifiable via an IP address) are indirectly connected to the optical backhaul through multiple gateways and relay wireless links. In the latter case, optical-wireless access networks employ multiple users and nodes that are connected to a hybrid BS equipped with two interfaces, i.e., the optical interface that terminates the optical fiber and the wireless interface that provides a 4/5G radio interface (cell, macrocell, or picocell). Details about the components of a hybrid optical-wireless FiWi architecture are provided in [6].

In the context of this paper, the former paradigm is adopted where multiple mobile users (or nodes) are connected each other in an ad-hoc basis (see Figure 1, top box). The optical domain in the fronthaul is a PON infrastructure where various PON technologies could be used, i.e., Ethernet PONs, Gigabit PONs, or multi-wavelength PONs. In the Central Office (CO) premises the Optical Line Terminal (OLT) is deployed, which acts as the main decision-making component of the optical domain. Then, the OLT is connected directly with the passive splitter/combiner via optical fiber; thus, single or multiple wavelength light-paths are created between the CO and the edge of the optical network. As a result, a cost-effective topology, mostly a tree topology, is realized that achieves several benefits such as low maintenance, protocol transparency, and low operation cost. At the edge of the optical network, the conventional ONU, which is used in pure PONs, is replaced by the enhanced ONU-BS consisting of two interfaces, an optical interface interconnecting the ONU-BS with the OLT through optical fiber and a radio interface, e.g., a Long-Term Evolution (LTE) radio access network. For instance, the architecture proposed in [7] introduces an ONU-eNB, where the optical interface supports an XG-PON system, while the radio interface supports an LTE network. The Evolved Packet Core (EPC), as part of the LTE radio technology, is located at the CO. Its architecture separates the user data (user plane) and the signaling (control plane) to make the scaling independent. Thus, telecom providers and operators could handle channel and (cellular) network configurations easily. In this way, two directions are defined, the downstream direction (supporting 9.95328 Gbps from the CO to the ONU-eNB) and the upstream direction (supporting either 2.48832 Gbps or even 9.95328 Gbps in a symmetric way).

Effective traffic engineering in FiWi networks is crucial for the provision of advanced QoE to users of hybrid next generation networks. A lot of interest was recently attracted by resource allocation techniques both at the optical and at the wireless domain. Most of the related research endeavors adopts the Dynamic Bandwidth Allocation (DBA) approach to improve QoS and energy efficiency in FiWi networks [8]. Another relevant factor, which has a high impact on traffic engineering, is resource allocation fairness [9], while network performance is maintained at high levels. Balancing fairness in bandwidth distribution with network efficiency is also the primary aim of the DBA scheme proposed in [10], which targets XG-PONs. At the wireless access domain, a number of techniques for the provision of QoS in heterogeneous wireless networks are presented in [11]. Game theory has arisen as a promising approach for fair resource allocation to mobile stations, as shown in [12]. Energy efficiency is of high importance for the autonomy of mobile devices and a major consideration of modern bandwidth distribution schemes, such as the Medium Access Control (MAC) protocol proposed in [13].

Finally, the integration of traffic engineering techniques traversing across the optical core and the wireless access domains represents a relevant challenge, currently addressed by the research community. Sarigiannidis and Nicopolitidis [14] have devised a holistic resource allocation solution in optical-wireless networks, focusing on balancing fairness and efficiency across WiMAX and 10-EPON sectors. A key aspect of this work is mapping service classes between optical and wireless domains in an effort to provide end-to-end

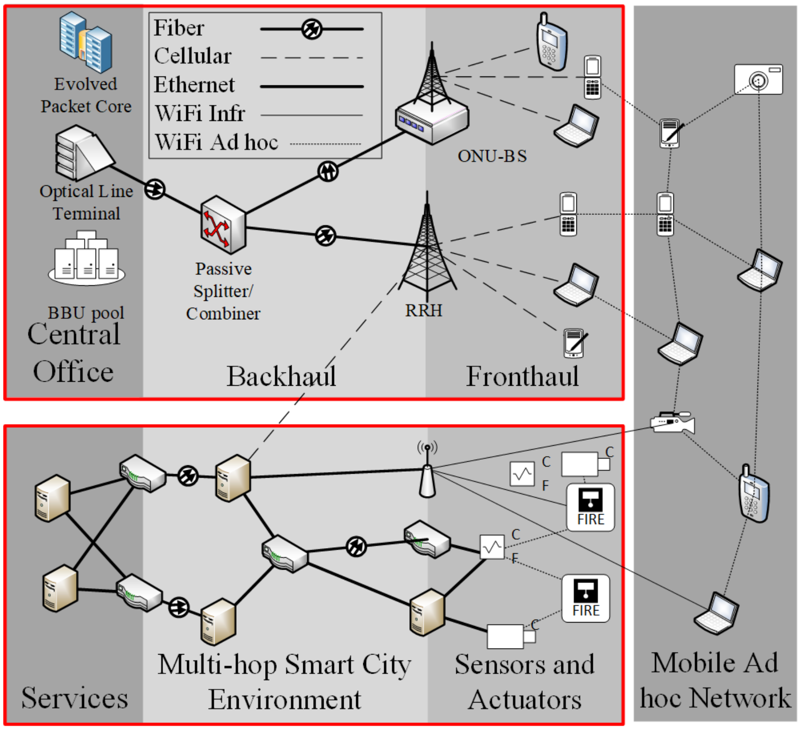


FIGURE 1. **Overall architecture with the FiWi access network (top box) and the Edge IoT environment (bottom box).**

QoS support. In more details, Unsolicited Grant Service (UGS), real-time Polling Service (rtPS), and Best Effort (BE) traffic services of WiMAX are mapped to Expedited Forwarding (EF), Assured Forwarding (AF), and BE classes of 10G-EPON, respectively. The bandwidth distribution process between the OLT and ONU-BSs is realized via the Multi-Point Control Protocol (MPCP). The former is used by the OLT to assign transmission opportunities to ONU-BSs, the latter is used by ONU-BSs to inform the OLT about its buffers' size and to ask for bandwidth allocation in the following frame. The related algorithm has demonstrated to efficiently balance fairness and performance.

B. EDGE IOT AND SPONTANEOUS MANETS FOR SMART CITIES

Smart Cities worldwide are embracing IoT technologies to streamline their operations and meet the growing expectations of their citizens. Just to provide some notable examples, consider that Smart Cities can provide a new generation of real-time and time-critical, location-, social-, and context-aware services to their digital citizens, such as for emergency and healthcare [15], surveillance [16], entertainment, and social good [17], [18]. Recent research activity has been focused on many different IoT-related topics such as event forecasting [19], WSN routing protocols [20], multi-sensor information fusion [21], business model and profit maximization [22], ontologies [23], service models [24], QoE [25], and even advanced concepts for the prioritization of raw data processing and information dissemination such as Quality of Information (QoI) [26] and Value of Information (VoI) [27]. Researchers have also developed a multitude of application-specific solutions for issues in diagnostics [28], [29], environmental monitoring [30], [31], and social interest [32].

To this purpose, the Edge IoT domain supports smart information processing, storing, and dissemination functions on top of a distributed architecture of software components running on top of i) fixed sensor systems to make easier the flexible dispatching of packets among nodes by exploiting an overlay network approach, ii) mobile nodes nomadically roaming and interacting with one another opportunistically by dynamically creating single-hop links and multi-hop paths, iii) edge devices located in proximity of either raw data sources or information consumers to more efficiently manage and distribute generated information, and iv) the Cloud with high performance nodes providing computing and storage services.

Figure 1 (bottom box) outlines how the Edge IoT network comprises not only sensors and actuators, but also services running in the Smart City itself together with network equipment (possibly connected to the FiWi domain). In addition, the figure outlines that mobile devices are able not only to get Internet connectivity from the FiWi and the Edge IoT domains, but also to take advantage of spontaneous ad-hoc interactions to create multi-hop mobile networks. In fact, we believe that smartphones will play a key enabling role, as they will be opportunistically adopted to dynamically extend and enhance the fixed environment, by dispatching data as well as by behaving as IoT devices that can monitor/control the surrounding environment. In particular, by taking advantage of their pervasive availability and increased software/hardware capabilities, smartphones will become an integrated part of Smart Cities and will collaborate to support multi-hop connectivity, by dynamically and directly interconnecting one another i) to create single-hop links in a peer-to-peer way and ii) to collaboratively dispatch packets by acting as intermediary nodes between senders and receivers (in addition to exploiting the ''more traditional'' availability of infrastructure connectivity, e.g., based on IEEE 802.11 Access Points).

In particular, the most relevant and specific property of the above multi-hop spontaneous networks (indicated later as spontaneous MANETs) is that they originate from the willingness of social interactions of people via impromptu interconnections of the personal devices they carry, e.g., smartphones, tablets, and laptops [33]. In spontaneous networks, devices discover and interact with one another opportunistically and without any prior mutual knowledge, by exploiting all supported connectivity opportunities, e.g., Wi-Fi or Bluetooth ad-hoc links and Long Term Evolution (LTE) infrastructure-based ones [34], [35]. In particular, group-related behavior and the ever-increasing willingness to share rich user-generated contents, also pertaining to the personal sphere, calls for a user-centric communication paradigm shift, where the ad-hoc interconnection of portable devices plays a central role. On the one hand, the user-centric nature of spontaneous networking partially relaxes the constraint of having infrastructure-based communication support (e.g., anywhere cellular coverage, which is often expensive). On the other hand, it naturally yields to very heterogeneous, uncoordinated, and dynamic networking environments where, for instance, any node can create its self-administered layer2 links. In addition, spontaneous networking nodes are expected to be able to take advantage of simultaneous exploitation of different communication interfaces to join/create multiple IP networks (via either ad-hoc or infrastructure connectivity); these networks are autonomously created, configured, and destroyed by collaborating users in a completely decentralized way.

It is worth noting that, traditionally, spontaneous network nodes take management decisions based on their limited scope visibility and without a global knowledge of network topology/conditions, by typically reacting to modifications in local resource availability. In fact, also because of its general-purpose and collaborative nature, spontaneous networking has usually focused on simplifying the dispatching of packets at multi-hop distance, eventually aiming at improving the QoS with a per-application view [36].

From a wider point of view, the efficient application and optimization of traffic engineering techniques have not been a primary topic in the MANET research area. While state-of-the-art literature recognizes the importance of improving QoS in MANET scenarios, traditional traffic engineering solutions based on strictly enforced resource allocation can be hard to adopt, in particular because of the general-purpose nature and the limited resources available over MANET nodes. In other words, MANET QoS has been mainly addressed so far by only considering localized visibility and decisions, e.g., based on link and path performance [37]. Abuashour and Kadoch [38] proposed a middleware solution to support timely MANET communications based on an adaptive approach where their solution reacts to dynamic network conditions by switching the employed channels to ensure their optimal and robust exploitation. Pease *et al.* [39] explored VANET QoS issues: in particular, they aimed at increasing path stability and throughput, while reducing delay, by selecting cluster heads based on vehicles' lifetime. Li and Shen [40] focused on hybrid networks (MANET nodes plus a wireless infrastructure), by exploiting anycast communication and by modeling packet routing issues as resource scheduling problems.

Differently from what already available in state-of-the-art literature, we claim that the SDN approach very well fits the dynamic and heterogeneous nature of spontaneous networking. On the one hand, since spontaneous networking nodes interact to offer and access services in a collaborative manner, there is no a priori knowledge of service availability. Thus, it is suitable to have a centralized point of view with full visibility, able to take proper control decisions. On the other hand, spontaneous networking nodes are willing to further cooperate to improve QoS by better exploiting the currently available networking opportunities. In fact, based on their limited visibility of the network, competing applications/nodes may exploit the same (apparently best) multi-hop path, while erroneously neglecting alternative paths that could be preferred because of more limited load. In other words, by properly managing the dynamicity of this kinds of networks and by adequately maintaining the most suitable tradeoff between freshness of traffic status and monitoring intrusiveness, we claim that the adoption of the SDN approach in spontaneous networking can gain deeper knowledge of the available topology and of its state, as well as can consider application requirements to adapt packet dispatching mechanisms accordingly. Additional information on our mechanisms and strategies for SDN-based management of spontaneous MANETs can be found at [41].

III. OVERALL ARCHITECTURE AND RUNNING EXAMPLE

As presented in Section II, we propose an overall integrated architecture consisting of two domains (see Figure 1): the FiWi access network (top box) and the Edge IoT environment (bottom box). The former is generally designed and optimized to provide high bandwidth and low latency, typically to smartphones carried by users. The latter mostly represents the network infrastructure to support Smart City applications. For example, it is used to gather data from sensors and to send commands to actuators. The interested readers can find the description of advantages, drawbacks, and peculiarities of the two domains in [42], [43]. In addition to what already presented in the previous sections, note that in the envisioned multi-domain scenario it holds that i) a fraction of sensors/actuators can get connectivity via ad-hoc links and ii) some nodes providing connectivity to sensors/actuators can be multihomed, i.e., with access to both the FiWi and Edge IoT networks. Moreover, mobile nodes can intermittently create multi-hop spontaneous networks that get Internet connectivity from either the FiWi or the Edge IoT domain, e.g., via IEEE 802.11 Access Points (APs) provided by the municipality.

The common trend of evolution is that, as recognized in the recent literature [3], [4], [44], each domain is managed by a domain-specialized SDN controller. It starts to be recognized that it is appropriate to have a FiWi SDN Controller that can dynamically tune RRH/ONU-BS nodes to reserve/optimize bandwidth from/to cellular-equipped mobile nodes, namely Mobile Gateways (MGs). Similarly, it is suitable to have an Edge IoT SDN Controller in charge of managing nodes in the Edge IoT domain (deployed and configured by Smart City administrators) as well as mobile nodes carried by users and intermittently connected to the Edge IoT (usually with limited bandwidth). It is worth noting that the Edge IoT SDN Controller interacts with mobile nodes also to identify users willing to cooperate in case of specific situations, e.g., smartphones carried by emergency personnel that should be alarmed in case of issues or users willing to send multimedia streams about the occurring events. While the above emerging trends on domain-specialized SDN controllers are innovative, this work demonstrates how the two separated SDN controllers could be integrated in allowing a flexible and efficient network control. To this end, a loose integration of the two domain-specialized SDN controllers is presented, in a way that they could be able to mutually exchange monitoring/control information, giving emphasis on their synergy towards improving the overall end-to-end QoS. In the light of the aforementioned remarks, the integration of FiWi and MANET networks is introduced by separating the control and the data planes, and thus allowing effective network capabilities such as load balancing, even between different domains (e.g., interpassing through both domains).

To clarify how the federation of SDN controllers can be appropriate for efficient and effective QoS management, let us present the notable example of an emergency situation involving video surveillance streams generated by fixed cameras and sent to emergency personnel dynamically identified and in the same neighborhood of the event:

- usually, fixed cameras in the IoT Edge domain send low resolution multimedia streams directed to a supervising application within the Edge IoT domain (note that the same could be hosted in the Cloud);
- low resolution multimedia streams are remotely observed by supervisors, e.g., by human operators or by an AI-based supervising application, to detect potential emergency situations;
- in case a potential emergency is detected, the supervisors interact with fixed cameras by switching them from low to high resolution to better assess and examine the potential emergency. To this purpose, the Edge IoT SDN Controller autonomously and independently manages the Edge IoT network to ensure the correct and timely delivery of the high resolution multimedia stream to the supervising application only by need, e.g., by properly configuring the traversed routers to provide higher priority to the critical multimedia stream;
- high-quality streams generated by fixed cameras are sent to the supervisors, e.g., to better allow operators to remotely monitor the situation with additional details and eventually trigger an alarm;
- in case an actual alarm is triggered,
    - to make possible the remote coordination/collaboration of remote and local personnel, a two-way multimedia stream is sent between the supervisor and the dynamically identified team of emergency personnel and volunteers. In this case the FiWi SDN Controller has to interact with the Edge IoT one to collect data about the unique identifiers of MGs in the path towards the smartphones carried by the emergency personnel;
    - high-resolution multimedia streams generated by fixed cameras are sent to dynamically identified mobile nodes carried by the emergency team, by exploiting connections between either mobile and Edge IoT nodes or multihomed Edge IoT nodes and the FiWi network. Note that while in both cases it is not required to send streams back and forth towards the server-side infrastructure, in the former case only the Edge IoT domain is exploited, while in the latter case both Edge IoT and FiWi domains are involved together.

In particular,

- first of all, the Edge IoT SDN Controller checks whether multimedia streams can be sent to the emergency team through the only Edge IoT domain itself, e.g., because target mobile nodes are directly connected to a Smart City AP with large bandwidth;
- in the negative case, the Edge IoT SDN Controller interacts with the FiWi SDN Controller to collaboratively verify if multimedia streams can be delivered through the FiWi access network, e.g., because target mobile nodes are conveniently cellular-equipped or there are suitable multi-hop ad-hoc paths from MGs to target nodes.

To maximize the end-to-end QoS, the presented example takes advantage of SDN controllers primarily as follows:

- the Edge IoT SDN Controller ensures QoS in the Smart City network by coordinating fixed and mobile nodes to i) identify mobile nodes carried by emergency personnel and the best path between them and one of available MGs, ii) support the prioritization of multimedia streams by enforcing their prompt dispatching if compared with regular Smart City traffic, iii) perform load balancing by rerouting multimedia streams from cameras to either

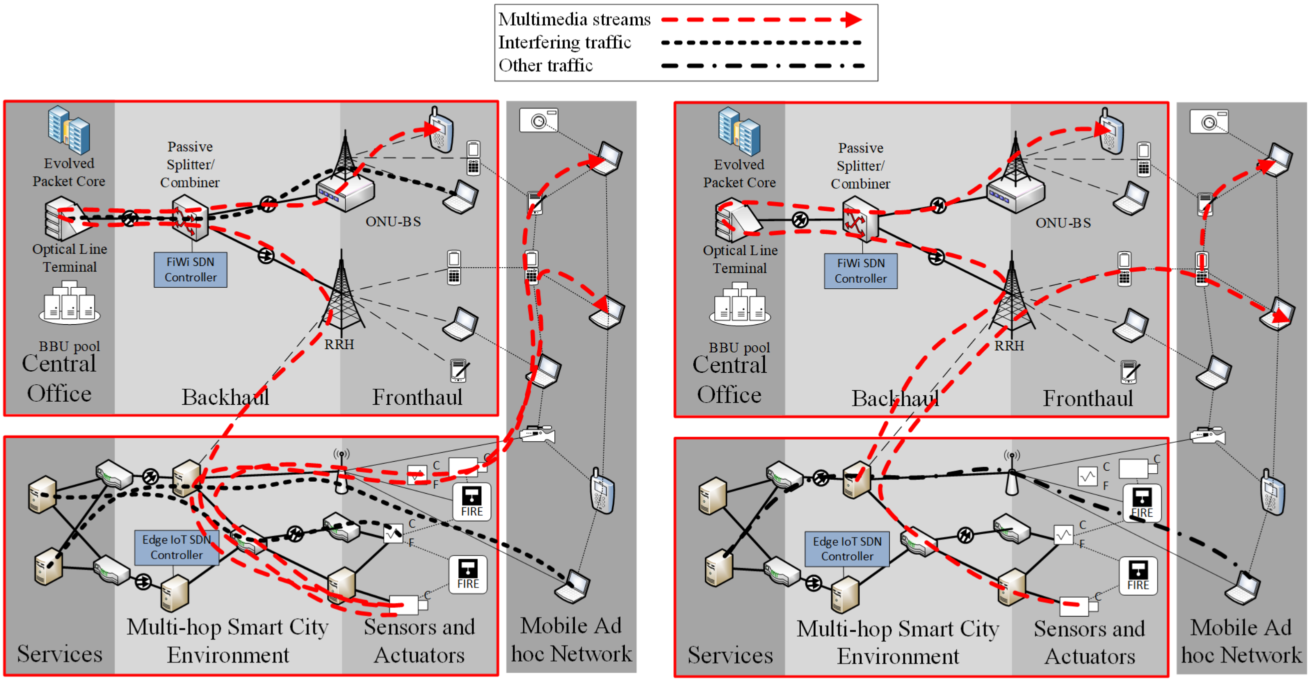


FIGURE 2. **Example without (left) and with (right) inter-domain traffic management.**

the spontaneously created mobile ad-hoc network or the FiWi domain through a multihomed Edge IoT node, and iv) support multicast stream delivery by duplicating streams only if and where required (at roots of the interested sub-trees of the application-level multicast distribution tree). In addition, the Edge IoT SDN Controller can also dynamically trigger multimedia stream quality reduction in relation to the current and monitored capabilities of the network (see [36]);

- the FiWi SDN Controller ensures the delivery of multimedia streams from multihomed Edge IoT nodes to MGs. It also ensures better network dynamics. For example, the polling schemes applied in the optical part of the FiWi is effectively designed and configured to support advanced traffic engineering such as load balancing and prioritization. To this purpose, the FiWi SDN Controller i) dynamically identifies most efficient RRHs/BSs allowing the most efficient utilization of the available capacity towards MGs, ii) adequately exploits available optical and wireless resources by serving the appropriate MGs, and iii) reroutes multimedia streams to the targeted MGs based on the ongoing traffic conditions in a dynamic manner.

Figure 2 presents the proposed running example without (left) and with (right) the adoption of multiple and federated SDN controllers. In both cases, first of all the Edge IoT Controller identifies three mobile devices carried by emergency personnel, one cellular-equipped and the other two not. Without federated SDN controllers, the Edge IoT SDN Controller triggers the delivery of three copies of the multimedia stream from the surveillance camera (bottom of the figure) to target nodes (no multicast capabilities). One of the streams traverses the FiWi domain, but the other two streams have to traverse the MANET because the multi-homed Edge IoT device has not enough cellular bandwidth to send the three streams towards the FiWi domain. In addition, multimedia streams compete with interfering traffic for network resources, thus limiting the actual bandwidth that it is possible to obtain. With SDN controller federation, instead, the Edge IoT SDN Controller interacts with the FiWi SDN Controller to ensure the reservation of enough networking resources in the FiWi domain. Moreover, it sends control packets to Edge IoT and mobile devices to instruct about the next node where the stream has to be forwarded to (eventually more than one in case of multicasting) and about the higher priority of the multimedia stream with regard to other traffic. Finally, the Edge IoT SDN Controller interacts with the surveillance camera to trigger the delivery of only one multimedia stream.

To this purpose, we claim that it is effective that the two SDN controllers interact in a federated way:

- the Edge IoT SDN Controller has to inform the FiWi SDN Controller about i) the forthcoming multimedia streams and the crucial quality-related information about their expected packet size and rate, and ii) the identifiers of the MGs that will receive the multimedia streams;
- the FiWi SDN Controller i) informs the Edge IoT SDN Controller about the bandwidth it can reserve towards each MG and ii) actually allocates bandwidth resources in case the Edge IoT accepts the proposed bandwidth. In addition, the FiWi SDN Controller informs the Edge IoT SDN one about possible bandwidth

modifications at service provisioning time, in order to possibly trigger suitable management operations for QoS adaption.

IV. MULTIMEDIA TRAFFIC MANAGEMENT VIA OUR FEDERATED SDN CONTROLLERS

As already anticipated, Edge IoT and FiWi domains are managed by different SDN controllers in charge of autonomously monitoring and configuring the associated network domain for QoS management purposes.

A. MULTIMEDIA TRAFFIC MANAGEMENT AT THE FIWI DOMAIN

One of the key contributions of the proposed architecture is the efficient allocation of resources to Edge IoT gateways. The primary aim is to demonstrate that it is possible to redistribute the bandwidth allocated to these gateways at service provisioning time and under latency constraints, for instance to satisfy the strict requirements of the corresponding dynamic multimedia streams provided in the example of Section III, without affecting the QoS experienced by existing cell users (UEs). By taking into account that the addressed multimedia traffic is mostly generated by real-time or even critical services, keeping end-to-end latency below acceptable thresholds becomes the key and challenging objective of the allocation scheme.

According to the proposed architecture, the Edge IoT SDN Controller communicates to the FiWi SDN Controller the bandwidth requests of the multimedia streams forwarded through specific gateways both at the uplink and the downlink. The FiWi SDN Controller allocates resources to the gateways ensuring low end-to-end latency. Moreover, it communicates to the Edge IoT SDN Controller new traffic rates for the gateways, compliant with overall traffic requirements. The Edge IoT Controller can then reroute the streams within the MANET, accordingly. Under this concept, apart from the low latency objective, a secondary goal emerges: the deviation of the latency experienced at each gateway from the average latency needs to be minimal. In that way, streams traveling through different gateways will exhibit similar network performance. Furthermore, in order to avoid major interventions in the current MANET routing decisions, we define as third objective the minimization of the deviation of the assigned traffic rates from the originally announced rates at the gateways. Table 1 provides the notations used in the presented analysis.

Towards satisfying the aforementioned objectives, we model the resource allocation scheme as a three-stage optimization problem. Each stage optimizes a different objective function, which corresponds to one of the following: end-to-end latency, latency deviation, and traffic rate deviation. In preparation of the optimization analysis, we have first modelled the addressed part of the overall system, covering the domain from the OLT up to the MG, and analyzed it as an open queuing system, both for the uplink and the downlink cases.

TABLE 1. Notations used in the analysis of the resource allocation scheme.

Notation	Explanation
m	Number of RRHs-MGs
k_i	Number of existing UEs connected to RRH i
C^u	RRH uplink capacity
λ^u	Traffic load rate at the OLT from all RRHs
λ_i^u	Traffic load rate at RRH i from all connected devices
λ_{ij}^u	Traffic generation rate at the existing UE j towards the connected RRH i
λ_{iG}^u	Announced traffic load rate (from MANET) at the MG connected to RRH i
$\hat{\lambda}_{iG}^u$	Assigned traffic load rate (from MANET) at the MG connected to RRH i
μ^u	Transmission rate from the OLT to the core network
μ_i^u	Transmission rate from RRH i to the OLT
μ_{ij}^u	Transmission rate from the existing UE j to the connected RRH i
μ_{iG}^u	Transmission rate from MG to the connected RRH i
T^u	Traffic delay from the OLT to the core network
T_i^u	Traffic delay from RRH i to the OLT
T_{iG}^u	Traffic delay from MG to the connected RRH i
L_{iG}^u	End-to-end latency experienced for streams traversing the MG connected to RRH i at the uplink direction
$\overline{L_G^u}$	Average end-to-end latency experienced for all streams traversing the connected MGs at the uplink direction
OFV_s^u	Objective function value derived by optimization stage s at the uplink direction
C^d	RRH downlink capacity
λ_i^d	Traffic load rate at the OLT interface i from the core network towards RRH i
λ_{ij}^d	Traffic load rate at the component j of RRH i towards the existing connected UE j
λ_{iG}^d	Announced traffic load rate at the component of RRH i which transmits to the connected MG
$\hat{\lambda}_{iG}^d$	Assigned traffic load rate at the component of RRH i which transmits to the connected MG
λ_{iM}^d	Traffic load rate at the MG connected to RRH i towards MANET
μ_i^d	Transmission rate from the OLT interface i to RRH i
μ_{ij}^d	Transmission rate from the component j of RRH i to the existing connected UE j
μ_{iG}^d	Transmission rate from the component of RRH i which transmits to the connected MG
μ_{iM}^d	Transmission rate from the MG connected to RRH i towards MANET
T_i^d	Traffic delay from the OLT interface i to RRH i
T_{iG}^d	Traffic delay from the component of RRH i which transmits to the connected MG
T_{iM}^d	Traffic delay from the MG connected to RRH i towards MANET
L_{iG}^d	End-to-end latency experienced for streams traversing the MG connected to RRH i at the downlink direction
$\overline{L_G^d}$	Average end-to-end latency experienced for all streams traversing the connected MGs at the downlink direction
OFV_s^d	Objective function value derived by optimization stage s at the downlink direction

Lemma 1: The average end-to-end latency experienced for streams traversing the connected MGs at the uplink direction is given by formula (1).

$$\overline{L_G^u} = \frac{\sum_{i=1}^{m} \left(\frac{1}{\mu^u - \sum_{l=1}^{m} \left(\hat{\lambda}_{lG}^u + \sum_{j=1}^{k_l} \lambda_{lj}^u \right)} + \frac{1}{\mu_i^u - \left(\hat{\lambda}_{iG}^u + \sum_{j=1}^{k_i} \lambda_{ij}^u \right)} + \frac{1}{\mu_{iG}^u - \hat{\lambda}_{iG}^u} \right)}{m} \tag{1}$$

Proof: The considered end-to-end latency is composed of the traffic delays introduced at the specific MG, the connected RRH, and the OLT. Hence, it holds:

$$L^u_{iG} = T^u + T^u_i + T^u_{iG} \tag{2}$$

Using Jackson's theorem, we can calculate all involved load rates and ultimately the above traffic delays.

$$\lambda^u_i = \hat{\lambda}^u_{iG} + \sum_{j=1}^{k_i} \lambda^u_{ij} \tag{3}$$

$$\lambda^u = \sum_{i=1}^{m} \lambda^u_i \tag{4}$$

$$T^u_{iG} = \frac{1}{\mu^u_{iG} - \hat{\lambda}^u_{iG}} \tag{5}$$

$$T^u_i = \frac{1}{\mu^u_i - \lambda^u_i} \tag{6}$$

$$T^u = \frac{1}{\mu^u - \lambda^u} \tag{7}$$

$$\overline{L^u_G} = \frac{\sum_{i=1}^{m} L^u_{iG}}{m} \xrightarrow[(5),(6),(7)]{(2),(3),(4)} (1) \tag{8}$$

□

A similar approach is also followed for the downlink direction.

Lemma 2: The average end-to-end latency experienced for streams traversing connected MGs at the downlink direction is given by formula (9).

$$\overline{L^d_G} = \frac{\sum_{i=1}^{m} \left(\frac{1}{\mu^d_i - \left(\hat{\lambda}^d_{iG} + \sum_{j=1}^{k_i} \lambda^d_{ij} \right)} + \frac{1}{\mu^d_{iG} - \hat{\lambda}^d_{iG}} + \frac{1}{\mu^d_{iM} - \hat{\lambda}^d_{iG}} \right)}{m} \tag{9}$$

Proof: For the queuing-based model at the downlink direction, the OLT is broken down to its m interfaces, each one connected to the corresponding RRH. Each interface is considered a separate queue, since it has its own service rate (μ^d_i) and individual traffic flow (λ^d_i) towards the connected RRH. Likewise, each RRH is broken down to its components, each one serving a different mobile user. In more detail, the performed queuing-based analysis models the downlink transmission rates provided by an RRH to each individual UE as a separate processing queuing node, called RRH component. In real-world deployments, this abstraction follows the principles of the dominant cutting-edge techniques for wireless access that adopt Orthogonal Frequency Division Multiple Access (OFDM) based approaches, which actually distribute the RRH downlink capacity among the connected UEs by assigning different slices of the formed superframe in the time and frequency domains. In our analysis, these allocated slices are considered as different RRH components. In addition, following the conditions of ergodicity, it is evident that the load rate of ingress traffic at an MG at the downlink direction should be equal to the egress traffic rate towards the MANET. The resulted end-to-end latency is composed of the traffic delays introduced at the specific MG, the corresponding RRH component, and the connected OLT interface.

$$L^d_{iG} = T^d_i + T^d_{iG} + T^d_{iM} \tag{10}$$

Using Jackson's theorem, we can calculate all involved load rates and ultimately the above traffic delays.

$$\lambda^d_i = \hat{\lambda}^d_{iG} + \sum_{j=1}^{k_i} \lambda^d_{ij} \tag{11}$$

$$\lambda^d_{iG} = \lambda^d_{iM} \tag{12}$$

$$T^d_{iM} = \frac{1}{\mu^d_{iM} - \lambda^d_{iM}} \tag{13}$$

$$T^d_{iG} = \frac{1}{\mu^d_{iG} - \hat{\lambda}^d_{iG}} \tag{14}$$

$$T^d_i = \frac{1}{\mu^d_i - \lambda^d_i} \tag{15}$$

$$\overline{L^d_G} = \frac{\sum_{i=1}^{m} L^d_{iG}}{m} \xrightarrow[(13),(14),(15)]{(10),(11),(12)} (9) \tag{16}$$

□

Based on this queuing model, resource allocation is formulated as a multi-stage optimization problem to assign the optimal traffic rate and transmission rate to MGs. A different (but very similar) problem is derived for the uplink and the downlink directions. An objective function is defined for each stage, according to the respective optimization factor. The optimal value found in each stage is used as a constraint in the next one. The idea is based on the realistic assumption that initially multiple optimal solutions typically exist, which are narrowed down in the next optimization stages. This approach prioritizes the early-stage optimization factors over the later-stage ones.

The motivation for adopting a multi-stage optimization approach is originated from the prioritization of different requirements regarding the resource allocation process. In more detail, as top priority is considered the minimization of the end-to-end latency exhibited by the multimedia streams. The reason is that real-time multimedia streams are characterized by strict delay requirements, hence, any increase in the overall latency significantly affects the provided QoS and the perceived QoE. In that sense, the first optimization stage is devoted to identifying the optimal combination of transmission and load rates that ensures the lowest possible average latency. As second priority in resource allocation is considered the elimination of large variations in the different multimedia streams′ latency. The concept is that the minimum overall average latency needs to be achieved by ensuring latency for most streams close to the average value. For that reason, the second optimization stage focuses on minimizing the respective deviation. The lowest priority criterion considered when allocating resources is the requirement to match the announced load rates with the assigned load rates. This objective ensures the lowest possible alternation of routing decisions within Edge IoT, hence, more reliable and robust ad hoc networking. Thus, the final optimization stage minimizes the respective deviation of the load rates. In the remainder of this subsection, the corresponding optimization sub-problems are presented stage-by-stage.

In the first optimization stage, the objective is to minimize the average end-to-end latency experienced for all streams traversing the connected MGs. The objective function and the corresponding constraints are provided below.

Stage 1 (UpLink):

$$\underset{\hat{\lambda}^u_{iG},\mu^u_{iG}}{\text{minimize}}\ \overline{L^u_G} \tag{17}$$

$$\text{s.t. } \mu^u_{iG} \leq C^u - \sum_{j=1}^{k_j} \mu^u_{ij} \tag{18}$$

$$\mu^u_{iG} \geq \hat{\lambda}^u_{iG} \tag{19}$$

$$\sum_{i=1}^{m} \lambda^u_{iG} = \sum_{i=1}^{m} \hat{\lambda}^u_{iG} \tag{20}$$

Stage 1 (DownLink):

$$\underset{\hat{\lambda}^d_{iG},\mu^d_{iG}}{\text{minimize}}\ \overline{L^d_G} \tag{21}$$

$$\text{s.t. } \mu^d_{iG} \leq C^d - \sum_{j=1}^{k_j} \mu^d_{ij} \tag{22}$$

$$\mu^d_{iG} \geq \hat{\lambda}^d_{iG} \tag{23}$$

$$\hat{\lambda}^d_{iG} \leq \mu^d_{iM} \tag{24}$$

$$\sum_{i=1}^{m} \lambda^d_{iG} = \sum_{i=1}^{m} \hat{\lambda}^d_{iG} \tag{25}$$

At the second optimization stage, the objective is to minimize the deviation of latency among MGs. The corresponding function and constraints are provided below.

Stage 2 (UpLink):

$$\underset{\hat{\lambda}^u_{iG},\mu^u_{iG}}{\text{minimize}}\ \frac{\sum_{i=1}^{m} |L^u_{iG} - \overline{L^u_G}|}{m} \tag{26}$$

$$\text{s.t. } (18),\quad (19),\ (20)$$

$$\overline{L^u_G} = OFV^u_1 \tag{27}$$

Stage 2 (DownLink):

$$\underset{\hat{\lambda}^d_{iG},\mu^d_{iG}}{\text{minimize}}\ \frac{\sum_{i=1}^{m} |L^d_{iG} - \overline{L^d_G}|}{m} \tag{28}$$

$$\text{s.t. } (22),\quad (23),\ (24),\ (25)$$

$$\overline{L^d_G} = OFV^d_1 \tag{29}$$

At the third optimization stage, the objective is to minimize the deviation of the traffic rates assigned to the MGs from the initially announced rates (by the Edge IoT Controller). The corresponding function and constraints are provided below.

Stage 3 (UpLink):

$$\underset{\hat{\lambda}^u_{iG},\mu^u_{iG}}{\text{minimize}}\ \frac{\sum_{i=1}^{m} |\hat{\lambda}^u_{iG} - \lambda^u_{iG}|}{m} \tag{30}$$

$$\text{s.t. } (18),\quad (19),\ (20),\ (27)$$

$$\frac{\sum_{i=1}^{m} |L^u_{iG} - \overline{L^u_G}|}{m} = OFV^u_2 \tag{31}$$

Stage 3 (DownLink):

$$\underset{\hat{\lambda}^d_{iG},\mu^d_{iG}}{\text{minimize}}\ \frac{\sum_{i=1}^{m} |\hat{\lambda}^d_{iG} - \lambda^d_{iG}|}{m} \tag{32}$$

$$\text{s.t. } (22),\quad (23),\ (24),\ (25),\ (29)$$

$$\frac{\sum_{i=1}^{m} |L^d_{iG} - \overline{L^d_G}|}{m} = OFV^d_2 \tag{33}$$

Eventually, the resource allocation scheme provides the traffic and transmission rates ($\hat{\lambda}^u_{iG}$ and μ^u_{iG}, respectively) assigned to the MGs, which are derived by the last optimization stage. The optimization problem is solved at the FiWi SDN Controller and the allocations are communicated to the Edge IoT SDN Controller. It is noteworthy that the optimization scheme is tunable: specific stages can be omitted if the corresponding factors are considered unimportant. Furthermore, the optimization stages can be reordered according to the adopted prioritization of the optimization factors.

B. MULTIMEDIA TRAFFIC MANAGEMENT AT THE EDGE IOT DOMAIN

The Edge IoT SDN Controller is deployed in a node within the multi-hop Smart City environment. Fixed/mobile nodes within the Smart City and mobile nodes connected to the Smart City (via WiFi APs as well as via multi-hop spontaneous paths) dynamically discover the Edge IoT SDN Controller and register themselves to it. During the registration phase, nodes provide their unique node ID and primary supported features, e.g., if they are cellular-equipped (and thus can behave as MGs) and if their user is willing to cooperate in the dynamic emergency team in case of alert. In addition, other computing/network-related information is provided periodically (with a configurable time period), e.g., to notify the Edge IoT SDN Controller about available CPU/memory and traffic status.

At service provisioning time, the Edge IoT SDN Controller provides registered nodes with features for QoS management that impact on network configuration/tuning operations. The following primary features are supported:

1) providing best route towards destinations: a node provides the Edge IoT SDN Controller with the ID of the receiver node and then the controller replies with the best route to that node, by exploiting its awareness of the overall network topology and of the traffic load. Note that in this case the traffic transmission is best-effort, since intermediate nodes forward this multimedia traffic in the "regular" way;
2) enforcing high priority traffic forwarding: if compared with the previous case, the sending node also specifies that the forthcoming traffic is of critical relevance. The Edge IoT SDN Controller replies with the best route and also a flow ID that the sender must use to label the generated traffic. In addition, the controller broadcasts a control message (via controlled flooding or a dynamically generated control spanning tree, see [45]) to notify the registered nodes that traversing traffic

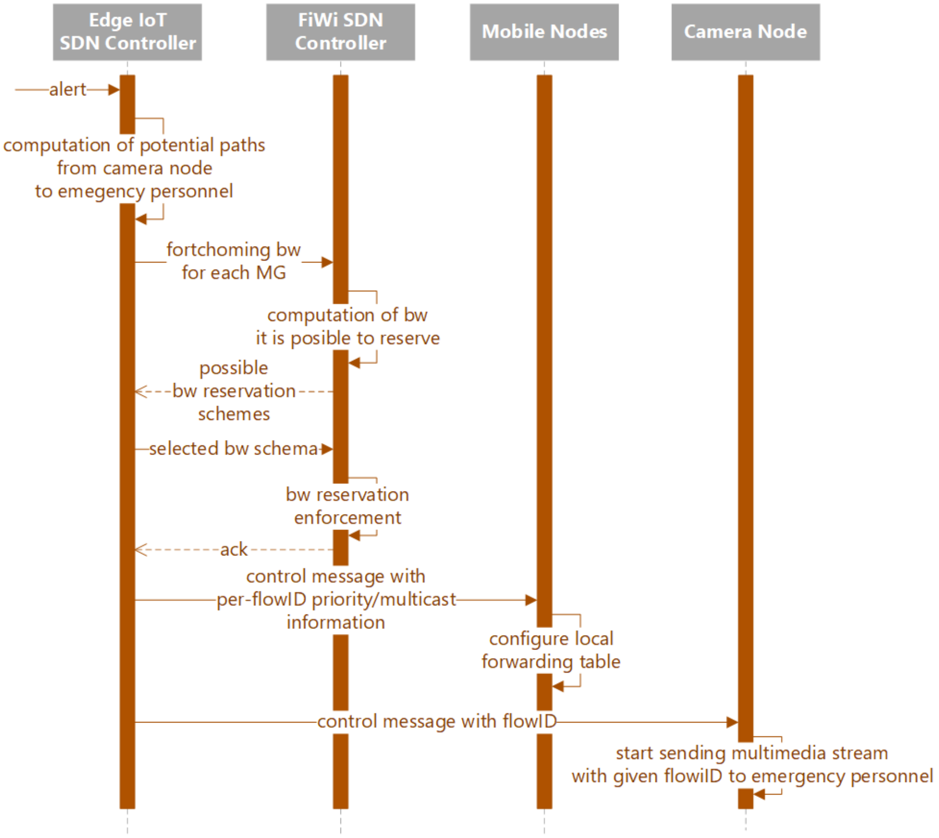


FIGURE 3. **Sequence diagram at alert.**

labeled with that ID must be forwarded with higher priority;

3) configuring multicast delivery paths: a node willing to send the same traffic (e.g., a multimedia stream) to multiple receivers sends the set of destination IDs to the Edge IoT SDN Controller. Then, the controller i) identifies a best spanning tree to maximize the QoS from the sender to the receivers, e.g., to minimize overall throughput or latency, ii) informs each node in the tree about the forthcoming traffic (identified by a unique flow ID) and the next hops (one or more for each node) that the traffic has to be forwarded to, and iii) provides the flow ID to the sender, thus triggering the start of multimedia streaming.

C. FEDERATED TRAFFIC MANAGEMENT

To effectively enable the delivery of multimedia streams to emergency personnel, there is the need for the cooperation between Edge IoT and FiWi domains, and in particular between their SDN controllers. In fact, the availability of one or multiple multi-hop paths based on spontaneous connectivity in the Smart City environment makes easier the monitoring and control of the MANET. However, these paths are usually characterized by limited capabilities, e.g., because their impromptu nature reduces connectivity availability/reliability and because the adoption of ad-hoc links typically imposes limited bandwidth, in particular in case of relatively long multi-hop paths. In other words, these paths can be fruitfully exploited as out-of-band monitoring and control channels, e.g., to dispatch relatively small control data packets, while they are not suitable for long-lasting and high-throughput multimedia streams with latency requirements.

To practically show the advantages of the proposed approach, by referring to the notable example presented in Section III, there are two primary cases where the federation of Edge IoT and FiWi SDN Controllers has shown to relevantly improve the overall QoS:

1) at alert rising, the Edge IoT SDN Controller contacts the FiWi SDN one asking for bandwidth reservation (see Figure 3);
2) in case of significant FiWi traffic perturbation, e.g., relevant additional traffic that is observed or predicted, the FiWi SDN Controller notifies the Edge IoT SDN one that the negotiated bandwidth will not (or is expected not to) be available anymore.

It is noteworthy that in the presented running example the Edge IoT SDN Controller jointly exploits the high-priority and multicast mechanisms presented above, while the best route one is not required (multimedia stream follows the multicast spanning tree). However, the QoS management operations of the Edge IoT SDN Controller would not be enough on its own because the ad-hoc links between the Smart City environment and the emergency personnel mobile nodes do not allow the delivery of high resolution multimedia streams. Only thanks to the coordination and collaboration among the two domains it is possible to effectively deliver the streams to mobile nodes, by taking advantage of the FiWi network that forwards streams to MGs and that ensures bandwidth reservation capabilities on its side.

V. PERFORMANCE RESULTS

This section presents and discusses some selected and relevant performance results of the introduced federated multimedia traffic management, by reporting quantitative indicators for both the FiWi and Edge IoT domains. To the best of our knowledge, these reported performance results about federated SDN controllers in FiWi-IoT integrated deployment environments are completely original in the literature in the field.

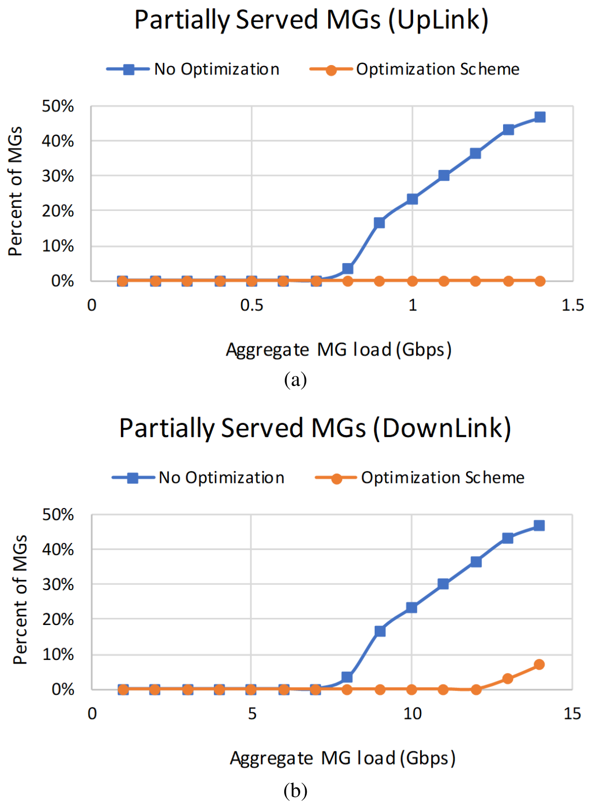
TABLE 2. Validation parameters.

Parameter	Value
OLT-to-core capacity (symmetric)	25 Gbps
OLT-to-RRH capacity (symmetric)	10 Gbps
RRH wireless capacity (uplink)	100 Mbps
RRH wireless capacity (downlink)	1 Gbps
Packet size	1000 bits
Operation time	100 sec
UE traffic rate (uplink)	1 Mbps
UE traffic rate (downlink)	10 Mbps
UE transmission rate (uplink)	2 Mbps
UE reception rate (downlink)	20 Mbps
MG transmission rate to MANET	2 × announced traffic rate
Number of RRHs	30
Number of existing UEs per RRH	25

A. EVALUATION AT THE FIWI DOMAIN

The introduced resource allocation performed by the FiWi SDN Controller is evaluated via a validation environment developed in MATLAB and using its Optimization Toolbox^{TM}. According to the adopted architecture, the conducted validation scenarios consider a topology where an OLT is connected to m ONUs, each one integrating an RRH. The validation parameters, presented in Table 2, are aligned to the specifications of cutting-edge technologies at the backhaul, fronthaul, and wireless access network segments (such as 25G-EPON, 10G-EPON, and LTE-Advanced Pro, respectively). The comparison of the results reveals the effectiveness of each optimization stage, both at the uplink and the downlink directions, for varying MG traffic rates announced by the Edge IoT SDN Controller. As a comparative baseline, non-optimizing resource allocation is considered, which just assigns the announced traffic load rates to the MGs and enough bandwidth if available (otherwise, the remainder of the corresponding RRH capacity).

The first performance evaluation metric that we have selected is the percentage of MGs that do not get fully served, i.e., they get lower transmission rate than the assigned traffic load rate. This may occur in case the available RRH capacity is not enough to allocate adequate bandwidth to the specific MG. The proposed resource allocation scheme addresses this issue via the first optimization stage by distributing traffic to each MG while taking also into account the available capacity of the RRH where it is connected to. To assess the effectiveness of the related technique, the proposed optimization scheme is compared against the non-optimizing reference scheme. As Figure 4 shows, on the one hand, the introduced optimization algorithm efficiently distributes the load to MGs, nearly nullifying the negative effect of partially served MGs, both at the uplink and downlink directions. On the other hand, the non-optimizing reference scheme starts to notably overload MGs when the aggregate load is higher than 700 Mbps and 7 Gbps for the uplink and downlink case, respectively.

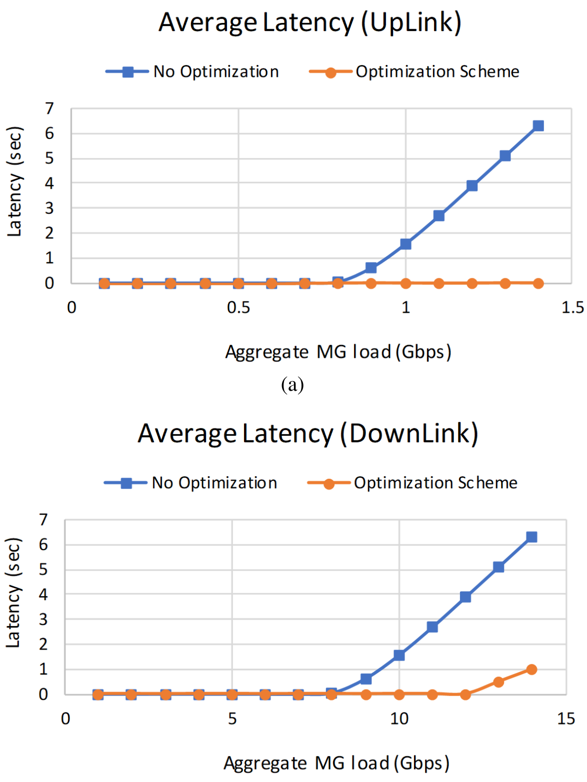


(a)

(b)

FIGURE 4. Percent of MGs receiving less transmission rate than their load rate versus the aggregate MG load, for (a) the uplink and (b) the downlink directions.

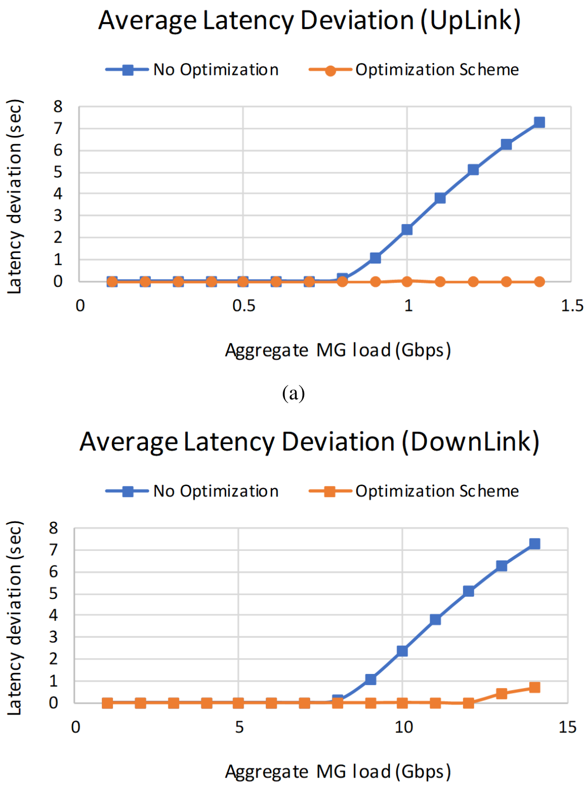
A key overall performance metric is the end-to-end latency experienced for all multimedia streams traversing the MGs. To show the effectiveness of our integrated solution, we compare the latency associated with the application of our optimization scheme against the reference baseline (non-optimizing scheme). The results plotted in Figure 5 indicate that the former keeps the average latency close to or even lower than the threshold of 0.01 sec for both the uplink and the downlink, whereas the latter exhibits significantly increasing



(a)

(b)

FIGURE 5. **Average end-to-end latency for multimedia streams traversing MGs versus the aggregate MG load, for (a) the uplink and (b) the downlink directions.**



(a)

(b)

FIGURE 6. **Average deviation of the end-to-end latency for multimedia streams traversing MGs versus the aggregate MG load, for (a) the uplink and (b) the downlink directions.**

latency for higher aggregate load, verifying the effectiveness of the conducted minimization. It should be noted that the optimization algorithm starts exhibiting increased latency at the downlink direction for aggregate MG load higher than 13 Gbps. This behaviour is due to the restrictions also imposed by the constrained transmission rate of the MGs toward the MANET. However, the latency is still maintained to much lower levels than the reference case.

Another considered evaluation criterion relates to the ability to ensure similar latencies to multimedia streams forwarded through different MGs. For this reason, we compare the average MG latency deviation of the introduced technique against the baseline. As Figure 6 depicts, on the one hand, at its second stage the optimization scheme optimally distributes bandwidth in a manner that eliminates the differences in latency of separate traffic flows. On the other hand, latency differences notably grow for high aggregate MG load, when no optimization is performed.

The last reported evaluation metric is the deviation of the assigned MG load rates from the initially announced values. One of the goals of our proposed integrated solution, in fact, is to identify the optimal allocation of resources that also reduces the load rate deviation. To reveal the respective performance, we compare the application of all three optimization stages against the second optimization stage, since the related minimization takes place in the third stage. The reference non-optimizing scheme is not considered in this case, due to the fact that it always assigns the announce MG load rate irrespective of the available bandwidth or the target latency.

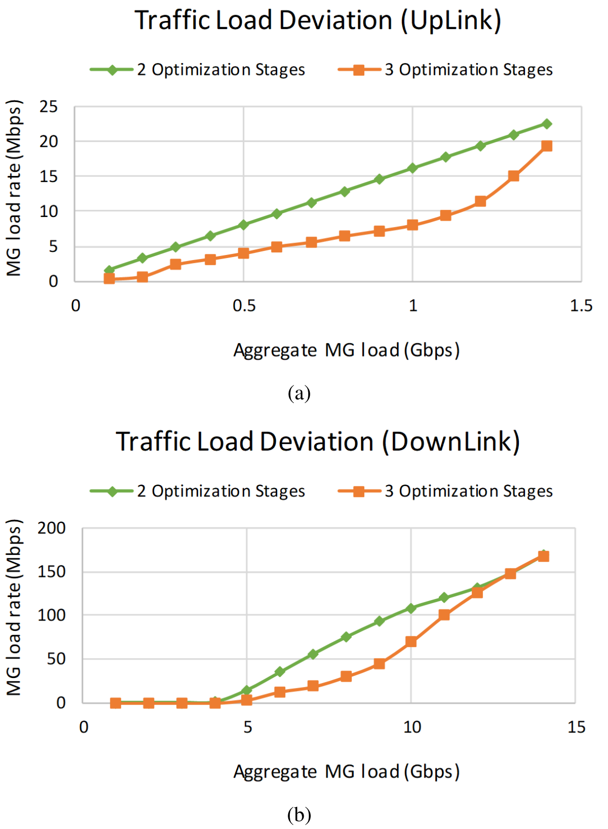
Ensuring minimal load deviation proves to be challenging while achieving optimal latency. However, the related results depicted in Figure 7 demonstrate that the proposed 3-stage scheme achieves this goal for a broad range of aggregate MG load values.

B. EVALUATION AT THE EDGE IOT DOMAIN

To fully understand the quantitative indicators provided below, let us start by giving some implementation insights about the two message types used in the Edge IoT Domain to trigger the primary QoS control operations:

1) simple control messages, containing multimedia stream flow ID (4 bytes), characteristics in terms of bitrate in kbit/s (2 bytes), and duration in seconds (2 bytes), e.g., 1250 kbit/s for about 5 minutes;
2) multi-hop control messages, with multimedia stream flow ID (4 bytes) and per-node next hops, thus depending on the amount of stream duplications a node should perform (4 bytes with only one destination and thus no duplication, 8 bytes for a duplication, and so on).

Both messages are provided to every node in the multimedia stream multicast spanning tree at alert time and whenever required, e.g., the former is sent in case of stream quality



Traffic Load Deviation (UpLink)

(a)

Traffic Load Deviation (DownLink)

(b)

FIGURE 7. Average deviation of the load assigned to multimedia streams traversing MGs versus the aggregate MG load, for (a) the uplink and (b) the downlink directions.

modifications, the latter in case of spanning tree variations. Moreover, it is worth noting that each packet is encapsulated within a RAMP [34] message, composed of a header with Dynamic Source Routing-like sequence of IP addresses towards the destination and from the sending source (thus 8 bytes per hop), the hop counter (1 byte), unique destination and source node IDs (8 bytes), the indication of the transport protocol (either UDP or TCP) that should be adopted to dispatch packets among nodes (1 byte), and the port the destination application-level process is waiting for (2 bytes). Overall, the header size is 52 bytes in case of 5-hop paths, deemed as appropriate in this context, leading to packets with size lower than 100 bytes in any reasonable scenario. When using WiFi connections with bandwidth limitation at 2Mbit/s, the observed latency is about 300ms for 3-hop paths, thus sufficient to promptly manage the Edge IoT Domain in case of alert.

In addition, Figure 8 shows the outgoing throughput of the camera node (up) and an intermediate node (down), without (left) or with (right) multicast activation. During the first phase (a), the camera node sends the stream to a destination node towards the intermediate one. During the second phase (b), the intermediate node also registers itself as a member of the emergency personnel team and thus is expected to receive the same stream. Without multicast (left), the camera node uselessly generates two streams along the whole path incurring in ineffective bandwidth usage. In case of multicast activation (right), the camera node sends only one multimedia stream, then duplicated by the intermediate node towards the other destination.

VI. RELATED WORK

The centralized nature of the SDN approach makes it the natural choice for managing networks of small-to-medium size related to a single organization. However, the adoption of the SDN approach has quickly proven its benefits also in different scenarios with more relaxed requirements in terms of closeness and geographical centralization. For instance, SDN is exploited in wide area networks to efficiently interconnect different datacenters [46], [47], eventually based on a multi-controller SDN architecture [48]. Nowadays, the state-of-the art literature is moving towards the adoption of SDN in scenarios differing from traditional datacenters, such as vehicular networks [49], naval systems [50], and access/transport networks [7], [46]. In particular, Alvizu *et al.* [51] present a survey modeling the state-of-the-art literature about SDN-based solutions managing heterogeneous transport networks based on monolithic, hierarchical, and flat or mesh control plane architectures. Some solutions propose the adoption of the SDN approach in edge computing environments, eventually also considering vehicular networks [52], [53] and advanced caching solutions [54], [55]. Baktir *et al.* [44] present the most relevant survey/tutorial paper about how SDN can be adopted as an enabler to facilitate the development of real Edge environments.

By considering traditional and general-purpose wireless networks, Abolhasan *et al.* [56] propose to extend the SDN approach towards a centralized/distributed mixed architecture, with a centralized SDN controller (gathering and pre-processing information) and several distributed nodes (typically BSs providing connectivity) performing decision-making and configuring the data plane of mobile nodes. By focusing on wireless sensor/actuator networks, Zhou *et al.* [57] exploit the SDN approach to efficiently manage cooperative communication and task execution. Some solutions in the wireless sensor network domain not only adopt the SDN approach, but also exploit OpenFlow-like protocols. For instance, SDN-WISE [58] extends OpenFlow to optimize the communication among sensor nodes and the controller and to program nodes as finite state machines. Anadiotis *et al.* [59] adopt SDN-WISE to optimize the deployment of MapReduce tasks among nodes, with the SDN controller in charge of actuating the data plane to efficiently route traffic from mappers to reducers. Luo *et al.* [60] propose an extension (backward compatible) of OpenFlow to improve its flexibility, thus making it more appropriate for the inherent dynamicity of wireless networks. Lai *et al.* [61] and Fontes *et al.* [49] exploit SDN to optimize vehicular networks for application-specific and application-level requirements, e.g., QoS management in challenging infotainment services with large-bandwidth multimedia streaming.

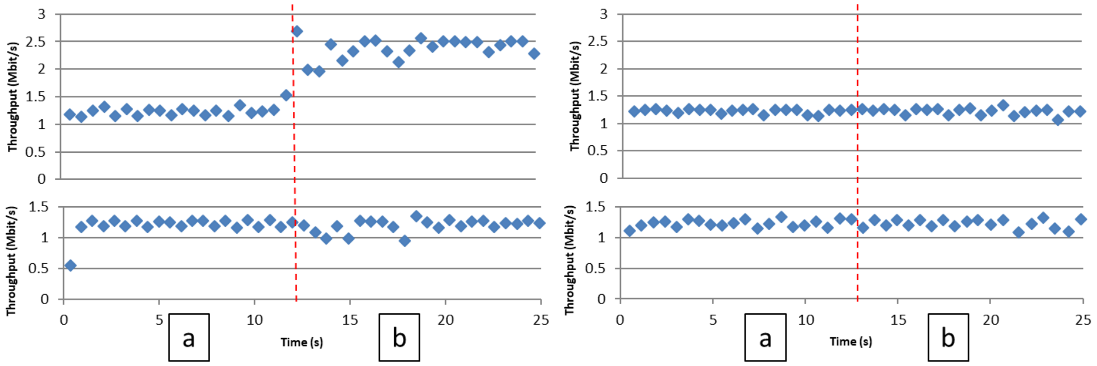


FIGURE 8. Multimedia throughput without (left) and with (right) multicast.

Even the SDN-based federation of heterogeneous domains is recently emerging, but usually in specific environments. For instance, Yu *et al.* [46] consider both datacenter and optical network domains, by adopting a multi-controller collaboration framework in charge of managing not only network devices but also cloud-based storage and computing resources. Similarly, Zhao *et al.* [62] jointly manage datacenter resources, optical networks, and IP-based networks in a unified control system providing available capabilities based on a unified resource description model.

VII. OPEN ISSUES, CONCLUSIVE REMARKS, AND ONGOING RESEARCH DIRECTIONS

This paper originally proposes a federated SDN approach to improve end-to-end QoS in dynamic and integrated heterogeneous network domains. In particular, our loosely federation of Edge IoT and FiWi domains has demonstrated to enable novel relevant scenarios for services and resources dynamically discovered in Smart City environments with spontaneous MANETs, while taking advantage of efficient and dynamic resource allocation (relocation) of FiWi networks. Let us note that, in addition to the multimedia stream example presented above, the proposed solution can relevantly improve the QoS of any application requiring guaranteed bandwidth among nodes in the Edge IoT domain and nodes getting connectivity via the FiWi domain. For instance, this is the case of mission critical applications where mobile nodes remotely monitor and control fixed devices deployed in the Edge IoT domain, imposing the adoption of a proper solution to make sure that mobile nodes have always up-to-date values and that their issued commands are dispatched in a reliable and prompt manner.

Notwithstanding the first interesting results presented in this paper, the industrial adoption and integration of multiple SDN controllers deployed in heterogeneous domains are still an early-stage research field, with several and very open issues that call for further research work from the community in the field in the near future. In particular, we see as promising the following primary directions for the research in the area:

1) OpenFlow is a promising protocol enabling the separation of the control and data planes in modern integrated telco infrastructures. One of the most important features of OpenFlow is that it allows network equipment of different vendors to be configured in an easy and efficient way. However, it mostly provides network features for switches/gateways while it is limited in routing processes, at least in its most widespread and available versions. This remark also holds for protocols similar to OpenFlow, such as the Network Configuration Protocol (NETCONF) [63]. All these protocols should be extended and expanded to enclose more functionalities and commands at multiple abstraction layers. For example, they should entail advanced network capabilities such as polling mechanisms, optical routing decisions, and Wavelength Division Multiplexing (WDM) support;
2) SDN controllers offer a centralized point of management. However, fault tolerance and availability issues are crucial as well. Load balancing could be also combined with fault tolerance techniques where alternative routing paths are efficiently (sometimes proactively) created to address node and link failures. While in the present work load balancing and prioritization are highlighted, high availability is also very relevant and has to be addressed properly in an integrated way;
3) industry-leading vendors of SDN and network virtualization controllers such as Cisco APIC, VMware Nuage, and Juniper Contrail, progressively create the environment for developing and integrating new schemes and algorithms for introducing novel and extended traffic engineering approaches. Given this trend, the introduced inter-domain scheme could be efficiently applied in emerging platforms, stemming from industry-leading vendors, while shedding new light to novel traffic engineering features that can provide enhanced network applications and services.

For what specifically relates to the ongoing research activities that our research group is working on, we are currently considering two primary lines:

1) the development of MANET-specific SDN Controllers in charge of managing groups of jointly moving smartphones, e.g., tourist moving around a city, to support MANET themselves as well as to interact with Edge IoT and FiWi SDN Controllers and increase the QoS of incoming and outgoing traffic flows;
2) more extensive performance evaluation based on simulated environments as well as real-world deployment over wide-scale environments and comprising the participation of off-the-shelf Android-based smartphones as Edge IoT final nodes.

Let us finally stress that we claim that SDN-based federation of heterogeneous domains will gain additional attention in the near future, based on the enabled easier management of heterogeneous resources that the SDN approach leverages. We hope that this paper (i.e., first research work in the literature about SDN federation in FiWi-IoT integrated deployment environments) can usefully contribute to this emerging trend.

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