

# Supporting Multi-interface Entities in Software-Defined Wireless Networks

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**Abstract**—Software-Defined Networking (SDN) has gained growing momentum from its earlier application for wired networks (e.g., data center networks) to its application for wireless and mobile networks. In addition, state-of-the-art wireless and mobile networks (cellular networks and mesh networks) have been enhanced through the integration of multiple radio access technologies or multiple interfaces. This paper considers how to evolve multi-interface wireless mobile networks according to a future SDN-based paradigm, and deals with the technical problems therein. It presents the design and implementation of mechanisms that support SDN-based control of two types of multi-interface wireless mobile networks: one with multi-interface user devices and the other with multi-interface switching entities. As a methodology of demonstrating the feasibility of the proposed solution, a novel testing suite incorporating a real SDN controller and a standardized network simulator is designed and built. The functional verification and performance of the proposed solution is demonstrated in a virtual network topology but with the orchestration of the real SDN controller. The results show the multi-interface wireless entities can exploit the multi-radio and multi-channel wireless resources with the help of SDN approach.

**Keywords**—Software-defined networking; multi-interface; multi-interface switch; flow-precision mobility; flow-precision routing

## I. INTRODUCTION

Software-Defined Networking (SDN) has recently drawn significant attention from the networking communities owing to its potential to introduce innovative networking mechanisms by decoupling the control plane from the data plane of networks and centrally controlling the resulting networks [1]. The recent high interest in SDN is greatly attributed to Google's B4, which has nicely applied the SDN principle to real operating wide-area networks connecting Google data centers globally [2]. B4 enables near 100% link utilization between data centers using SDN-based centralized traffic engineering and OpenFlow-based switch management [1]. In addition to works on SDN-based data center networks, other SDN applications to wired networks include applying SDN for inter-domain routing [3], and adopting multiple controllers for wide-area wired network orchestration [4]. Gupta and co-workers proposed an SDN-based Internet Exchange Point (IXP) and solved various challenges in building real deployable software defined exchange points [3].

The application of SDN to wireless networks has been recently and extensively studied, for example, wireless local

area networks (WLANs), wireless mesh networks, and cellular networks like Long Term Evolution (LTE) [5], [6]. SDN-based approaches to WLANs, both enterprise WLANs [7]-[9] and community WLANs [10], have been proposed for various purposes of network virtualization, radio resource management, flow-based quality of service (QoS), and mobility support. The SDN-based control of wireless mesh networks has been examined from the perspective of load balancing and mobility management [11], [12]. LTE cellular networks have been recently examined for an SDN rebase from the perspective of both the core network part [13]-[20] and radio access network part [21]- [23].

Apart from SDN-driven research, it is noticed that multi-RAT(Radio Access Technology) wireless networks have been a promising approach to resolve the ever-increasing bandwidth demand as various radio access technologies become available with different communication ranges, and radio interfaces become more and more affordable in terms of the unit price [24]-[26]. In multi-RAT wireless networks, either devices (e.g., smartphones) or switching entities (e.g., routers) can be equipped with multiple radio interfaces to provide and utilize an enhanced network capacity. A typical example of the former case is multi-RAT LTE/WLAN heterogeneous networks where user equipment (UE) such as smartphones have LTE and WLAN radio interfaces available for radio access. A typical example of the latter case is multi-RAT, multi-channel wireless mesh networks where wireless routers are equipped with multiple WLAN radio interfaces simultaneously operating on different WLAN channels for capacity enlargement [25]. It is envisaged that these multi-radio wireless mobile networks can be orchestrated based on the SDN paradigm with a centralized holistic view on multi-radio resources more effectively than traditional distributed local control. For example, congestion on LTE access networks can be alleviated by offloading LTE/WLAN multi-radio devices to WLAN access points (APs) based on the centralized decision of the SDN controller, thereby leading to more enhanced multi-radio resource utilization and load balancing.

This trend toward softwarizing networks and enhancing multi-interface availability motivates the authors to examine, to the best of the authors' knowledge, the first in-depth investigation into the feasibility of SDN-based centralized control of multi-RAT wireless mobile networks as a next-generation evolution. In so doing, technical issues induced by multi-radio inherency are studied, which can be further classified into handling (i) multi-RAT devices and (ii) multi-

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RAT switching entities in the SDN paradigm. Mechanisms are proposed to resolve the issues of these two categories and implement them into an integrated suite of a real SDN controller and standard-compliant software switches in a simulation space. The first issue is considered in the context of emerging LTE/WLAN heterogeneous multi-radio networks, and thus, how to support LTE/WLAN multi-radio devices using an SDN controller and what benefits an SDN-based approach will bring. The second issue is considered in the context of multi-radio, multi-channel wireless mesh networks, and thus, how to support multi-radio routers using an SDN controller and its effectiveness. Although a case for SDN-based heterogeneous networked environments has been made [27] [42] [43], our investigation tackles detailed technical issues of resolving the limitation of the current open SDN standard in supporting multi-interface wireless network entities and incorporates procedural mechanisms.

The rest of the paper is organized as follows. Section II summarizes previous related works. Section III discusses the problem of supporting devices with multi-RAT interfaces in SDN-based wireless networks and proposes a novel solution to enable it. Section IV discusses the problem of supporting switching entities with multi-RAT interfaces in SDN-based wireless networks and proposes a novel solution to support it. Section V demonstrates the performance evaluation of the proposed solutions. Section VI provides some concluding remarks regarding this research.

## II. RELATED WORK

There are previous works applying SDN approaches to WLANs, both enterprise WLANs [7]-[9] and community WLANs [10]. Suresh and co-workers proposed Odin as an open SDN framework for an enterprise WLAN, where the Odin master on an SDN controller communicates with Odin agents at the access points to support seamless mobility, load balancing, hidden terminal mitigation, and other management functions [8]. Schulz-Zander and others proposed a two-tiered control architecture, called AeroFlux, where global control servers deal with global mobility management and load balancing, and near-sighted control servers manage the per-client or per-flow Wi-Fi transmission settings [9]. Yiakoumis and co-workers studied SDN-based home WLANs and proposed a mechanism called BeHop for virtual slicing of a physical WLAN, a personal AP abstraction, and infrastructure management such as for the channel and power [10]. Lee and others proposed an extension of SDN to mobile phones called meSDN [7]. By incorporating an OpenFlow-based local controller in a mobile device, they enabled application-aware uplink flow QoS, a network fault diagnosis, and WLAN virtualization.

Applying the SDN paradigm to multi-hop wireless mesh networks with Wi-Fi radio interfaces has also been studied [11], [12], [32]. Detti and co-workers proposed wmSDN, which is an SDN-based multi-hop wireless mesh network, mainly for the purpose of load balancing between multiple WMN gateways [12]. Dely and others proposed an OpenFlow-based architecture for flexible routing in wireless mesh networks [11] [32]. They demonstrated that the simplification of client mobility between mesh access points is feasible in

conformance to OpenFlow messaging triggered by the handover decision of a monitoring server. Although both works introduced an SDN implementation of wireless mesh networks, they did not consider multi-radio capable routers in terms of topology management and routing. Peng et al. proposed Access Point handoff in SDN-based wireless networks by exploiting dual network interfaces [40].

Cellular networks, particularly LTE networks, have recently drawn significant interest from the research community and industries. Some works have studied the issues and solutions for an SDN-based core network (wired part) [13]-[20], and others have focused more on the issues and directions for an SDN-based radio access network (wireless part) [6], [22]. Nagaraj and co-workers propose offloading flows from the evolved packet core (EPC) to other IP transport networks based on flow classification [13]. Mahoodi and others considered SDN-based EPC and studied the case of an intra-LTE handover procedure [14]. Heinonen and co-workers proposed a mechanism for dynamically switching the user plane tunnels in SDN-based cellular core networks [15]. Moradi and others looked into the scalability issue of SDN-based cellular WANs and proposed a three-level control of the switch regions and a recursive topology discovery mechanism [16]. Jin and co-workers proposed a scalable and flexible LTE core network architecture that can program forwarding to middle boxes based on service policies [17]. Pentikousis and others studied applying SDN to mobile core networks, and proposed a flow-based forwarding architecture for the benefit of the operators [18]. Basta and co-workers examined possible scenarios for the placement of EPC functions with a consideration of network function virtualization (NFV) [19]. Hampel and others proposed using SDN to program the encapsulation and decapsulation on top of IP to enable flow-based policy enforcement and mobility [20]. Gudipati and co-workers considered applying the SDN concept to LTE radio access networks, and proposed abstracting multiple eNBs as a single big base station and centrally managing radio resources together for load balancing and utility optimization [21], [22]. There are works that seek joint coordination of radio access networks and transport core networks [33], [34]. Bernardos and co-workers considered accommodating various wireless mobile networks in the SDN realm, and proposed a high-level architecture and the required northbound and southbound interfaces [33]. Tan and others proposed a wireless SDN architecture with a distributed user plane and a centralized function-oriented control plane, and demonstrated end-to-end QoS management and a content-aware data broadcast in converged LTE and Wi-Fi networks [34]. Most recently, Abdulghaffar [39] proposed SDN-based 5G core networks.

Most relevant to our work, some works have considered SDN-based control of heterogeneous wireless mobile networks, including works by Mendonca and co-workers [27], CROWD [35] [36], OpenRoads [37], and SoftMobile [23]. Mendonca and others first examined the possibility of applying an SDN approach in heterogeneous networks consisting of wired networks, infrastructure-based wireless networks, and infrastructure-less wireless networks (e.g., mobile ad hoc networks) [27]. They considered typical use cases such as an SDN-based gateway assignment and data offloading. Ali-

Ahmad and co-workers dealt with very dense networks of multiple radio technologies, and proposed a two-tier controller architecture for scalability in the control of dense networks [35], [36]. Yap and others proposed an OpenFlow-based wireless architecture for orchestrating and virtualizing heterogeneous wireless networks, and demonstrated a case study of WiMAX to/from a Wi-Fi handover [37]. Chen and co-workers considered complex control plane issues in multi-RAT heterogeneous mobile networks, and proposed a holistic control framework for providing a global network view (spectrum, connection, and interference map, among others) and abstraction along with coordination algorithms (for example, joint scheduling and interference cancellation) [23]. Mafakheri and co-workers took software-defined radio access network approach for LTE and WLAN coordination [38]. Alshaer et al. considered the problem of providing application QoS in SDN-based heterogeneous dense wireless networks [41].

### III. SUPPORTING MULTI-INTERFACE DEVICE

As the first type of multi-radio wireless mobile networks, the authors consider the LTE/WLAN multi-RAT wireless network illustrated in Fig. 1, where user devices (e.g., smartphones) are equipped with both an LTE radio interface and a WLAN radio interface. In 3GPP terminology, these are called UE. An entire LTE network in the data plane consists of an access network part, i.e., evolved node B (eNB), and core network parts, i.e., the serving gateway (S-GW) and packet data network gateway (P-GW). Although 3GPP has specified a tight integration of an LTE network and WLAN networks with P-GW as an anchor, most mobile network operators resist deploying it owing to the high cost of backhauling WLAN networks to an LTE core network part [26], [28]. Thus, the current norm is a loose integration or non-seamless integration of both networks, as depicted in Fig. 1. In this network, multi-radio devices typically make a radio access technology (RAT) selection using their connection manager software with only local logic. Furthermore, once selected initially for a flow, a RAT cannot be changed to another RAT dynamically. For these reasons, the current network has difficulties in achieving an optimal multi-radio resource utilization and providing quality of experience (QoE) dynamically [26]. It is envisaged that the SDN-based integration of LTE and WLAN networks can resolve the above issues without causing a severe backhaul cost.

Tailoring multi-radio wireless mobile networks to the SDN rebase basically involves making OpenFlow channels between an SDN controller and each switching entity, as indicated by the dotted lines in Fig. 1 and 2. Note that we assume OpenFlow to be used as an SDN standard [29]. Issues in the design of such SDN-based multi-radio networks arise in two facets: supporting multi-radio devices and supporting multi-radio switching entities.

In Fig. 1, as per the current SDN standard, each interface of a multi-radio device is separately known to attach a port of a corresponding switching entity to an SDN controller. For this reason, the SDN controller cannot distinguish a LTE/WLAN multi-RAT device from two single-radio devices with LTE and Wi-Fi, respectively. Identifying a multi-radio device and

serving it with a combination of adequate radios with the help of the SDN controller is not possible in the current SDN standard, and hence, some new enhancements are needed to resolve this issue.

An SDN controller's awareness of multi-radio devices is a key enabler to the effective utilization of multi-radio access technology (RAT) resources. For example, flow-precision inter-RAT mobility for a multi-radio device can be supported in the SDN context to ensure load balancing for a holistic network perspective. For this purpose, the authors propose mechanisms for integrated device identification and inter-RAT flow mobility control.

Fig. 2 illustrates the mechanisms in the form of a message sequence chart and explains each step. SDN controllers should incorporate device management module with multi-RAT device support: When a device attaches to a RAT base station through a radio interface, the controller keeps track of an interface mapping from the radio interface (with a unique MAC address) to a {switch, port} tuple. When a device has multi-RAT attachments concurrently, the controller keeps track of a list of multiple interface mappings per device.

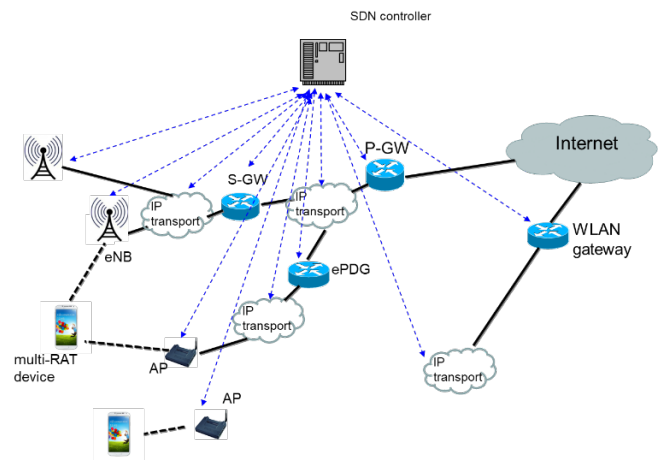


Fig. 1. An LTE/WLAN Network with Multi-RAT Devices. Its SDN Rebase is indicated by the Dotted Lines.

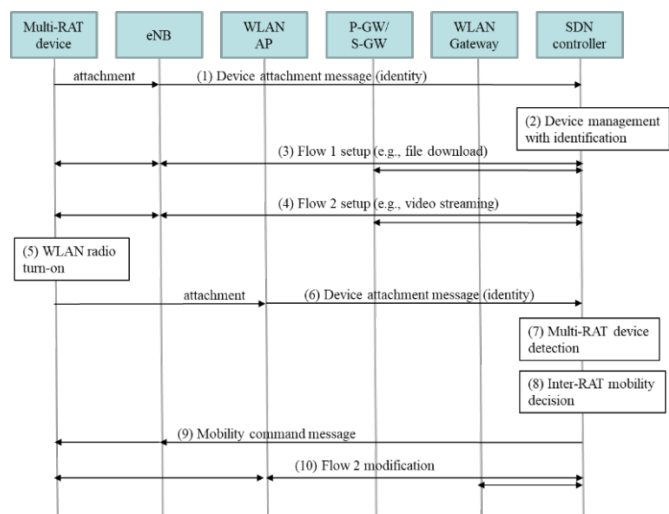


Fig. 2. A Message Sequence Chart for Handling a Multi-RAT Device.

(Step 1) A multi-radio device attaches to RAT 1, which is LTE, and a switching entity corresponding to eNB then notifies the SDN controller of the attachment and identification of the device. For the purpose of identification, an international mobile equipment identity (IMEI) can be used. (Step 2) The controller becomes aware of the device through LTE. (Steps 3 and 4) Two flows are set up based on the OpenFlow standard. (Step 5) The multi-radio device turns on its RAT 2 interface, which is a Wi-Fi interface, and discovers a WLAN AP. (Step 6) The device attaches to a WLAN AP and the AP in turn notifies the SDN controller of the attachment and identification of the device on WLAN. For the purpose of identification, the same IMEI can be used. (Step 7) Through the identification, the controllers handle the device as multi-radio capable. (Step 8) The controller makes a decision on the mobility of flow 2 from RAT 1 to RAT 2. (Step 9) A mobility command is sent out to the RAT 1 base station and device. (Step 10) A new flow table entry for flow 2 on RAT 2 is configured using an OpenFlow Flow Modify message.

#### IV. SUPPORTING MULTI-INTERFACE SWITCH

As the second type of multi-interface wireless networks, the authors consider the multi-radio multi-channel wireless mesh network illustrated in Fig. 3, where mesh routers are equipped with multiple IEEE 802.11-based radio interfaces operating on separate physical channels in parallel. In the figure, three different colors are used to indicate three non-overlapping WLAN channels. How to map each interface to a channel is a key concern for resource utilization, and static, dynamic, and hybrid channel assignments have been extensively studied. The current state-of-the-art method is a distributed approach that can rely only on local information for a channel assignment [25]. The authors believe that an SDN-based holistic coordination of multiple (homogeneous) radio interfaces of each wireless mesh router and their operating channels can result in better utilization throughout the entire network.

In Fig. 3, each interface of a multi-radio switch (mesh router) should operate on different channels to fully exploit the available Wi-Fi channels. However, as per the current SDN standard, information regarding on which physical channel a port (i.e., a wireless interface) operates is lacking, and thus, the optimization of multi-RAT resource utilization is hard to achieve. Furthermore, a port for a wireless interface of a wireless switch should actually be used for both incoming packets and outgoing packets because it uses the wireless broadcast medium. However, the SDN standard only specifies that an incoming port should be different from an outgoing port, and thus, we need some mechanisms for supporting wireless ports in the SDN paradigm.

For a multi-interface switch, a radio port is first configured for each RAT interface (e.g., IEEE 802.11 radio interface) and its operating channel is initially configured. Because a radio interface uses the wireless broadcast medium, forwarding rules can be properly specified only by distinguishing which neighbor is the intended receiver. For this purpose, for a radio port, virtual radio ports should be defined for each neighbor relation. A wireless interference and channel reconfiguration may impact wireless neighbor links and hence trigger the creation or deletion of virtual radio ports. The neighbor

switches of each switch can be discovered using the peer management protocol (PMP) of the IEEE 802.11s mesh standard. Thus, the switches themselves can determine whether a virtual radio port should be set for each discovered neighbor.

Fig. 4 illustrates mechanisms for handling multi-radio switches and multi-radio multi-channel aware routing in the form of a message sequence chart, and explain each step. (Step 1) A wireless port is set up, and a radio port status message including its operating channel is sent to the controller. (Step 2) Depending on how many neighbors the wireless port has, virtual radio ports are set up and known to the controller. (Step 3) Another wireless port is set up, and a radio port status message is transmitted. (Step 4) virtual radio ports for this port are set up and known to the controller. (Step 5) The controller is aware of a multi-radio switch, as well as its radio and virtual radio ports. (Step 6) A new flow 1 is created. (Step 7) The controller sets up a route for flow 1 from switch 1 to switch 2 and switch 4. (Step 8) Another flow 2 is created. (Step 9) The controller's multi-radio, multi-channel aware routing module determines whether to support the new flow 2 on a route from switch 1 to switch 3 and switch 4. (Step 10) The interfaces on the route use channel 2, which is less utilized than channel 1, and hence, can benefit from the multi-channel enhanced network capacity.

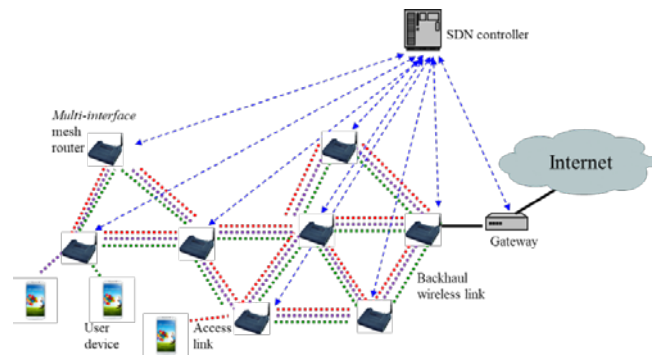


Fig. 3. A Wireless Mesh Network with Multi-interface Mesh Routers. Its SDN Rebase is indicated by the Dotted Lines.

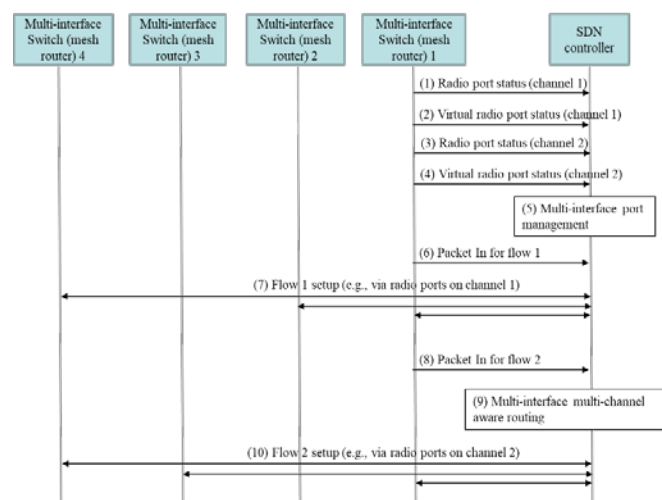


Fig. 4. A Message Sequence Chart for Handling a Multi-radio Switch (Mesh router). A Routing Procedure Exploiting Multi-channel Diversity is also included.

Switch management module with multi-radio switch support: The controller keeps track of each switch's radio ports and the mappings from each radio port to a list of virtual radio ports. The data structure for the radio ports and virtual radio ports includes operating physical channels for multi-channel awareness.

Forwarding module: When a new flow arises on multiple radio switches, a route for the flow can be determined based on a multi-radio, multi-channel aware algorithm to exploit channel diversity. Without multi-radio, multi-channel awareness, traditional shortest-path routing algorithms such as the well-known Dijkstra algorithm will only consider the link costs. For a multi-radio device, an existing flow on one radio can be examined to move to another radio based on an inter-RAT mobility algorithm with a holistic view of the entire multi-radio network.

### V. PERFORMANCE EVALUATION

The authors built an integrated testing suite for SDN controller implementation [30] [31] and software switch implementation using a network emulation scheme. It is verified that the controller and switches interoperate with each other in conformance with the OpenFlow specifications. For the implementation of the proposed mechanisms for multi-radio wireless mobile networks, we use Vendor messages to carry the additional proposed information on multi-radio devices and multi-radio switches. In this way, legacy single-radio devices and switches can still be supported without modification. The modules in the switch software are coded in C/C++ languages. The authors designed and implemented the proposed mechanisms using a multi-radio switch and device support in a widely used network simulator space (ns-3), and made them interoperate with a real SDN controller. Hence, the inherent benefits of ns-3 (e.g., module reusability and extensibility) can be exploited. Our experience in this paper shows that researchers and developers can prototype and test new ideas and mechanisms for OpenFlow switches used in software in a timely and flexible manner.

The authors present two exemplary performance results to demonstrate the benefits of the proposed mechanisms. The tests were conducted using simple but effective topologies to highlight the benefits. We first examine the performance of the proposed SDN-based LTE/WLAN flow mobility procedure for a multi-radio device. We use a small topology in Fig. 5 for the ease of analysis. Initially, two flows (flows 1 and 3) exist over the LTE radio access technologies for a multi-radio device, and later, another flow (flow 2) over LTE is created. At time 24, the multi-radio device turns on its Wi-Fi radio interface, and according to the proposed mechanisms, the SDN controller instructs inter-RAT flow mobility for flow 3. The topology in Fig. 5(a) shows the flows after the flow mobility is performed. The traffic load on LTE is distributed to Wi-Fi, and hence, the network utilization is improved and individual flows can enjoy higher rates. This result highlights the strength of SDN-based

holistic orchestration of heterogeneous multi-radio resources and flows.

Next, we examine the performance of the proposed WMN flow-precision multi-channel routing. In Fig. 6(a), a wireless mesh network topology is illustrated. Each node is equipped with two Wi-Fi radio interfaces, and flow 1 (blue) and flow 2 (red) are considered for the simulation. First, Fig. 6(b) shows the throughput for when both flow 1 and flow 2 use the same channel, i.e., the SDN controller does not have a notion of multi-channel routing. Initially, flow 2 monopolizes the channel, and at time 30, flow 1 is created and uses the same channel. We observed that the channel is shared between the two flows. Next, Fig. 6(c) shows the throughput for multi-channel aware routing. The scenario is the same, but when flow 1 is created, the SDN controller can conduct multi-channel aware routing, and thus two orthogonal channels can be utilized by the two flows, respectively. We observed that the throughput is significantly better for multi-channel aware routing by the SDN controller. Although we use a simple multi-channel aware routing algorithm in this evaluation, we anticipate that more sophisticated algorithms can solve a very complex channel assignment and routing problems more effectively.

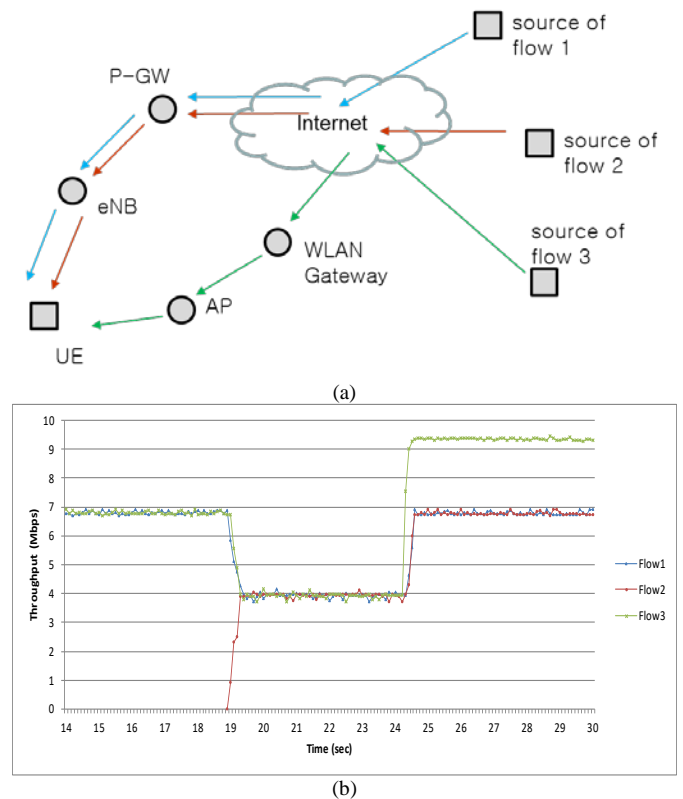


Fig. 5. An Example LTE/WLAN Topology for Evaluation of Inter-RAT flow Mobility: (a) LTE/WLAN Topology and (b) Throughput with inter-RAT Flow Mobility.

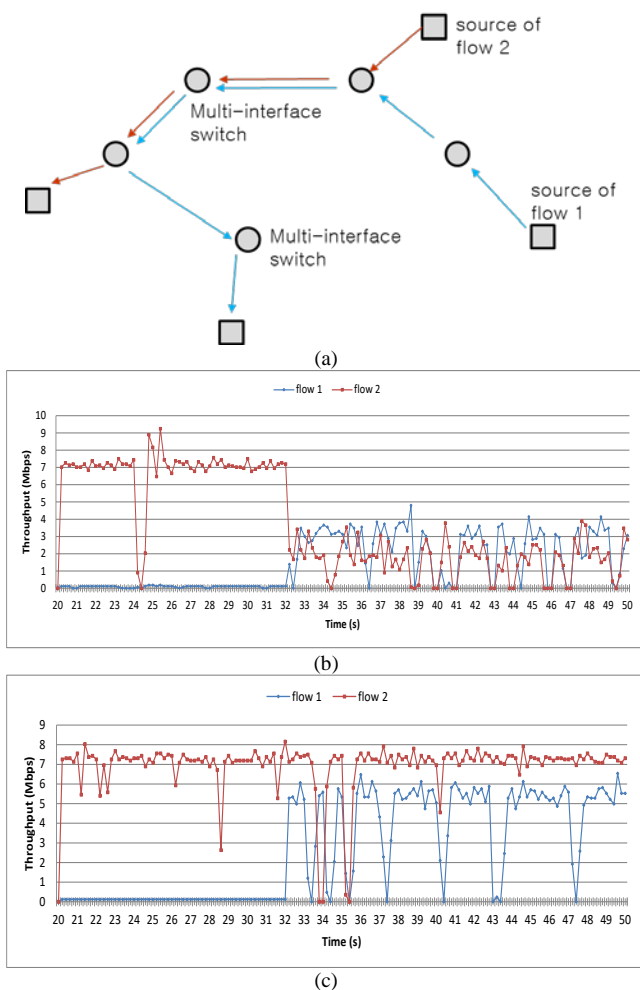


Fig. 6. An Example Multi-radio Mesh network Topology for Evaluation of Multi-channel Flow Routing: (a) Wireless Mesh network Topology, (b) Throughput with Single-channel Routing, and (c) Throughput with Multi-Channel aware Routing.

## VI. CONCLUSION

As the emergence of multi-radio (heterogeneous or homogeneous radio) wireless mobile networks increases, the mechanism of centrally coordinating all available multi-radio network capabilities in a holistic manner has become essential. This paper presented the first in-depth study on how to incorporate multi-radio devices and multi-radio switches within the SDN paradigm. We examined the possibility of SDN-based control of two promising multi-interface wireless mobile networks, i.e., LTE/WLAN heterogeneous networks and multi-radio multi-channel wireless mesh networks, and proposed their control mechanisms. Through the integration of a real SDN controller and standard-compliant simulated switching entities, it is demonstrated the functional verification and performance of the proposed mechanisms. Future work may include the implementation and experimentation of the proposed solution in real network settings.

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