Fine-grained Access Provisioning via Joint Gateway Selection and Flow Routing on SDN-aware Wi-Fi Mesh Networks

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***Abstract*—In recent years, dramatic growth of mobile data traffic has left the operators no choice but to consider Wi-Fi networks as an economic complementary solution. To achieve this, WLANs require to adopt some of the key features of carrier-grade operators, such as centralized resource management. As an emerging paradigm, Software Defined Networking (SDN) can be used to provide salient centralized network solutions for Wi-Fi infrastructures. In fact, applying SDN to different wireless platforms, e.g., Wi-Fi Mesh Networks (WMNs), brings unprecedented opportunities to improve the network performance by employing more sophisticated algorithms at SDN controllers. Moreover, it should be noted that traffic engineering over WMNs incorporates tightly correlated steps including association control, gateway selection and flow routing which are individually NP-hard problems. In this paper, we present an agile and fine-grained access provisioning solution via bridging the cellular and Wi-Fi technologies that empowers us to address the users demand by steering data flows on different tiers of WMNs. In contrast to the prior work, we present a detailed unified formulation for joint gateway selection and flow routing in Multi-Channel Multi-Radio (MC-MR) WMNs that considers the key attributes of wireless networks. The functionality of the presented solution is evaluated through various experiments with extensive numerical results.**

***Keywords*-SDN; WMN; Wi-Fi; Gateway Selection; Flow Routing; Fine-grained Access; Joint Optimization**

I. Introduction

In 97 countries, the proliferation of portable devices has led to more smart gadgets than people [1], which imposes a tremendous load on cellular networks. Over the past few years, some of the largest cellular operators restricted their unlimited data plans and proposed tiered charging plans enforced by either strict throttling or large overage fees [2]. While cellular operators are trying to guarantee the QoS of their services in a cost-effective and profitable manner, Wi-Fi can be considered as a viable complement. It is interesting to know that in 2016, more data traffic was offloaded from cellular networks to WLANs than remained on cellular networks and 50% of all IP traffic will be on Wi-Fi networks by 2021 [1]. In fact, the massive growth of Wi-Fi-enabled devices and hotspots makes Wi-Fi an attractive data offload technology for operators to avoid significant deployment cost of cellular equipment. Hence, WLANs offer cost-effective and efficient solutions to customers of different networks for seamless roaming with no extra charge.

Regarding the stated facts, Wi-Fi is an indispensable part of the next-generation access architecture and it requires to adopt some of the key characteristics of carrier-grade operators such as centralized network and resource management. In recent years, centralized network solutions have made significant headways in communication networks. Although the decentralized systems may seem more realistic, the growth of centralized solutions due to the feasibility of using more efficient algorithms at the centralized network controllers is an undeniable fact. Software Defined Networking (SDN) provides a promising approach for the deployment of centralized networking solutions. In this approach, the control and management functions of network devices are performed by logically centralized controllers, and the equipment becomes simple traffic forwarding engines. Indeed, SDN technology enables us to utilize more advanced and sophisticated algorithms at controllers to achieve near-optimal performance. Applying SDN to Wi-Fi Mesh Networks (WMNs), as a widely accepted and flexible solution to provide diverse kinds of services, brings many advantages for the end-users. As the main components of each WMN, Mesh Routers (MRs) are in charge of forming an interconnected network to serve the wireless users. By empowering MR nodes with SDN technology, we are able to benefit from all SDN features to enhance the service-level and user satisfaction. Indeed, WMNs formed by SDN-aware MRs offer great flexibility and granularity for packet processing and optimized traffic engineering.

In WMNs, we have three essential operations including Access Point (AP) association, gateway selection and flow routing for service provisioning. It should be noted that although each of these tasks can be mapped to a classic NP-hard problem, there is a close correlation among them and they cannot be considered as independent problems. By exploiting SDN-aware MRs, it would be possible to present a fine-grained joint solution for traffic flows on WMNs.

To have a big picture about the problem, suppose that we intend to run an educational workshop and we have to provide free Internet access to the participants. Although seemingly the easiest way is using a group of APs connected to the wired backbone, there are still some places in which using wired backbone is either too costly or not possible (especially in developing countries). On the other hand, cellular

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networks are accessible almost everywhere, and they allow quick service provisioning. However, deployment costs of cellular networks w.r.t. equipment and spectrum licensing fees are quite high. Furthermore, due to the high price of data plans and overage fees, many people are not interested in using data plans. In contrast, the construction cost of WLANs, using free unlicensed spectrum and inexpensive APs is substantially low. Hence, we can use a wireless bridge solution for Internet access provisioning through migration of data traffic from cellular to Wi-Fi networks. To do this, we first need to equip each AP with a cellular interface to function as an Internet gateway. Then, it can offload the data traffic from its cellular interface to its access users.

The main downside of this approach is exposed when all the users run traffic-greedy applications, e.g., HD video streaming, that imposes a significant cost on the service provider by increasing the number of gateway-enabled APs. To deal with this concern, we have to cap the greedy flows and guarantee a minimum level of QoS for the users. So, we can form a WMN by MRs equipped with cellular interfaces that can function as AP, router and gateway. Next, by activating the gateway functionality just for limited number of MRs and steering the traffic flows, we are able to reduce the cost of service provisioning, significantly. Note that to do this, the flows should be served in all tiers of a WMN (access, gateway and backhaul) in an optimal fashion. By utilizing an SDN-aware solution, the described scenario can be formulated as a set of optimization problems to find the optimal configuration of gateway selection and routing. Fig. 1 shows the big picture of the described scenario.

In this paper, we introduce a fine-grained network paradigm for fast access provisioning at flow level through migration of data traffic from cellular networks to metropolitan WLANs via SDN-aware WMNs. Indeed, we propose an economic and efficient solution to address the drastic growth of user demands by steering data flows over different tiers of WMNs while considering the defined QoS constraints.

Our main contribution in this work is twofold. First, we present an optimization framework for joint traffic engineering including gateway selection and flow routing, that enables the service providers to build cost-effective SDN-aware WMNs by optimal adjustment of the number of cellular gateways. Second, for the first time, we illustrate the existing correlation among different tiers of WMN through extensive experiments. The outcomes substantiate the practicality of the presented scheme in terms of service provisioning.

The rest of the paper is organized as follows. In the next section, related work on SDN-based WMNs and joint gateway selection and routing is discussed. Then, in Section III, the proposed architecture and the problem formulation are delineated. In the succeeding section, the performance evaluation of the defined scenarios is elaborated. Finally, the acquired results are analyzed in Section V and the conclusion and future work are presented in the last section.

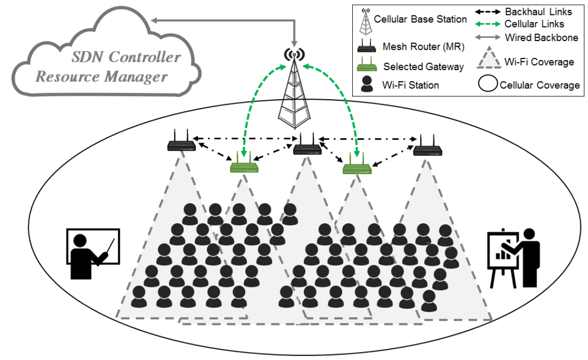

Figure 1: A possible scenario of the proposed solution.

II. Related Work

In this section, we first introduce some of the related work on SDN-aware WMNs. Then, we review the recent publications on joint gateway selection and flow routing.

A. SDN-aware Wireless Mesh Networks

During the past few years, several studies are conducted to deploy SDN technology over WMNs [3]–[5]. In one of the recent ones [6], an SDN architecture for traffic orchestration over WMNs is presented. The authors used Dijkstra algorithm to implement a simple traffic routing that does not necessarily guarantee optimal performance over WMNs. In another work [7], the authors proposed a crowd-shared WMN platform to interconnect home routers, that provides multiple Internet gateways and utilizes an SDN-based control plane for traffic sharing. Furthermore, there is limited work on the development of efficient SDN-aware routing protocols for WMNs. In [8], a novel hybrid routing forwarding algorithm based on SDN and OSPF protocol is presented which divides the network into conventional and SDN-enabled segments. Although the performance of the presented work is evaluated through simulation, limited analysis is carried out. Another form of hybrid SDN routing based on OLSR protocol is presented in [9], but the proposed solution is not adapted to be applied for Multi-Channel Multi-Radio (MC-MR) WMNs. One of the missing aspects of the former work on SDN-aware WMNs is the presentation of a joint optimization to route network flows over the mesh backhaul w.r.t. QoS constraints such that the selected routes are correlated with access demands and gateway capacity. In the next subsection, we introduce some of the most related work on joint gateway selection and flow routing mechanisms over MC-MR WMNs.

B. Joint Gateway Selection and Flow Routing over WMNs

As mentioned earlier, there is a strong correlation among AP association, gateway selection and flow routing processes. Due to the NP-hardness of these problems, we need to use approximation or heuristic schemes to find sub-optimal solutions. For the first problem, several studies were carried out on WLANs that can be extended to WMNs. In one of the most recent works [10], a meta-heuristic solution to find a guaranteed approximation of the optimal result is presented. In another work [11], the authors formulated a joint station association and rate allocation problem in WMNs. Despite the efficacy of the presented solution, it can only be applied to the single gateway scenarios. Moreover, the utilized traffic routing algorithm is elementary and it is assumed that the capacity of backhaul is unlimited.

To solve the flow routing problem through a centralized scheme, Multi-Commodity Flow Problem (MCFP) is one of the most popular approaches. This can be formulated as an optimization problem with multiple constraints that reflects the characteristics of a communication network. Since finding an optimal solution for such a problem in large-scale networks is not feasible, many studies are conducted to find near-optimal solutions for wireless applications. For instance, an optimal capacity planning for MC-MR wireless networks based on MCFP is presented in [12]. By adopting a multi-dimensional conflict graph, a structured approach for finding the optimal capacity is introduced. In a similar work [13], the performance of a 2-hop routing strategy for mobile ad-hoc networks is investigated and a near-optimal solution is presented. Applying meta-heuristic schemes such as Ant Colony Optimization (ACO) to the given flows for finding a near-optimal set of routes is another approach that is introduced in [14]. In one of the recent works [15], a joint resource allocation scheme for both backhaul and radio access links is proposed. The offered solution obtains a sub-optimal result in a distributed manner. In another work [16], the scholars presented centralized and distributed MCFP-based solutions with MIMO support to find an approximation of the optimal routing. Note that in the majority of the prior works, the gateway selection is ignored.

Although by having many active gateways with cellular links we can promote the network throughput, it increases the deployment cost and we have to find a trade-off between the number of gateways and the network capacity. In one of the works to address this problem [17], an Internet gateway deployment strategy for MC-MR WMNs is introduced. The authors formulated a multi-objective linear program and utilized a hierarchical clustering scheme for gateway selection. There is another work [18] in which the authors used grid-based placement of gateways as an intuition to maximize the network throughput. Moreover, applying Capacitated Facility Location Problem (CFLP) to WMN topologies for finding the optimal result is one of the dominant techniques that is used in [19], [20]. Building spanning trees and clustering the given network topologies are the key steps of the gateway selection problem in most of the former studies that facilitate the solving process of the joint problem.

Despite the efficacy of the prior work for the specific problems, none of them proposed a fine-grained and thorough joint solution. Furthermore, note that finding optimal results

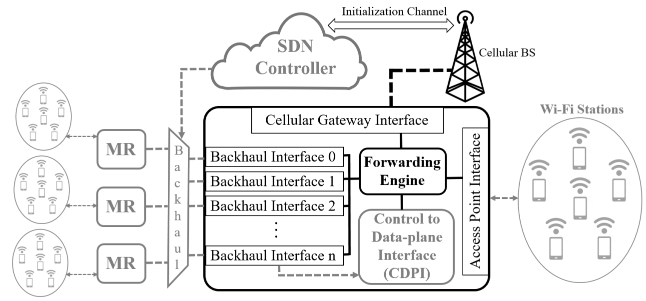

Figure 2: The proposed MR architecture.

for the joint problems in multi-dimensional scenarios, i.e., MC-MR WMNs, necessitates to deal with NP-hard problems [12]. In the next section, our proposed joint solution is delineated in detail.

III. Proposed Solution

Before introducing the structure of our solution, we briefly explain the architecture of its key component (MR).

A. MR Architecture

Fig. 2 illustrates the architecture of an MR. As shown, each MR has three types of network interfaces including Access Point (AP), backhaul and gateway interfaces. The first interface type is in charge of association control and serving the Wi-Fi stations. After association, the access traffic should be routed through backhaul interfaces. Every MR may have multiple interfaces to form an MC-MR backhaul network with other MRs. In addition, it is assumed that each MR is equipped with a cellular interface that enables its gateway functionality. The integrator of these interfaces is the Forwarding Engine that receives the control traffic from the SDN controller through Control to Data-Plane interface (CDPI) module. Forwarding Engine switches the traffic flows among different interfaces based on the decision of controller. Moreover, it is assumed that all MRs are deployed in an area with cellular coverage. The initial configuration of MRs by SDN controller can be carried out through a secure communication channel. Then, the control traffic (with a priority higher than regular traffic flows) can be delivered from the controller to the CDPI (and vice versa) through either cellular or mesh backhaul network.

B. The Structure of the Proposed Solution

As explained in Section I, we intend to propose an optimization problem formulation for traffic engineering of data flows over the constructed WMN in an optimal manner. The required steps to achieve this goal are illustrated in Fig. 3. The first step of this process is access association problem (Step 1), and the second one includes the required preprocessing tasks for joint optimization (Step 2). Finally, we solve the joint gateway selection and flow routing problem in the last step (Step 3). According to Fig. 3, it can be seen that the second step involves three subsections to determine the

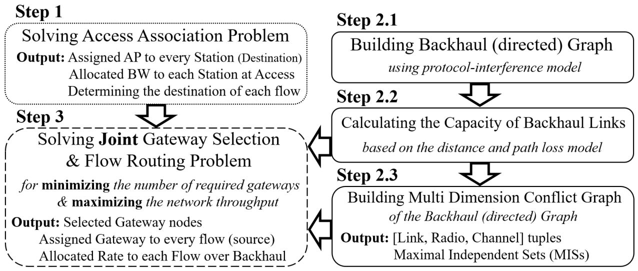

Figure 3: The structure of the proposed fine-grained solution.

source and destination of the given flows for routing process as well as solving a joint optimization problem. More details are provided in the succeeding subsections.

C. Association Control Formulation

At the first step of Fig. 3, we determine the MRs that the stations have to be associated with. Indeed, we intend to solve an optimization problem by mapping every station to an MR such that it maximizes the objective function (network throughput). By finding the corresponding MR for every station, it is possible to calculate the throughput of each station in the access layer. These values are the inputs (flow demand) for the next step which solves the joint optimization problem. Note that AP association is a Mixed Integer Linear Problem (MILP) and NP-hard that can be mapped to the Generalized Assignment Problem (GAP). By taking the relaxation and rounding techniques, we can find an approximation of the optimal solution for the access association problem in polynomial time. Due to the page limit, we skip the detailed delineation of this part and refer the readers to [10], [21]. The obtained results at this step will be used as the inputs of Step 3 to estimate the optimum value for the aggregate throughput of the flows over the mesh backhaul while considering the QoS constraints.

D. Joint Gateway Selection and Flow Routing Formulation

According to the presented details in Fig. 3, before solving the joint optimization problem at Step 3, we need to walk through three preliminary steps. First, considering the given position of MR nodes and the communication range of their backhaul radios, we build a network graph (Step 2.1). In the next step, we calculate the physical data rate of each wireless link in the constructed graph by using the nodal distance and the chosen path loss model (Step 2.2). We utilize the introduced approach in [12], [22] to consider the impact of interference over the backhaul links. In fact, to consider the impact of interference on a mesh backhaul consists of radio interfaces and multiple channels, we build a Multi-Dimensional Conflict Graph (MDCG) based on the backhaul links and the number of backhaul radios/channels. Each vertex of the MDCG demonstrates a resource entity of the MC-MR WMN and it can be represented as a *Link-Radio-Channel (LRC)* tuple (Step 2.3). Once we have the MDCG, we can compute its Maximal Independent Sets (MISs) that represent the non-adjacent vertices of MDCG. Thus, the vertices (tuples) placed in these MISs determine the links, channels and interfaces, that can transmit simultaneously without interfering with each other. Note that the protocol interference model, as a well-known technique, is utilized in the introduced works to model the link interference, and can be converted to physical interference model accurately [23]. We use the same model to build our proposed solution. Finally, in Step 3, we formulate the joint optimization.

As stated before, the main goals are minimizing the number of the required active gateways and maximizing the network throughput regarding the QoS constraint. Since achieving these goals at the same time and through a single objective function is intractable, the problem is formulated to find the maximum network throughput for a predetermined number of gateways. Thus, we need to solve the optimization problem through an iterative process. First, we present the joint optimization to maximize the objective function for a given number of gateways. Then, we propose an algorithm to find the optimal number of gateways in the next subsection.

The term in (1) demonstrates the objective function that maximizes the total allocated bandwidth (throughput) to the traffic flows of all the stations over the backhaul network. In this equation, S and F_s represent the set of the stations and the set of network flows that belong to station s, respectively. Also, b'_{fs} shows the acquired bandwidth by flow f associated with station s over the backhaul. The first constraint in (2) assures that the bandwidth of each flow (b'_{fs}) is no less than the guaranteed bandwidth ($b_{\min}$) and no more than its demand, b_{fs} (the acquired bandwidth in the access layer).

The second one in (3) ensures that the allocated bandwidth to flow f belongs to station s (r_{fsl}) over the egress (out) links of its assigned gateway m is no more than its demand. In this constraint, y_{fsm} is a binary variable that is equal to 1 when flow f associated with station s is assigned to MR m as its selected gateway, otherwise it is 0.

The next relation in (4) expresses that the sum of outgoing traffic from the selected gateways is no more than the gateway capacity (G_m). Note that the outgoing traffic contains the egress traffic to the associated stations with MR m (S'_m) and the egress traffic that belongs to the reachable stations from MR m over the backhaul network topology (S''_m). Also, in this constraint, e_m is the gateway selection variable that represents either MR m functions as a gateway or not.

The next two equations ensures the flow conservation over the mesh backhaul. The relation in (5) guarantees the total ingress (in) and egress (out) traffic of the flows that traverse a given MR m are equal if m is not the selected gateway of the flows (i.e., $z_{fsm} = 0$). In this constraint, we use binary variable z_{fsm} to show whether flow f associated with station s is assigned to gateway m or not. The relation in (6) assures the similar situation for the network flows that are destined to the associated stations with MR m. The next constraint in (7) ensures the total load of all assigned flows to their selected gateway m is no more than its capacity. The relation in (8) assures that the aggregate load of the assigned flows to gateway m is no more than the total capacity of its egress links. Note that the presented condition in (8) is valid only for downlink traffic. For the uplink traffic, the outgoing backhaul links have to be replaced with the incoming links.

$$\text{Maximize} \qquad \sum_{s\in S}\sum_{f\in F_s} b'_{fs}, \tag{1}$$

$$\text{s.t.} \quad b_{\min} \le b'_{fs} \le b_{fs}, \qquad \forall s\in S, \forall f\in F_s \tag{2}$$

$$\sum_{m\in M}\sum_{\substack{l\in L\\ out(m)}} r_{fsl}\, y_{fsm} \le b_{fs}, \forall s\in S, \forall f\in F_s \tag{3}$$

$$\sum_{\substack{l\in L\\ out(m)}}\sum_{s\in S''_m}\sum_{f\in F_s} r_{fsl}\, y_{fsm} + \sum_{s\in S'_m}\sum_{f\in F_s} b'_{fs}\, y_{fsm} \le G_m\, e_m, \forall m\in M \tag{4}$$

$$\sum_{\substack{l\in L\\ in(m)}}\sum_{f\in F_s} r_{fsl}\,(1-z_{fsm}) = \sum_{\substack{l\in L\\ out(m)}}\sum_{f\in F_s} r_{fsl}\,(1-z_{fsm}), \quad \forall m\in M, \forall s\in S''_m \tag{5}$$

$$\sum_{\substack{l\in L\\ in(m)}}\sum_{f\in F_s} r_{fsl}\,(1-z_{fsm}) = \sum_{f\in F_s} b'_{fs}(1-z_{fsm}), \quad \forall m\in M, \forall s\in S'_m \tag{6}$$

$$\sum_{s\in S}\sum_{f\in F_s} b'_{fs}\, z_{fsm} \le G_m\, e_m, \qquad \forall m\in M \tag{7}$$

$$\sum_{s\in S''_m}\sum_{f\in F_s} b'_{fs}\, z_{fsm} \le \sum_{\substack{l\in L\\ out(m)}} C_l, \qquad \forall m\in M \tag{8}$$

$$\sum_{s\in S}\sum_{f\in F_s} r_{fsl} \le C_l, \qquad \forall l\in L \tag{9}$$

$$\sum_{i\in I}\alpha_i \le 1, \qquad 0\le \alpha_i \le 1 \tag{10}$$

$$\sum_{i:l\in i}\alpha_i w^c_{li} = C_l, \qquad \forall l\in L, \forall c\in C \tag{11}$$

$$\sum_{m\in M} z_{fsm} = 1, \qquad \forall s\in S, \forall f\in F_s \tag{12}$$

$$z_{fsm} \le e_m, \qquad \forall s\in S, \forall f\in F_s, \forall m\in M \tag{13}$$

$$\sum_{m\in M} e_m = N_g \tag{14}$$

$$0\le y_{fsm} \le e_m, \quad \forall s\in S, \forall f\in F_s, \forall m\in M \tag{15}$$

$$0\le y_{fsm} \le z_{fsm}, \quad \forall s\in S, \forall f\in F_s, \forall m\in M \tag{16}$$

$$e_m + z_{fsm} - y_{fsm} \le 1. \forall s\in S, \forall f\in F_s, \forall m\in M \tag{17}$$

The next constraint in (9) guarantees that the total load of passing flows through link l is no more than the link capacity (C_l). As stated before, the interference over the mesh backhaul has to be taken into account by building the MDCG of the network topology. Then, by finding MISs of the created MDCG, we are able to show the relationship between the link capacity and the physical link data rate as shown in (10) and (11). Indeed, these equations solve the optimal capacity planning of an MC-MR WMN, and ensure that just one MIS can be active at any time. It is important to note that although flow routing over wired networks (with links that have known capacity) is a well-studied problem, it is quite challenging over multi-hop wireless networks due to the impact of interference and dynamic capacity of wireless links. One of the key features of the presented formulation is to consider this fact by finding MISs of the built MDCG to estimate the allocated bandwidth to the network flows. Suppose I represents the set of calculated MISs of the MDCG that is derived from the backhaul topology. So, the first relation in (10) represents the assigned fraction of time to MIS i ($\alpha_i, i\in I$), the value of which is in [0, 1]. The sum of these fractions should be less than or equal to 1.

The next constraint in (11) utilizes this factor to determine the average capacity of link l under traffic scheduling w.r.t. the impact of interference. In this equation, w^c_{li} shows the physical data rate of link l over channel c in MIS i. In addition, note that although finding MISs for a given graph is NP-hard and out of the scope of this work, there are heuristic solutions to find an approximation of MISs [22]. The next two equations show the gateway selection constraints which are based on the CFLP. The constraints in (12) and (13) assure that each flow is assigned to only one MR as their selected gateway. The next constraint in (14) defines the total number of selected gateways. Note that if this number (N_g) is not selected properly, the optimization problem becomes infeasible and cannot be solved. Finally, we use the last three constraints to apply the McCormick envelopes [24] to y_{fsm} variable. This variable is defined as the product of two binary variables, including e_m and z_{fsm}. In fact, we use y_{fsm} to avoid cubic constraints in the presented formulation.

Although the illustrated formulation is a Mixed Integer Non-Linear Problem (MINLP), still by applying McCormick envelopes to the equations in (3–8), it is possible to transform the illustrated formulation to an MILP. Then, we are able to solve the problem either by regular solvers or applying approximation algorithms [25], [26] to the MILP. Furthermore, by applying the network segmentation techniques to the large-scale topologies, the limitation of computing resources can be alleviated to achieve better sub-optimal results. Now, the key challenge is finding a way to estimate the optimal value of the required gateways (N_g) for the given topology. In the next subsection, we introduce a simple and fast algorithm to achieve this goal. A summary of the used symbols is shown in Table I.

Table I: Utilized Parameters in Problem Formulation.

Symbol	Description
M	The set of all Mesh Routers (MR)
S	The set of all Stations
F_s	The set of the flows that belong to station $s \in S$
S'_m	The set of the associated stations to $m \in M$
S''_m	The set of the reachable stations from $m \in M$
C	The set of backhaul Channels
L	The set of Links of the given network graph
$b_{\min}$	Min guaranteed bandwidth for all the flows on backhaul
b_{fs}	Throughput of flow f from station s in access layer
b'_{fs}	Throughput of flow f from station s in backhaul layer
r_{fsl}	Allocated rate to flow f of station s over backhaul link l
C_l	Capacity of backhaul link l
w^c_{li}	Data rate of link l on channel c in independent set $i \in I$
G_m	Capacity of node m as a gateway
e_m	1, if m is selected as a gateway
z_{fsm}	1, if flow f of station s is assigned to MR (gateway) m
N_g	Number of the selected gateways
y_{fsm}	A replacement for the multiplication of e_m and z_{fsm}
α_i	Fraction of time that is allocated to independent set $i \in I$

E. The Algorithm for Joint Optimization

The proposed solution to find the optimal number of required gateways is demonstrated in Algorithm 1. The algorithm attempts to pinpoint the optimum value by searching over an interval $[lb, ub]$ with variable bounds. In fact, it carries out an iterative process that checks the feasibility of the optimization problem and adjusts the bounds of the search interval. At the beginning of the process, we make an initial guess ($\frac{lb+ub}{2}$) for the optimal N_g, and in each iteration we shrink the search scope. Note that the initial value of the lower bound is calculated based on the predetermined values including the minimum guaranteed bandwidth ($b_{\min}$), number of stations ($|S|$) and the gateway capacity (G_m). Moreover, the upper bound is initialized to its maximum value which is the number of MRs. When the lower bound reaches the upper bound, the search process stops and $\lceil N_g \rceil$ will be used as the number of required cellular gateways. Then, we have an accurate approximation of the optimal number of required gateways as well as the allocated rate to each flow f. In addition, note that δ is a small number that can be used to adjust the time complexity of Algorithm 1.

IV. Performance Evaluation

It should be noted that evaluation of WLANs/WMNs in dense networks using a packet-level simulator is too complex and time-consuming. Moreover, since our main interest is the performance assessment of the service provisioning process and we do not need to explore the dynamics of protocol stack, using a packet-level simulator is not necessary. Hence, we carried out the experiments using our own simulator with extensive numerical results. In this section, we delineate more details on the key assumptions and setup that are used to conduct the experiments.

Algorithm 1 Finding Optimal No. of Required Gateways.

$lb \leftarrow \frac{b_{\min}|S|}{G_m}$
$ub \leftarrow |M|$
while $ub > (1+\delta)lb$ **do**
  $N_g \leftarrow \frac{lb+ub}{2}$
  Solve the Joint Optimization problem for $\lceil N_g \rceil$.
  if the Joint Optimization is $feasible$ **then**
    $ub \leftarrow N_g$
  else
    $lb \leftarrow N_g$
  end if
end while
Consider $\lceil N_g \rceil$ as the number of the required gateways.

A. Key Assumptions

For all the scenarios, it is assumed that one flow is assigned to every station and all the flows have the same priority. Our scheme is evaluated under a stable network condition, i.e., no new station joins or leaves our network which is consistent with our scheme when the scale of join/leave events is larger than the period of service provisioning.

We have utilized multi-rate MRs that serve stations with diverse data rates. In addition, it is supposed that all MR nodes use omni-directional Single-Input Single-Output (SISO) antennas for the access association and Multi-Input Multi-Output (MIMO) antennas for backhaul routing. Moreover, different frequency bands are utilized for access (2.4 GHz) and backhaul (5 GHz) layers, and the impact of Hidden Terminals (HTs) can be taken into account during the creation of the MDCG. Note that in most of the Wi-Fi commodities, the impact of HTs can be avoided by enabling the restart-mode in Wi-Fi chipsets. This feature enables the radio to capture the stronger signal when multiple signals are received (capture effect). The same technique for the similar scenarios is adopted in [27], [28]. Moreover, we use protocol interference model to consider the impact of interference in the conducted experiments. The same approach is used in the introduced work in Section III-D [12], [22], [23].

The backhaul topology is represented using a directed graph and it is assumed that all network flows are downlink greedy (greedy in download time). It means, the network traffic streams from the selected gateways to the MRs that stations are associated with, and transmit queues are always full. We use homogeneous demands and capacities for the flows and the selected gateways, respectively. Moreover, since according to [29], two-thirds of the top activities on smart-phones are primarily nomadic, e.g., web browsing, and making video calls, rather than mobile, we use nomadic scenarios. Note that the presented scheme can be applied directly to the scenarios that a large number of nomadic users are placed in a restricted area, such as conference halls or stadiums. The majority of the assumptions is based on [21].

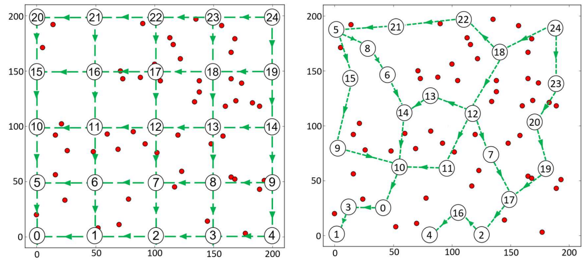

Figure 4: Grid and random topologies for 50 stations.

B. Experiment Setup

We have conducted a collection of experiments over grid and random topologies that are deployed within 200×200 m^2 areas. Fig. 4 represents the introduced topologies that contain 25 MRs with uniformly distributed stations (shown by red circles). In our setup, the data rate of backhaul links can reach up to 600 Mbps by enabling 4×4 MIMO streams (of 802.11n Wi-Fi interfaces) at MRs. The stations are equipped with Wi-Fi interfaces that support 802.11 g/n standards. In addition, we apply the wireless channel that used in [10] to our scenarios. For running the experiments, we develop our own network simulator in Python/Gurobi [30] (version 6.5.2) and we use $igraph$ library to find the MISs of the derived MDCG from the network topologies.

For particular cases, such as the explained scenario in Section V-D, we use a specific $b_{\min}$ value (3.3 Mbps) to present a clear picture on the performance of our presented solution. In addition, to grasp the severe impact of link interference in our results, we consider the shown grid in Fig. 4 as the dominant topology to construct the mesh backhaul network. Moreover, except Section V-D, we use Single-Channel Single-Radio (SC-SR) setup in all the experiments to demonstrate a clear picture on the performance of our solution. The utilized parameters in the conducted scenarios of the following section are delineated in detail therein.

V. Results and Discussion

In order to investigate the impact of different parameters, we conduct a set of experiments as follows.

A. Impact of $b_{\min}$ on Throughput and Number of Gateways

In the first experiment, the influence of $b_{\min}$ on the per-flow throughput, number of required gateways and Jain's Fairness Index (JFI) is studied. To do this, we consider 100 network flows over the grid topology such that the gateway capacity and the physical data rate of backhaul links are assumed 100 Mbps and 150 Mbps, respectively. Fig. 5 illustrates the obtained results in ascending order that includes the number of required gateways, aggregate throughput and JFI values for every $b_{\min}$. According to the results, our solution assigns $b_{\min}$ to all the network flows first and then it distributes the residual capacity of the selected gateways among the stations that are either directly associated or are placed in their vicinity. The main reason for

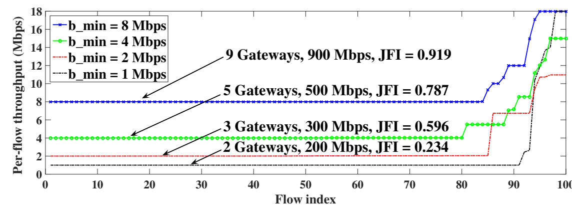

Figure 5: The impact of $b_{\min}$ on flow throughput and JFI.

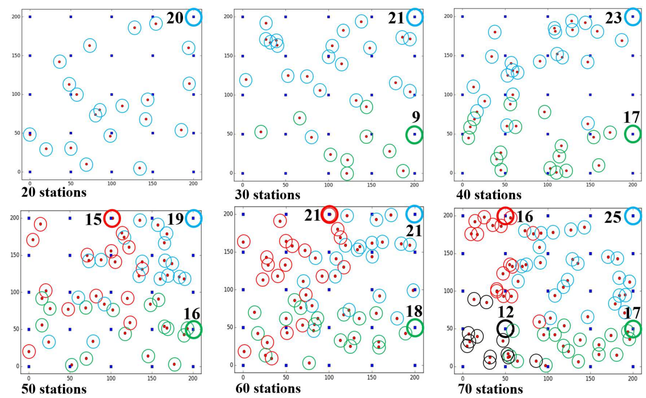

Figure 6: The selected gateways for different flow densities.

taking this approach is avoiding the impact of interference especially when the network flows traverse multiple hops to reach their destinations. Indeed, this strategy guarantees to meet the QoS constraint, minimizing the number of gateways and maximizing the network throughput, simultaneously. Moreover, as we can see in Fig. 5, increasing $b_{\min}$ has a significant impact on improvement of JFI values which is the consequence of increasing the greediness of flows that leads to equal dissemination of gateway capacity. Furthermore, due to the impact of interference on the access and backhaul links, the number of required gateways for different $b_{\min}$ values is not known prior to solving the optimization problem. For instance, when $b_{\min} = 1$ Mbps, it seems that we need just 1 gateway to guarantee the demands of 100 flows, but as shown, at least 2 gateways are required. It is important to note that our presented scheme still is able to guarantee $b_{\min}$ for the network flows only by using a limited number of MRs, that their gateway functionality are enabled.

B. Gateway Placement and Flow Load Balancing

In the second experiment, we study the distribution and the number of assigned flows to the selected gateways. Hence, for different flow densities and fixed $b_{\min}$ (4 Mbps) on the grid topology, we illustrate the results in Fig. 6. In the shown graphs in this figure, the selected gateways are displayed by the bold colored circles and the number of associated flows with them are shown close to them. Moreover, the stations (flows) that are assigned to the same gateway are represented with the same color, used for the gateway. For example, in the top-right graph of Fig. 6, two gateways are selected that 23 stations (shown by light blue)

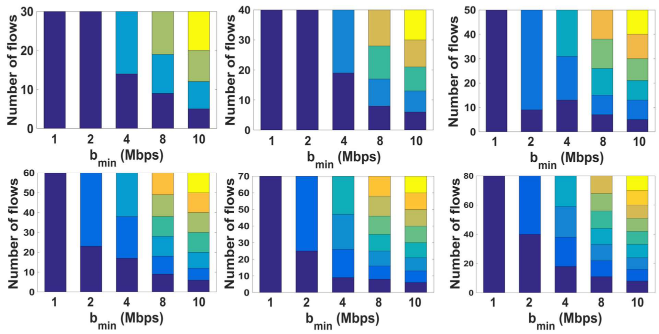

Figure 7: Load (flow) balancing over the selected gateways.

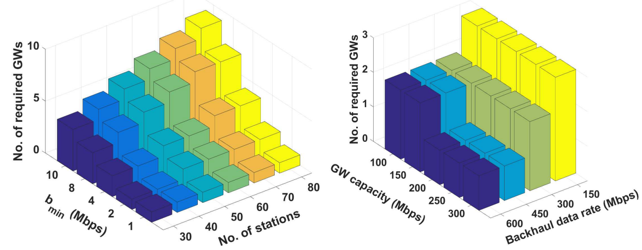

Figure 8: The impact of $b_{\min}$ and stations on gateways.

are assigned to the first gateway and 17 (shown by green) are assigned to the second one. In addition, according to the shown distribution of the assigned flows to their selected gateways, the majority of flows are allocated to the closest selected gateway. Nevertheless, there are cases that this approach has been ignored to alleviate the undesired impact of interference on the throughput of network flows. It can be seen that to avoid the destructive impact of interference on internal backhaul links, in most cases, edge MRs are selected as the gateways. The symmetry of the grid and the position of stations are the other factors that influence the placement of the selected gateways. However, in dense topologies with many greedy flows, the selection of non-edge MRs as gateway is inevitable. This fact can be observed in the last graph of Fig. 6 with 70 stations and 4 selected gateways. Note that the presented results are consistent with the outcomes of similar setup for undirected network graphs.

In addition, to demonstrate a better picture about load balancing of network flows, we carry out another experiment on the grid topology for different $b_{\min}$ values. Fig. 7 shows the obtained results for 6 different flow densities over multiple $b_{\min}$ values. In each graph, the number of assigned flows to the selected gateways for different $b_{\min}$ values are illustrated. In fact, every bar of each graph represents the number of flows that are assigned to all the selected gateways such that the length of each colored segment indicates the number of assigned flows to one of the selected gateways for the predetermined $b_{\min}$ value. For instance, in the top-left graph of this figure (with 30 network flows), for $b_{\min} = 4$ Mbps, two gateways are needed and 14 flows are assigned to the first one and 16 to the second one. It can be seen that our proposed solution distributes the network flows among the selected gateways in a fair manner. In distinct cases, e.g., the top-right graph of Fig. 7 for 50 flows and $b_{\min} = 2$ Mbps, to avoid the impact of interference on the bandwidth of the internal flows and maximizing the network throughput, 9 flows are allocated to the first gateway and the rest are assigned to the second one. Moreover, note that changing the data rate of backhaul links can change the gateway placement of the same configuration as well. Also, there is a strong correlation between the throughput of each flow and its acquired bandwidth from the access layer, mesh backhaul and its assigned gateway. The existence of a bottleneck at any of these layers limits the performance.

C. Impact of Backhaul Capacity and Access Load

In this subsection, we have investigated the impact of backhaul/gateway capacity and access load on the number of required gateways. The presented results are acquired from the grid topology with 50 network flows. In addition, it is assumed that the backhaul links have the same physical data rate. In the displayed results in Fig. 8, the left-side graph shows the number of selected gateways as a function of $b_{\min}$ and the number of stations (flows). The right-side graph represents the same outcome on z-axis, but it is a function of the gateway capacity and the data rate of backhaul links.

To have the left-side graph, the gateway capacity is set to 100 Mbps and it is assumed that maximum link data rate of both access and backhaul layers are 150 Mbps. As illustrated, both selected factors can cause drastic changes on the number of required gateways. As an example, for the given topology with 80 stations and $b_{\min} = 10$ Mbps, the gateway functionality of at least 9 MRs should be activated. It is important to note in contrast with most of the former works on MC-MR WMNs that increasing the number of radios and non-overlapping channels over the backhaul network leads to the increment of network throughput, the proposed solution in this work does not follow the same approach. Since one of the main goals of our scheme is reducing the number of cellular gateways, it acts as a restrictive measure that limits the rise of throughput. In addition, it can be seen that the growth of each of the selected inputs ($b_{\min}$ or the number of stations) raises the load of access layer that increases the number of gateways.

According to the illustrated result in the right-side graph, it is not possible to use only one gateway to meet the QoS constraint by increasing the gateway capacity. For instance, when the backhaul links have limited capacity (150 Mbps), for different values of the gateway capacity, still we need 3 gateways to guarantee $b_{\min} = 4$ Mbps for 50 flows. However, this number can be reduced to 1 if we increase the capacity of backhaul links to 450 and 600 Mbps through enabling MIMO streams at MRs. This result substantiates

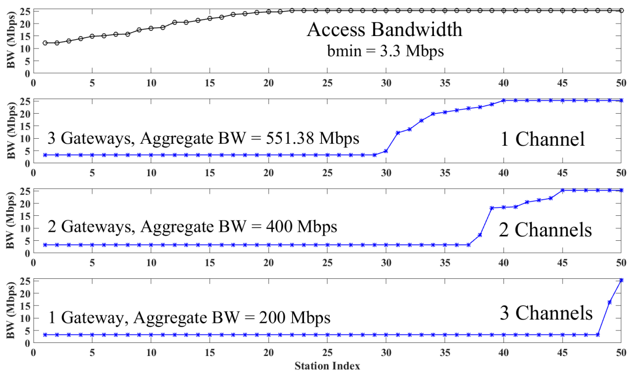

Figure 9: The results of MC on random topology.

that both gateway and backhaul tiers play pivotal roles to determine the number of required gateways.

D. Impact of MC-MR on the Number of Gateways

To explore the impact of using MC-MR on the performance of our scheme, we conduct an experiment on the illustrated random topology in Fig 4. In this experiment, we first set the gateway capacity and $b_{\min}$ to 200 Mbps and 3.3 Mbps, respectively. Then, we calculate the bandwidth of each flow for different number of backhaul channels. The presented graphs in Fig. 9 illustrate per-flow throughputs for the given number of channels. The first graph shows the sorted flow throughputs in access layer which is the upper bound of the flow bandwidth in the backhaul network.

The next three graphs in Fig. 9 represent the calculated flow bandwidth for different number of backhaul non-overlapping channels. According to these graphs, increasing the number of backhaul channels has an evident impact on the number of required gateways. For instance, by increasing the number of backhaul channels from 1 to 2, the number of required gateways has reduced from 3 to 2. The same outcome can be seen when the number of channels is increased from 2 to 3. Moreover, according to the illustrated result in the second graph (1 Channel), it can be seen that although 3 gateways with the total capacity of 600 Mbps are used, due to the severe impact of interference on the backhaul links, just 551.38 Mbps is utilized and more than 8% of of this capacity is under-utilized. On the other hand, in the third graph, by increasing the number of backhaul non-overlapping channels to 2, the capacity of two selected gateways is fully utilized (2 x 200 = 400 Mbps). The same result is shown in the last graph of Fig. 9, where by using 3 backhaul channels, we can guarantee $b_{\min} = 3.3$ Mbps for all the network flows. In addition, it is interesting to notice that by reducing the number of required gateways (through increasing the number of channels), the number of flows, with achieved bandwidth more than $b_{\min}$, is decreased as well. Note that the same trend of results can be observed when we increase the number of Wi-Fi radios in MR nodes.

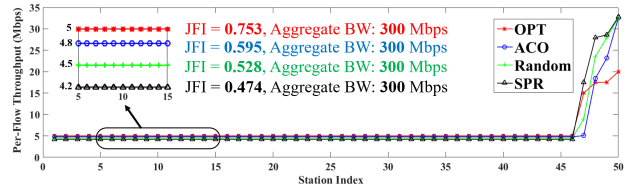

Figure 10: Comparative results in terms of flow routing.

E. Comparative Analysis of Flow Routing

Finally, we conducted the last experiment for a comparative analysis in terms of flow routing performance between our scheme (OPT) and three existing routing schemes, including Shortest Path Routing (SPR), Randomized routing (Random) and ACO-based flow routing [14]. The calculated throughput for a set of given flows with pre-calculated source and destination nodes (MRs) are shown in Fig. 10. The experiment is carried out on the grid topology with 50 stations and predetermined $b_{\min} = 5$ Mbps. As illustrated, only our introduced scheme (OPT) is able to guarantee the defined $b_{\min}$ for all the flows through its centralized SDN-aware routing solution. On the other hand, SPR and Randomized routing schemes could achieve at most 4.2 Mbps and 4.5 Mbps as their guaranteed bandwidth, respectively. Although this value is 4.8 Mbps for ACO-based routing, still it is not able to guarantee the predetermined $b_{\min}$ for all the flows at all times. This performance difference is due to having a holistic view of the network topology and flow demands by our presented solution (provided by SDN) that are utilized to find the optimal result. In addition, our scheme can achieve better outcome in term of fairness index (JFI) as shown in Fig. 10. Note that we present the average outcomes for ACO and Random schemes over 1000 runs.

For all the explained scenarios, our developed framework (using Python/Gurobi) is able to find the optimal results within a reasonable time interval (less than 10 seconds for 100 stations in 5x5 grid). However, as stated in the last paragraph of Section III-D, for large-scale cases, we can reduce this duration using approximation algorithms.

VI. Conclusion

Applying SDN to agile communication platforms such as WMN brings unprecedented opportunity to present cost-effective and efficient schemes for guaranteed service provisioning. In this paper, we proposed a fine-grained joint solution for optimal traffic engineering of network flows over WMNs. In contrast with most of the prior work, our solution considered most of the key restrictive factors in the different tiers of WMN in order to present practical and realistic outcomes. To do this, we presented a joint optimization formula for SDN-aware WMNs that solves gateway selection and flow routing problems jointly. The presented scheme maximizes the total network throughput while satisfying the QoS constraints and reducing the number of required active cellular gateways. The performance of our solution is evaluated for different scenarios with extensive numerical results. Moreover, we compared the performance of our scheme with some of the popular centralized routing solutions in terms of flow routing. For the future work, we intend to find a good approximation of the proposed formulation for enterprise scenarios. In addition, we are planning to evaluate the performance of our solution through an SDN-aware MC-MR WMN testbed setup which is the extension of the presented testbed in [10].

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