Gateway Selection Scheme for Throughput Optimization in Multi-radio Multi-channel Wireless Mesh Networks Under Physical Interference Model (Invited Paper)

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***Abstract*—In this paper, we investigate the gateway selection problem for throughput optimization in multi-radio multi-channel wireless mesh networks. In contrast to the various methodologies in the literature, we not only explicitly model the delay overhead that is incurred during channel switching, and consider this delay-related issue in the design of our mechanism but also employ the most reliable interference model in our approach, e.g., physical interference model. From our best knowledge, it is the first time to take account switching overhead into the scenario of gateway selection in multi-radio multi-channel wireless networks under physical interference model. Given the number of gateways to be deployed in the network system and the interference model adopted for the communication, we study how to select a proper subset of mesh nodes to be equipped with gateway functionality in the network such that the total network throughput is maximized meanwhile a certain fairness among all mesh nodes can be also guaranteed. In this paper, we formulate the scenario mentioned above as a NP-hard optimization problem. Due to extremely high computational burden to generate an optimal solution, we propose a new gateway selection scheme (e.g., a new approximation algorithm) using a cross-layer throughput optimization. Combining with a new interference-aware link-channel scheduling algorithm we proposed in this work, we show that the performance on the achieved network throughput by our gateway selection scheme is only a logarithmical factor far to the optimum in terms of the size of network.**

***Index Terms*—Gateway selection, throughput optimization, interference-free link-channel scheduling, approximation algorithms, multi-radio multi-channel wireless mesh networks, physical interference model.**

I. Introduction

Wireless Mesh Networks (WMNs) [4] have drawn lots of intensive attention in recent years due to its various potential applications such as broadband home networking, community and neighborhood networks, and enterprise networking. The WMNs have been envisioned as an emerging communication paradigm to enable resilient, cost-efficient and reliable services for the future-generation wireless networks, and can significantly improve the network throughput with multi-radio multi-channel architecture. Moreover, it has also been used as the last mile solution for extending the Internet connectivity for the mobile users [23]. Many cities and wireless companies have already deployed mesh networks around world. For instant, in Cambridge on the 3rd June 2006, WMNs were used at the "Strawberry Fair" to run mobile live television, radio and internet services to roughly $80,000$ people. More examples can be found in [23]. One of most important features of WMNs is that the communication channels can be shared by different wireless terminals, which leads to the reduction of network capacity due to interference caused by simultaneous transmissions. The interference can be alleviated but not be eliminated by employing multiple channels and multiple radios in WMNs. Consequently, these related issues bring an very interesting and challenging cross-layer throughput optimization problem in terms of joint channel assignment and link scheduling in WMNs.

In the WMNs, the system consists of mesh routers and mesh clients. Each mesh routers operates not only as a host but also as a router, forwarding packets on behalf of other mesh routers that may not be within direct wireless transmission range of their destinations. A WMN is dynamically self-organized and self-configured, with mesh nodes in the network automatically establishing and maintaining mesh connectivity among themselves. This feature brings many advantages to WMNs such as low up-front cost, easy network maintenance, robustness, and reliable service coverage [4]. The common network infrastructure of WMNs is illustrated in Figure 1. The mesh routers with gateway functionality connect to the Internet by wires and act as the Internet gateways for the WMN. Meanwhile, other original mesh routers without gateway functionality take the responsibility of relaying traffic between the gateways and the wireless mesh clients in a multi-hop fashion.

In this paper, we are interested in how to select the fixed number of mesh routers to be equipped with gateway functionality in the WMN under considerations of physical interference model and switching overhead such that the total network

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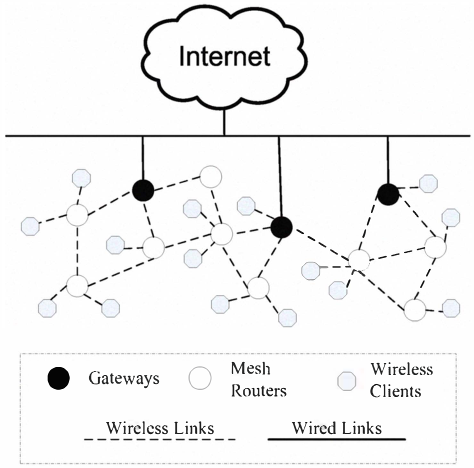

Fig. 1. The network infrastructure of wireless mesh network.

throughput is maximized meanwhile it also ensures a certain fairness among all mesh routers. To the best of our knowledge, it is the first time to investigate such a scenario under physical interference model in the WMN.

A. Related Work

Optimal placement of gateways in a wireless network is a very challenging problem which has been proven to be NP-hard for most formulations and scenarios of network deployment [10], [8], [26]. Chandra et al. [9] presented a series of gateway placement algorithms that focused on the impact of link capacity constraints, wireless interference, fault tolerance, and various traffic demands. Gupta and Kumar [12] studied the asymptotic capacity of multi-hop wireless networks. Investigation of the capacity of wireless networks under different models can be found in [22], [13]. Kyasanur and Vaidya [21] studied the capacity region on random multi-hop multi-radio multi-channel wireless networks. Kodialam and Nandagopal [18] investigated the problem of jointly routing the flows and scheduling transmissions to achieve a given rate based on the protocol interference model in single channel wireless networks. In [19], Kodialam and Nandagopal extended their previous work to the scenario with consideration of multiple radios and multiple channels. Alicherry et al. [1], presented a linear programming based method for joint schemes of multi-path routing, link scheduling, and static channel assignment for throughput optimization in multi-radio multi-channel WMNs. All these work either focused on the capacity of multi-hop WMNs without gateways or assumed the static situation such that the positions of the mesh routers and gateways are fixed and given in advance. Very recently, Li et al. [23] studied the unfixed scenario for the gateway placement, e.g., where to place the gateways in the mesh backbone in order to achieve optimal throughput, and they also proposed a novel grid-based gateway deployment method using a cross-layer throughput optimization.

Many algorithms that tried to optimize the efficiency of multi-radio multi-channel WMNs using the strategies that requires frequent change of channels, which obviously leads to a large of accumulation of switching delays between end to end mesh nodes. Moreover, the impact of switching delays on the overall network performance becomes even more significant when switching occurs across different frequency bands [21]. For example, when a mesh router has two radio interfaces such as $802.11a$ card (operates on 5 GHz band) and $802.11b/g$ card (operating on 2.2 GHz band), switching between two bands is possible with the delay much larger than the delay from the switching within the same band. As a result, the switching overheads not only affect the end to end delays but also degrade network capacity. According to the work in [21], the switching delay degrades the network capacity as a function of $\frac{S}{S+T}$, where S is switch delay and T is transmission time. From the function above, the value of S can approach the value of T. Consequently, it can cause a significant degradation in network capacity. This highlights the need to investigate the delays induced due to the switching overhead in the development of gateway placement schemes for throughput optimization in multi-radio multi-channel WMNs which had been also addressed in [36].

Research on the gateway placement problem has also been conducted in wireless sensor networks (WSNs) [7], [5], [29], [9], [30], [2], [17], [3], [15], [39]. Typically, it can be defined as the optimal layout for a known number of gateways in order to maximize some performance metrics, such as total communication throughput [7] and area coverage [5]. In some applications [29], the number of gateways may not be known in advance and thus the optimal number and location of the gateways need to be configured. Chandra et al. [9] formulated the scenario of gateway placement as a network flow problem and a max-flow min-cut based algorithm was developed for the selection of the gateways. In [30] by Prasad and Wu, the gateways are chosen from a given potential set of the gateways, in which a recursive OPEN/CLOSE heuristic starts from a feasible solution and repeatedly decreases the cost in order to find proper gateways for the corresponding applications. Recently, Aoun et al. [2] proposed a QoS-based gateway selection approach for wireless mesh networks and developed a recursive algorithm with the purpose of minimizing the number of gateways and also guaranteeing the QoS requirements. Genetic algorithms have been employed for optimizing the design and operation in WSNs [17], [3], [15], [39]. In [17], Kanna et al. took into account the minimization of power consumption while maximizing sensor exposure and coverage. The problem considered in [3] is to maximize the throughput and coverage, whereas [15], Jin et al. focused on minimizing the interference in the WSNs. Recently, Youssef and Younis [39] presented a solution for minimizing the data latency through optimal placement of gateways.

Deployment schemes of gateways have been studied in WLANs and cellular infrastructure as well. However, most of this work focused on guaranteeing signal coverage or minimizing the number of gateways to provide better coverage. In [20], Kouhbor et al. attempt to find the optimal number of gateways and their locations for WLAN environment that includes obstacles. Pabst et al. [27] showed that the deployment of fixed relay nodes can enhance the capacity of hybrid cellular networks. Fong et al. [11] investigated some fixed broadband wireless access deployment schemes to increase the network capacity.

The most related work to ours is the one [36] in which a time-efficient approximation algorithm with constant approximation ratio guarantee in terms of the network throughput had been proposed for gateway selection problem that also took into account the switching overhead which incurred due to switch radios dynamically between different channels during the transmission schedule. However, the work in [36] employed an unrealistic graph-based interference model that can not capture the interference between links more accurately compared to the physical interference model [19] we adopted in this work.

B. Our Contributions

In this paper, we investigate the problem of gateway selection for throughput optimization in multi-radio multi-channel wireless mesh networks. In contrast to the various methodologies in the literature, we not only explicitly model the delay overhead that is incurred during channel switching, and consider this delay-related issue in the design of our mechanism but also employ the most reliable interference model in our approach, e.g., physical interference model. From our best knowledge, it is the first time to take account switching overhead into the scenario of gateway selection in multi-radio multi-channel wireless networks under physical interference model. In this paper, we formulate such a gateway selection scenario as a NP-hard optimization problem. Due to extremely high computational burden to generate an optimal solution, we also propose a new time-efficient gateway selection method (e.g., a new approximation algorithm with polynomially computational time in terms of the size of the network) using a cross-layer throughput optimization. Combining with a new interference-aware link-channel scheduling algorithm proposed also in this work, we can show that our gateway selection scheme can effectively exploit the available resources, and prove that the performance of our scheme on the achieved network throughput is only a logarithmical factor far to the optimum in terms of the size of network. Simulation results demonstrate that the proposed scheme in this work can effectively exploit the available resources and achieve much better network throughput than existing random, fixed deployment and grid-based methods in the literature.

The rest of the paper is organized as follows. In Section II, the general model of WMNs and communication principles are described. The gateway placement problem for throughput optimization under considerations of the switching overhead and physical interference model is defined and mathematically formulated in Section III. In Section IV, a new interference-aware link-channel scheduling under considerations of switching overhead and physical interference model in multi-radio multi-channel WMNs is proposed, which is the core component of our approach in order to guarantee the performance in terms of the network throughput and will be used as a post-procedure of the gateway selection scheme we will introduced in later section. In Section V, we present a new gateway selection scheme for throughput optimization. Simulation results are shown in Section VI, before Section VII concludes this paper.

TABLE I
NOTATIONS

Term	Definition
WMN	Wireless mesh network
n	Size of WMN
V	Set of mesh nodes
E	Set of directed communication links
G	Directed communication graph $G = (V, E)$
$E^+(v)$	Set of directed link that start at mesh node v
$E^-(v)$	Set of directed link that end at mesh node v
k	Number of gateways
Φ	Set of k gateway nodes $\Phi = \{\phi_1, \phi_2, \cdots, \phi_k\}$
$R_T(i)$	Transmission range of mesh node v_i
$R_I(i)$	Interference range of mesh node v_i
$T(v_i)$	The subset of mesh nodes within the transmission range of v_i
$I(v_i)$	The subset of mesh nodes within the interference range of v_i
γ_i	Interference-transmission ratio $\gamma_i = \frac{R_I(i)}{R_T(i)}$ for v_i
γ	$\gamma = max_{v_i \in V} \frac{R_I(i)}{R_T(i)}$
P_i^f	The transmission power at mesh node i on channel f
h_{ij}^f	The power attenuation from i to j on channel f
$\tau_{i,j}^f$	The interference power received by j from i on channel f
B	The channel bandwidth
$l(v)$	Traffic demand of mesh node v from its wireless clients
T	Time duration for period scheduling
$\mathfrak{f}$	Channel set of the WMN
$c(e, f)$	Maximum data transmit rate of link e on channel f
$I(e, f)$	Set of links that interfere with link e on channel f
$\alpha(e, f)$	Traffic delivery requirement for link e on channel f
$f(e)$	Total scheduled traffic on link e
$X_{e,f,t}$	Binary variable
	indicates whether e transmits on channel f at time $t \in [1, T]$
ζ	Switching overhead
$T_j^I(f)$	The interference power accumulated at j on channel f
$\lambda_{i,j}^f(t)$	Data transmission rate for $e = (i, j)$ on f at time slot t
G_i^f	The antenna gain of i on channel f
d_{ij}	The distances from i to j
α	The path fading factor
$\delta(e, f)$	Binary variable
Γ_j^f	The pre-defined interference threshold at j on channel f
	indicates whether channel f can be used by a link e
$\Re(u)$	Number of radio interfaces equipped at u
λ_0	Minimum fairness

II. The WMN Model and Communication Principles

In this section, we first introduce the model of multi-radio multi-channel WMNs which followed by the interference model we adopted in this work. Some relevant terminologies, e.g., SINR and data transmission rate are described as well. For easy reading, we summarize all used notations of the system in this paper in Table 1.

A. The Network Model

A WMN can be modeled as a directed graph $G = (V, E)$, where $V = \{v_1, v_2, \cdots, v_n\}$ is the set of n mesh nodes which includes the ordinary mesh routers and the ones to be equipped with gateway functionality in the WMN, and E is the set of possible directed communication links. Note that we only focus on the mesh backbone in this paper that is the same consideration as those work in [23], [36]. Let $E^-(v)(E^+(v))$ denote the set of directed links that end (start) at node v. Moreover, $R_T(i)$ and $R_I(i)$ present the transmission range and the interference range of the mesh node i respectively. Typically, $R_T(i) < R_I(i) \leq cR_T(i)$ for some constant $c > 1$. Normally, We call the ratio $\gamma_i = \frac{R_I(i)}{R_T(i)}$ as Interference-Transmission ratio for mesh node v_i, where $2 \leq \gamma_i \leq 5$ in practical. For all mesh nodes, let $\gamma = max_{v_i \in V} \frac{R_I(i)}{R_T(i)}$. Furthermore, let $T(v_i)$ and $I(v_i)$ denote the subsets of mesh nodes which contain the mesh nodes within the transmission range and the interference range of mesh node v_i respectively. Every mesh routers v_i has a transmission range $R_T(i) : ||v_i - v_j|| \leq R_T(i)$ which is not the sufficient condition for $(v_i, v_j) \in E$ due to the physical barriers or the selection of routing protocols. For each link $e = (u, v)$, the maximum data transmission rate at which a mesh router u can communicate with another mesh router v in one-hop communication fashion by link e on channel f is denoted by $c(e, f)$.

Among the set V for all mesh nodes, only limited number of mesh nodes at most k can be equipped with the gateway functionality and provide the connectivity to the Internet as gateways for the WMN. To simplify our presentation, let $\Phi = \{\phi_1, \phi_2, \cdots, \phi_k\}$ be the set of k gateways. All other mesh nodes $v \in V - \Phi$ are ordinary mesh routers. Each ordinary mesh router v will aggregate the traffic from all its wireless mesh clients and then route them to the Internet through some gateways. We assume that the capacity between any gateway to the Internet is sufficient large. We denote the total aggregated outgoing (incoming) traffic load from mesh node u by $l_O(u)(l_I(u))$. In this paper, we will focus on outgoing traffic pattern. Note that it is easy to extend our work to the scenario under consideration of both incoming and outgoing traffic patterns by defining routing flows for both traffic patterns separately. To simplify our presentation, we use $l(u)$ to denote such traffic load for mesh node u. Note also that the traffic load $l(u)$ is not requested to be routed through a specific gateway, neither requested to be using a single path routing protocol since we are interested and investigating what is the best achievable throughput in the given multi-radio multi-channel WMN by using best possible routing and link-channel scheduling protocols under considerations of switching overhead and physical interference model. From our best knowledge, it is the first time to investigate such a scenario in the literature.

B. Interference Model

Different types of interference models have been studied in the literature, which include protocol interference model [12], fixed protocol interference model [33], RTS/CTS model [1], and physical interference model [19], [37], [38]. In this paper, we adopt the physical interference model. When the mesh nodes $v_i \in I(v_j)$ transmit, v_j will receive interference power from all transmitting mesh nodes in $I(v_j)$. Let $\tau_{i,j}^f$ denote the interference power received by mesh node j due to the transmission from mesh node $i \in I(v_j)$ on channel f. According to the definition of the physical interference model [19], [34], [37], $\tau_{i,j}^f$ can be expressed as follows.

$$\tau_{ij}^f = h_{ij}^f P_i^f, \forall i \in I(v_j) \wedge f \in \mathfrak{f}, \quad (1)$$

where P_i^f and h_{ij}^f denote the transmission power at mesh node i and the power attenuation from i to j on channel f respectively. Note that we take into account the fixed power scheme in this work however it is not difficult to adopt the adaptive power control scheme to further improve the network throughput by employing the strategies of the power control in [34]. Due to the space constraint, we defer these issues to the extended version of this work. According to the description of physical interference model, h_{ij}^f can be calculated as follows.

$$h_{ij}^f = \frac{G_i^f G_j^f}{(d_{ij})^\alpha}, \forall i \in I(j) \wedge f \in \mathfrak{f}, \quad (2)$$

where G_i^f, G_j^f, d_{ij}, and α denote the antenna gains of i and j on channel f, the distances from i to j, and the path fading factor respectively.

Consequently, the interference power $T_j^I(f)$ accumulated at j due to the simultaneous transmissions from all active mesh nodes on channel f within the interference range of v_j at the time slot t can be formulated as follows.

$$\begin{aligned} T_j^I(f,t) &= \sum_{i=1}^{|I(j)|} \tau_{ij}^f X_{(i,j),f,t} \\ &= \sum_{i=1}^{|I(j)|} \frac{G_i^f G_j^f P_i^f X_{(i,j),f,t}}{(d_{ij})^\alpha} \leq \Gamma_j^f, \forall j \in V \wedge f \in \mathfrak{f}, \end{aligned} \quad (3)$$

where $X_{e=(i,j),f,t}$ is a binary variable and the situation when $X_{e,f,t} = 1$ indicates mesh node i is scheduled to transmit to the intended receiver j in the given time step t on channel f, otherwise i stays in listening mode on the channel f. Due to the coexistence regulation of different transmitting mesh nodes under physical interference model, $T_j^I(f,t)$ can not exceed the predefined system threshold Γ_j^f at any intended receiver j on channel f.

To make the gateway selection problem feasible, interesting and challenging, we always assume that $\tau_{ij}^f \leq \Gamma_j^f$ (e.g., single transmission) for all $i, j \in V \wedge f \in \mathfrak{f}$.

To schedule multiple links at the same time slot, we have to ensure that the accumulated interference power at corresponding receivers of each link due to the simultaneous transmissions will not exceed the pre-defined interference threshold, e.g., constraint Equation 3.

C. SINR and Data Transmission Rate

According to the description of physical interference model, signal-to-interference-plus-noise ratio (SINR) of link $e = (i, j)$ on channel f at time slot t can be expressed as follows.

$$\xi_{i,j}^f(t) = \frac{h_{ij}^f P_i^f X_{e,f,t}}{N_0 + I_j^f - h_{ij}^f P_i^f X_{e,f,t}}, \forall i \in I(v_j) \wedge f \in \mathfrak{f} \quad (4)$$

where h_{ij}^f and P_i^f denote the power attenuation from mesh node v_i to mesh node v_j and the transmission power of v_i on channel f respectively. Moreover, N_0 presents the background noise received at v_j, I_j^f denotes the interference powers received from all transmitting mesh nodes within the interference range of v_j on channel f at time slot t. According to the definition of SINR, I_j^f can be defined as follows.

$$I_j^f = \sum_{i=1}^{|I(v_j)|} h_{ij}^f P_i^f X_{e=(i,j),f,t}. \tag{5}$$

According to Shannon' channel capacity formulation, the data transmission rate (DTR) $\lambda_{i,j}^f(t)$ for link $e = (i,j)$ on channel f at time slot t can be estimated by

$$\lambda_{i,j}^f(t) = B \log_2(1 + \xi_{i,j}^f(t)) \tag{6}$$

where B is the channel bandwidth and $\xi_{i,j}^f(t)$ is the corresponding SINR.

III. Problem Formulation

In this section, we formulate the problem how to select at most k mesh nodes to be equipped with gateway functionality in the given multi-radio multi-channel WMN to make the best achievable throughput by using best possible routing and link-channel scheduling protocols under consideration of physical interference model meanwhile we also take into account the switching overhead between different channels varied on the time domain. In this work, we assume that the routing between a given mesh router and some gateways can use multiple paths. The essential assumption we used in this paper is that the aggregated traffic loads between the mesh routers and the gateways can be infinitely divisible. Moreover, we also assume that the time is slotted and synchronized. However, these assumptions are acceptable in the scenario we investigated in multi-radio multi-channel WMNs here according to the arguments mentioned in [23], [36]. Note also that the exactly same assumptions had been made in [23], [36] as well. However, the schemes proposed in [23], [36] are mainly designed for the scenario under the protocol interference model and that can not be implied to the scenario we investigated here under consideration of physical interference model.

Every mesh router u has a traffic demand $l(u)$ that needs to be routed to the Internet via some gateways ϕ. We want to select a proper subset of mesh nodes to be equipped with the gateway functionality in order to maximize the total routed traffic to the Internet under physical interference model meanwhile the minimum traffic demand of each mesh router from itself and its wireless mesh clients should be also guaranteed. The approach we developed here is to give each link e on channel f an interference-aware transmission schedule which assigns the time slots for transmission on the corresponding links in order to maximize the overall network throughput meanwhile we take account into the switching overhead between different channels during the schedule. A interference-aware link-channel scheduling is to assign each link e with channel f a set of time slots $\subset [1,T]$ in which it can transmit at the allocated time slots and the accumulated interference power (e.g., simultaneous transmissions) at any intended receiver at any time slot during the schedule will not exceed the pre-defined system threshold (e.g., Equation 3), where T is the scheduling period. We assume that each mesh node is equipped with at least one radio interface and can dynamically switch radios from one channel to another channel with additional overhead ζ which represents as a fraction of the duration of one single time slot, where $0 \leq \zeta < 1$. Let $X_{(i,j),f,t} \in \{0,1\}$ be a binary variable which indicates whether the link $e = (i,j)$ on channel f is scheduled to transmit at time slot t. $X_{e,f,t} = 1$ means that the link e is allowed to transmit on channel f at time slot t in the schedule, otherwise $X_{e,f,t} = 0$. Moreover, if $X_{e,f,t} = 1$ and the link e does not turn on the channel f in the previous time slot $t-1$, then it has to take ζ time to switch the channel to f during the current time slot t. We focus on periodic schedule here, which means that $X_{e,f,t} = X_{e,f,t+i\cdot T}$ for every link e, channel f, and time slot t within every schedule period T, where $i \geq 0$ is any integer (e.g., same assumption is also used in [23], [36]).

We can now formulate the gateway selection problem for throughput optimization in multi-radio multi-channel WMNs under considerations of physical interference model and switching overhead as a nonlinear NP-hard optimization problem that can be formulated as follows.

$$Max \sum_{i=1}^{k} f(\phi_i); \tag{7}$$

subject to:

$$\sum_{v_i \in V} \pi_i \leq k; \tag{8}$$

$$f(\phi_i) = \sum_{e \in E^-(\phi_i)} f(e) - \sum_{e \in E^+(\phi_i)} f(e), \forall \phi_i \in \Phi; \tag{9}$$

$$f(u) = \sum_{e \in E^+(u)} f(e) - \sum_{e \in E^-(u)} f(e), \forall u \in V - \Phi; \tag{10}$$

$$f(u) \geq \lambda_0 l(u), \forall u \in V; \tag{11}$$

$$f(e) = \sum_{f \in \mathfrak{f}} \alpha(e,f) \cdot c(e,f), \forall e \in E; \tag{12}$$

$$\sum_{i=1}^{|I(j)|} \frac{G_i^f G_j^f P_i^f X_{(i,j),f,t}}{(d_{ij})^\alpha} \leq \Gamma_j^f,$$
$$\forall j \in V, \forall i \in I(j), \forall f \in \mathfrak{f}, \forall t \in [1,T]; \tag{13}$$

$$\alpha(e,f) = \frac{1}{T} \sum_{1 \leq t \leq T} X_{e,f,t} X_{e,f,t-1} \frac{\lambda_{i,j}^f(t)}{c(e,f)} + \frac{1}{T} \sum_{1 \leq t \leq T} (1-\zeta) X_{e,f,t} X_{e,f',t-1} \frac{\lambda_{i,j}^f(t)}{c(e,f)},$$
$$\forall e \in E, \forall f, f' \in \mathfrak{f} \wedge f \neq f'; \tag{14}$$

$$\lambda_{i,j}^f(t) = B \log_2(1 + \xi_{i,j}^f(t)),$$
$$\forall (i,j) \in E, \forall f \in \mathfrak{f}, \forall t \in [1,T]; \tag{15}$$

$$\xi_{i,j}^f(t) = \frac{h_{ij}^f P_i^f X_{e,f,t}}{N_0 + I_j^f - h_{ij}^f P_i^f X_{e,f,t}},$$

$$\forall i \in I(v_j), \forall f \in \mathfrak{f}, \forall t \in [1, T]; \quad (16)$$

$$\alpha(e, f) \le \delta(e, f), \forall e \in E, \forall f \in \mathfrak{f}; \quad (17)$$

$$\sum_{f \in \mathfrak{f}} \alpha(e, f) \le \Re(u), \forall e \in E, \forall u \in V - \Phi; \quad (18)$$

$$\alpha(e, f) \ge 0, \forall e \in E, \forall f \in \mathfrak{f}; \quad (19)$$

$$\alpha(e, f) \le 1, \forall e \in E, \forall f \in \mathfrak{f}; \quad (20)$$

$$\delta(e, f) \in \{0, 1\}, \forall e \in E, \forall f \in \mathfrak{f}; \quad (21)$$

$$X_{e,f,t} \in \{0, 1\}, \forall e \in E, \forall f \in \mathfrak{f}, \forall t \in [1, T]; \quad (22)$$

$$\phi_i \in \{1, 2, \cdots, n\}, \forall \phi_i \in \Phi \subset V; \quad (23)$$

$$\pi_i \in \{0, 1\}, \forall v_i \in V. \quad (24)$$

The objective (Equation 7) of our gateway placement scheme is to maximize the maximum throughput for the given multi-radio multi-channel WMN. The first constraint (Equation 8) bounds the number of gateways at most k. The second constraint (Equation 9) describes the traffic loads achieved at the gateways, which is the difference between the traffic flow comes to gateway ϕ_i and the flow goes out of ϕ_i, where $f(e)$ is the total scheduled traffic over link e. Similarly, the third constraint (Equation 10) calculates the traffic loads achieved by a mesh router u without gateway functionality. The fourth constraint (Equation 11) refers to the fairness constraint on each mesh router, where λ_0 denotes the minimum fairness constraint in terms of data delivery ratio. Each link $e = (u, v)$ can only operate a subset of the channel set $\mathfrak{f}$ in the WMN. Let $\alpha(e, f) \in [0, 1]$ denote (or be considered roughly equivalent to) the fraction of the time slots in one scheduling-period that link e is actively transmitting using maximum data transmission rate (e.g., capacity of link $c(e, f)$) on channel f. The specific definition of $\alpha(e, f)$ will be given by Equaiton 14. Obviously, $\alpha(e, f) \cdot c(e, f)$ is the corresponding achieved flow at link e on channel f. Consequently, the fifth constraint (Equation 12) exactly presents the total scheduled traffic loads over link e. Note that the purpose to define and employ the notation $\alpha(e, f)$ is to quantitatively analysis the performance of our scheme. The sixth constraint (Equation 13) says that a schedule should guarantee that the the accumulated interference power at any intended receiver j on channel f due to the simultaneous transmissions from the scheduled links within the interference range of j will not exceed the pre-defined interference threshold Γ_j^f. The seventh constraint (Equation 14) specifies the calculation of $\alpha(e, f)$ at each link e on channel f through one scheduling-period T under considerations of switching overhead ζ between the different channels during the schedule and physical interference model. Note that $\alpha(e, f)$ also indicates the achieved traffic flow at corresponding links by the schedule. The eighth constraint (Equation 15) mentions the relation between the data transmission rate and SINR. Moreover, the ninth constraint shows how to explicitly calculate the SINR. The tenth constraint (Equation 17) says the availability of a channel f over link e in the schedule, where $\delta(e, f) \in \{0, 1\}$ is a binary variable which indicates whether a channel f can be used by a link e in the WMN since each mesh node only allows to access a subset of the channel set $\mathfrak{f}$ in the system. The eleventh constraint (Equation 18) says the feasibility of the channel usage in which the number of channels can be used simultaneously should be less than the total available radio interfaces equipped at mesh node u in the system. The next two inequalities (Equations 19 and 20) give the lower and upper bounds for the feasible flow which can be achieved. The last four constraints (Equations 21, 22, 23 and 24) define the values of four variables $\delta(e, f)$, $X_{e,f,t}$, ϕ_i, and π_i.

IV. Interference-aware link-channel scheduling in Multi-radio Multi-channel WMNs

Interference-aware link-channel scheduling for wireless networks has been studied in [33], [23]. However, none of these work had taken account of the issues of channel switching overhead in the link-channel scheduling algorithms. Note also that the existing methodologies in these work can not be directly implied to the scenario under consideration of delay overhead due to switching radios from one channel to another. Moreover, the existing methodologies cannot guarantee the performance in terms of network throughput when the switching overhead is taken account into, specially for the condition when the switching overhead fraction ζ is approaching to 1. Very recently, the switching overhead had been taken account into the throughput optimization in WMNs [36]. However, the approach proposed in [36] mainly designed for the scenario under consideration of protocol interference model and that can not be implied to our scenario based on physical interference model. In this section, we propose a new interference-aware link-channel scheduling scheme which not only explicitly considers the switching overhead in multi-radio multi-channel WMNs but also employs the most reliable interference model, e.g., physical interference model. The details are illustrated in Algorithm 1. This approach will be used as a post procedure of our gateway selection scheme described in Section V and takes a crucial role to achieve a logarithmical fraction of the optimum in terms of the network throughput. For the instant, we assume that we know exact mesh nodes with gateway functionality that will serve as the Internet gateways.

A. Subset Oblivious Algorithm

To simplify our presentation and the analysis of our interference-aware link-channel scheduling algorithm later, we briefly introduce the frame work for the set covering problems which called ρ-approximation subset oblivious algorithm in [6]. A various version of [6] will be used as a sub-procedure in the design of our new interference-aware link-channel scheduling approach that will be described in Section IV-B.

Given a set I of d-dimensional items, the i-th corresponding to a d-tuple $(t_i^1, t_i^2, \cdots, t_i^d)$, that must be packed into the smallest number of unit-size bins, corresponding to the d-tuple $(1, \cdots, 1)$. Given an instant I, let $opt(I)$ denote the value of the optimal solution for I. This problem can be formulated as the following general set covering problem, in which a set I of items has to be covered by configurations from the collection $\mathcal{C} \subseteq 2^I$, where each configuration $C \in \mathcal{C}$ corresponds to a set of items that can be packed into a bin:

$$min\{\sum_{C\in\mathcal{C}} y_C : \sum_{i\in C} y_C \geq 1(i \in I), y_C \in \{0,1\}(C \in \mathcal{C})\} \tag{25}$$

Since the collection $\mathcal{C}$ is exponentially large for the given application item set I, an approximation algorithm (or LP relaxation of 25) can be very useful for such an application.

The dual of this LP (Equation 25) is given by

$$max\{\sum_{i\in I} w_i : \sum_{i\in C} w_i \leq 1(C \in \mathcal{C}), w_i \geq 0(i \in I)\} \tag{26}$$

Note that the separation problem for the dual is the following knapsack-type problem: given weights w_i on each item i, find a feasible configuration in which the total weight of items does not exceed 1. In the literature, it has been show that:

Theorem 1: If there exists a Polynomial-Time Approximation Scheme (PTAS) for the separation problem for 26, that is given $w_i \in \mathbb{R}_+^{|I|}$ solve $max_{C\in\mathcal{C}} \sum_{i\in C} w_i$, then there exists a PTAS for the LP relaxation of 25.

Based on Theorem 1, an approximation solution of the set covering problem 25 has been constructed in [6], which consists the following steps, where $\delta > 0$ is a parameter whose value can be specified later.

Step 1: Solve the LP relaxation of 25, possibly approximately in case $\mathcal{C}$ is exponentially large in the input size. Let y^* be the (near-)optimal solution of the LP relaxation and $z^* = \sum_{C\in\mathcal{C}} y_C^*$ be its value. Let $C_1, C_2, \cdots, C_m \in \mathcal{C}$ be the configurations associated with the nonzero components of y^*;

Step 2: Define the binary vector y^r starting with $y_C^* = 0$ for $C \in \mathcal{C}$ and $S = I$ (i.e., all items are uncovered) and then repeating the following for $\lceil \delta z^*/(1-\sigma\psi/2)\rceil$ iterations: select the configuration $C' \in \{C_1, C_2, \cdots, C_m\}$ such that $\Phi(S-C')$ is minimum and let $y_{C'}^r = 1$ and $S = S - C'$, where σ is a small parameter such that $\sigma\psi < 1$ to be specified later. For an arbitrary set of items S, $\Phi(S) = \ln(\sum_{j=1}^d e^{\sigma \sum_{i\in S} w_i^j})$;

Step 3: Consider the set of items $S \subseteq I$ that are not covered by y_r, namely $i \in S$ if and only if $\sum_{i\in C} y_C^r = 0$, and the associated optimization problem for the residual instance

$$min\{\sum_{C\in\mathcal{C}} y_C : \sum_{i\in C} y_C \geq 1(i \in S), y_C \in \{0,1\}(C \in \mathcal{C})\}. \tag{27}$$

Apply some approximation algorithm to the problem 27 yielding solution y^a;

Step 4: Return the solution $y^h = y^r + y^a$.

For the abbreviation, we denote this approach by $\text{SETCOVER}(I, w)$, where w is the weight vector for $\forall i \in I$.

A crucial notation used in [6] is called the ρ-approximation subset oblivious algorithm which defined as follows.

Definition 2: A ρ-approximation algorithm for problem 25 is called subset oblivious if, for any fixed $\varepsilon > 0$, there exist constraints d, ψ, ϖ (possibly depending on ε) such that, for every instance I of 25, there exists vectors $w^1, w^2, \cdots, w^d \in \mathbb{R}^{|I|}$ with the following properties: (i) $\sum_{i\in C} w_i^d \leq \psi$, for each $C \in \mathcal{C}$ and $j = 1, 2, \cdots, d$; (ii) $opt(I) \geq max_{j=1}^d \sum_{i\in I} w_i^j$; (iii) $appr(S) \leq \rho max_{j=1}^d \sum_{i\in S} w_i^j + \varepsilon opt(I) + \varpi$, for each $S \subseteq I$.

The main theorems in [6] we need for the analysis of our new interference-aware link-channel algorithm are as follows.

Theorem 3: d-dimensional bin packing is a d approximation subset oblivious algorithm.

Theorem 4: The cost of the final heuristic solution for d-dimensional bin packing produced by procedure $\text{SETCOVER}(I, w)$ with $\delta = \ln d, \sigma = (2\varepsilon/\ln d)/(\psi + \psi\varepsilon/\ln d)$ and $\psi = 1$ is at most

$$(\ln d + 1 + 2\varepsilon)opt(I) + \delta + \frac{(2\ln d)(1 + \varepsilon/\ln d)}{(2\varepsilon/\ln d)} + 1, \tag{28}$$

i.e., this is a deterministic $O(\log d)$-approximation algorithm for d-dimensional bin packing (e.g., problem 25).

In what follows, we introduce some new observations from [34] (e.g., an extension from [6]) which will be employed as a sub-procedure in our new interference-aware link-channel scheduling scheme in order to guarantee the proper approximation ratio in terms of achievable network throughput.

Theorem 5: ι d-dimensional (multiple multi-dimensional) bin packing is a $O(\iota \cdot d)$-approximation subset oblivious algorithm.

Theorem 6: The cost of the final heuristic solution for ι d-dimensional bin packing produced by procedure $\text{SETCOVER}(I, w)$ with $\delta = \ln d \cdot \iota, \sigma = (2\varepsilon/\ln d \cdot \iota)/(\psi + \psi\varepsilon/\ln d \cdot \iota)$ and $\psi = 1$ is at most

$$(\ln d \cdot \iota + 1 + 2\varepsilon)opt(I) + \delta + \frac{(2\ln d \cdot \iota)(1 + \varepsilon/\ln d)}{(2\varepsilon/\ln d \cdot \iota)} + 1, \tag{29}$$

i.e., this is a deterministic $O(\log d + \log \iota)$-approximation algorithm for ι d-dimensional bin packing (e.g., problem 25).

B. Interference-aware link-channel scheduling algorithm

The basic idea of our interference-aware link-channel scheduling algorithm is that we first sort the links based on some specific order and then process the requirement $\alpha(e, f)$ for each link e on channel f in a greedy manner under consideration of switching overhead based on the physical interference model. In order to minimize the interference due to the simultaneous transmissions from the selected subset of mesh nodes (e.g., a proper subset of the links) meanwhile the logarithmical fraction of maximum network throughput can be also guaranteed, we reduce such a interference-aware link-channel scheduling under the considerations we mentioned above to the multiple multi-dimensional bin packing problem in which the number of channels correspond the multiple bins, all intended receivers associating on the corresponding links correspond to a n-tuple unit-size bin $(1, \cdots, 1)$, and the each corresponding transmitter p associating on the selected links corresponds to a n-tuple item $(w_p^1(f), w_p^2(f), \cdots, w_p^n(f))$, where

$$w_p^q(f) = \frac{\tau_{pq}^f}{\Gamma_q^f} = \frac{G_p^f G_q^f P_p^f}{(d_{pq})^\alpha \Gamma_q^f}. \quad (30)$$

After execution of the heuristic algorithm for multiple multi-dimensional bin packing produced by extended version of procedure SETCOVER(V, w) in [34], we can guarantee that the total time slots used to schedule all selected transmissions under consideration of interference constraints can be bounded at most logarithmical factor far from the optimum in terms of the size of the WMN due to Theorem 6. From these constructed bins by the approach SETCOVER(V, w) in [34], we choose one of them $\mathfrak{B}$ with maximal throughput achievement that corresponds the one with

$$Max\Big(\sum_{(e=(i,j),f)\in\mathfrak{B}} (X_{e,f,t-1}\lambda_{i,j}^f + (1-\zeta)X_{e,f',t-1}\lambda_{i,j}^f)\Big),$$
$$\forall e \in E, \forall f, f' \in \mathfrak{f} \wedge f \neq f'. \quad (31)$$

Consequently, we can allocate $X_{e,f,t} = 1$ for all transmissions at current time slot t for the corresponding links e at channels f which have been "packed" in the bin $\mathfrak{B}$. We execute such selection and allocation scheme for several iterations until all traffic delivery requirements on each corresponding link and channel are satisfied. Moreover, we also ensure that the scheduling scheme satisfies the availability constraints on the radios and channels in the WMN.

Regarding to Algorithm 1, in what follows we show that the proposed link-channel scheduling scheme is interference-aware and the performance of the proposed approximation algorithm in terms of the achievable throughput is only poly-logarithmical factor far from the optimum.

Algorithm 1 Interference-aware link-channel scheduling

Input: Graph $G = (V, E)$ of m links, $\alpha(e, f)$, $c(e, f)$, T for all links and channels and switching overhead ζ.

Output: An interference-aware link-channel scheduling.

```
Sort the links of G in descending order according to Σ_{f∈𝔣} α(e,f)·c(e,f). Let (e_1, e_2, ···, e_m) denote the sorted list of links.
for each link e_i ∈ E do
    for each channel f ∈ 𝔣 do
        N(e_i, f) = T·α(e_i, f)·c(e, f) be the total throughput to be achieved at link e_i on channel f during the time T;
for j = 1 to T do
    for each link e_i ∈ E with Σ_{f∈𝔣} N(e_i, f) ≠ 0 do
        Select one unique f ∈ 𝔣 with Max(N(e_i, f));
    Assume e_i = (u, v). Set w_u^v(f) = G_u^f G_v^f P_u^f / ((d_uv)^α Γ_v^f) according to Equation 30;
    Execute SETCOVER(V, w) for multiple multi-dimensional bin packing [34];
    Select one bin 𝔅 with maximal throughput achievement according to Equation 31;
    for ∀(e = (u, v), f) ∈ 𝔅 do
        Set X_{e=(u,v),f,j} = 0;
    for ∀(e = (u, v), f) ∈ 𝔅 do
        if Σ_{f,e':e'=(u,x)∈E∧x∈V} X_{e',f,j} < ℜ(u) then
            if X_{e,f,j-1} = 1 then
                Set X_{e,f,j} = 1;
                Set N(e, f) = N(e, f) − λ_{u,v}^f;
            else
                Set X_{e,f,j} = 1;
                Set N(e, f) = N(e, f) − λ_{u,v}^f (1 − ζ);
```

Theorem 7: Algorithm 1 produces an interference-aware link-channel scheduling.

Proof: It directly follows due to the selection strategy from the extended version of procedure SETCOVER(V, w) in [34] we employed in this work, e.g., the simultaneous transmissions from the corresponding mesh nodes packed in the same bin will not lead to the situation that the accumulated interference power at any intended receiver exceeds the predefined system threshold since the interference threshold at the corresponding intended receiver is the upper bound of the size for the bins at corresponding dimension. ∎

Theorem 8: Algorithm 1 produces an interference-free link-channel scheduling whose achieved system throughput is at least logarithmical fraction of the optimum if $\alpha(e, f)$ is a feasible solution of the gateway selection problem we defined in Section III.

Proof: Assume that we have the value of $\alpha(e, f)$ from a solution of gateway selection problem we defined in Section III. It is not difficult to see that the Algorithm 1 can be computed in polynomial time in terms of size of the WMN. Due to the space limitation here, we defer the exact computational complexity in the full version of this paper. The crucial part we need to show is that the approximation ratio of Algorithm 1 in terms of achievable network throughput by our scheme compared to the optimum. According to Algorithm 1, we choose the channel for each link with highest traffic demand to be schedule in each iteration. Due to the selection strategy (e.g., extended version of procedure SETCOVER(V, w) for multiple multi-dimensional bin packing in [34]) we employed in this work, we can guarantee that the total time slots we need to schedule all selected links is only logarithmical factor away from the optimum. Moreover, we schedule the transmissions of the links "packed" in the bin $\mathfrak{B}$ with maximal throughput achievement in each time slot during the period schedule time T. Consequently, it implies that $OPT^{(T)} \leq$

$$\Theta(\log n) \sum_t Max\Big(\sum_{\mathfrak{B}(t)} (X_{e,f,t-1}\lambda_{i,j}^f + (1-\zeta)X_{e,f',t-1}\lambda_{i,j}^f)\Big).$$

It completes the proof. ∎

Note that there may not always exist a feasible solution for the gateway selection problem we formulated due to the fairness constraint $f(u) \geq \lambda_0 l(u), \forall u \in V$ and the traffic requirement $\alpha_{e,f}, \forall e \in E \wedge f \in \mathfrak{f}$. However, we can always set the minimum fairness factor λ_0 a small constant value ≥ 0 to make the problem feasible in the given WMN.

V. Gateway selection scheme

Due to extremely high computing complexity to find an optimal solution of the gateway selection we formulated in Section III, we propose a new polynomial-time approximation algorithm for selection of exact k mesh nodes as the Internet gateways in order to maximize overall network throughput in WMNs under considerations of switching overhead and physical interference model. Our new scheme based on the framework of gateway selection proposed in [36], but we propose a new weighting scheme to alternate the original weighting approach for protocol interference model, which is used to associate and capture the unique characters of the physical interference model in order to maximize the network throughput. Combining with our new interference-aware link-channel scheduling scheme (Algorithm 1, e.g., crucial component to guarantee the performance) proposed in Section IV, we can show that the network throughput achieved by our scheme is only a poly-logarithmical factor away compared to the optimum. Note also that the scheme specially on the interference-free link-channel scheduling approach proposed in [36] is mainly designed for the scenario under protocol interference model that can not be implied to guarantee the performance in terms of network throughput for scenario based on physical interference model.

For the completeness of our presentation, we reproduce some notions introduced in [36].

Definition 9: Given a graph $G = (V, E)$, a dominating set is a subset D of V such that every node $v \in V - D$ is adjacent to at least one node in D.

Definition 10: A minimum dominating set for a given graph G is a dominating set with minimum cardinality.

Compared to the existing work in [36], we define a new weighting scheme for each pair of mesh nodes (u, v) : $\forall u \in V, \forall v \in V$ of the communication graph G that is used to describe the throughput gain by mesh node u if u votes v as a potential gateway. Note that it is unnecessary that $(u, v) \in E$. Moreover, the new weighting scheme can capture the characters of the physical interference model more precisely compared to the one in [36].

Definition 11: The throughput gain $\beta(u, v)$ achieved at mesh node u due to voting v as a potential gateway is defined as follows: $\beta(u,v) = \frac{\xi \sum_e \sum_{f \in \mathfrak{f}} c(e,f)(\Gamma_v^f - \sum_e \tau_{uw}^f)}{2^{h_{u,v}} \cdot |\cup_{f \in \mathfrak{f}(e)} I(e,f)|} : |e = (u, w) \in E \wedge h_{w,v} \leq h_{u,v}$, where $h_{u,v}$ is the minimal number of hops from u to v, and the amplitude factor ξ is a constant integer.

Note that $\beta(u, v)$ may not be the same as $\beta(v, u)$ due to asymmetric capacity on links (u, v) and (v, u). It is clear from Definition 11 that the throughput gain $\beta(u, v)$ can be significantly large if the total link capacity on all selected links e are large, the minimal hop distance from u to v is small, the cardinality of set of links that can cause interference with e is small, or the difference between the pre-defined interference threshold at v and the total accumulated interference power by the links e is large. In practical (our simulation results), we found that the amplitude factor $\xi = 1$ is good enough to distinguish different throughput gains over the WMN. According to the different value of the throughput gains, it also leads to a new weighting scheme in which the computing complexity of our new weighting scheme is very small and also such a scheme is much easy to be implemented. Moreover, it takes an important role in the gateway selection scheme to reduce the computing burden.

Based on the throughput gains $\beta(u, v)$, we employ the ranking approach in [36] for every mesh node $v \in V$, which indicates the "importance" of v to be a gateway. This ranking approach can be used to produce an optimal gateway selection scheme when single gateway scenario is considered.

Definition 12: The importance of $v \in V$ to be a gateway is defined as follows: $\varrho(v) = \sum_{\forall u \in V} \beta(u, v)$.

Consequently, by ranking the "importance" of all mesh node v according to Definition 12, the one with largest value of rank will be selected as the Internet gateway for the single-gateway scenario. However, in this paper, we focus on multi-gateway scenario in the WMNs and simple greedy-based approach can not guarantee the performance in terms of achievable network throughput. From such a ranking approach for single-gateway scenario, a subset $\Im \subset V$ that contains exact k mesh nodes with largest "importance" weights among all mesh nodes can be constructed for later use in the design of multi-gateway selection scheme which is the exactly same approach as the one introduced in [36].

According to the throughput gains, we now define a new complete graph $G^\dagger$ to present and reserve the properties of the throughput gains in original graph G we addressed above.

Definition 13: Given $G = (V, E)$ and the throughput gains by Definition 11, the graph $G^\dagger = (V^\dagger, E^\dagger)$ defines as a weighted complete graph such as $V = V^\dagger, (u, v) \in E^\dagger)$ for $\forall u \in V, \forall v \in V$, and the weight associating on link $(u, v) \in E^\dagger)$ is $\beta(u, v)$.

For the technical sakes, we also define another graph G^* which induced from $G^\dagger$ based on a parameter ς, the optimal value of ς will be determined during construction of our multi-gateway selection scheme later.

Definition 14: Having $G^\dagger = (V^\dagger, E^\dagger)$ and a parameter ς, the graph $G^*(V^*, E^*, \varsigma)$ can be defined as a subgraph of $G^\dagger = (V^\dagger, E^\dagger)$ such that $V^* = V^\dagger$ and $(u, v) \in E^* \subset E^\dagger$ if and only if $(u, v) \in E^\dagger$ and $\beta(u, v) \geq \varsigma$.

Our gateway selection scheme based on the framework in [36] but the different weighting scheme had been proposed in order to capture the unique characters of physical interference model. The essential idea of the gateway selection scheme is to use the combination of a 2-approximation minimum dominating set algorithm and parametric pruning techniques [14], [24], [25], [31] in our new constructed graph $G^*(V^*, E^*, \varsigma)$ to select k mesh nodes, which leads to an approximate configuration of the best k mesh nodes which can be used to act the Internet gateways. Combining our new interference-aware link-channel scheduling approach proposed in Section IV with the "good" properties we constructed in $G^*(V^*, E^*, \varsigma)$ and the selection scheme produced by the approximation algorithm for the minimum dominating set in G^*, we claim that the network throughput achieved by our algorithm is only poly-logarithmical factor far from the optimum. The details are illustrated in Algorithm 2.

Algorithm 2 Selection of k Gateways.

Input: Graph $G = (V, E)$, the parameter of the number of gateways k and the capacity $c(e, f), \forall e \in E, \forall f \in \mathfrak{f}$.
Output: Set of gateways Φ.

Compute throughput gains $\beta(u, v)$ for $\forall u \in V, \forall v \in V$ according to Definition 11;
Compute $\varrho(v), \forall v \in V$ according to Definition 12;
Construct the set $\Im$ based on $\varrho(v), \forall v \in V$;
Construct the weighted graph $G^{\dagger}$ by Definition 13;
Sort the weights of link e_i in nondecreasing order $c_1, c_2, \cdots, c_m$, where $m = |E^{\dagger}|$ and $1 \leq i \leq m$;
$low \leftarrow 1$; (Φ can be all V)
$high \leftarrow m$; (Φ can be a single $v \in V$)
repeat
    $mid := \lceil \frac{high+low}{2} \rceil$;
    construct $G^* = (V, E^*, c_{mid})$ by Definition 14;
    Φ :=DominatingSet(G^*) (by the Algorithm in [24]);
    if $|\Phi| > k$ **then**
        $high := mid$;
    else
        $low := mid$;
until $high \leq low$ (binary search)
if $|\Phi| < k$ **then**
    Add the top $k - |\Phi|$ nodes $v \in \Im$ to Φ for $v \notin \Phi$;
Output(Φ);

Theorem 15: The Algorithm 2 can produce an efficient gateway selection scheme in polynomial time in terms of the network size.

Proof: The correctness and efficiency of Algorithm 2 directly follows from Theorem 10 in [36] since we only modify the weighting scheme compared to the original gateway selection scheme in [36]. ■

In what follows, we show the performance of our gateway selection approach, e.g., combination of gateway selection scheme (Algorithm 2) and our new interference-aware link-channel scheduling approach (Algorithm 1) can be guaranteed in terms of the achieved network throughput, which is specified in the following theorem.

Theorem 16: The network throughput achieved by our gateway selection approach (Algorithm 2 followed by Algorithm 1) is at least a poly-logarithmical fraction of the optimum.

Proof: It had been shown in [34] that the Algorithm 2 can generate a constant approximation guarantee in terms of the network throughput by execution of an optimal interference-aware link-channel scheduling scheme. Combining with our $O(\log n)$-approximation interference-aware link-channel scheduling scheme (Algorithm 1), it directly follows that the network throughput achieved by our new gateway selection scheme is only a poly-logarithmical factor away compared to the optimum. ■

VI. SIMULATIONS

In this section, we evaluate the performance of different gateway selection schemes in terms of network throughput in randomly generated multi-radio multi-channel WMNs under physical interference model. We compare the performance of our scheme with three well known existing gateway placement schemes in [23] that includes random, fixed and grid-based deployments. The simulation results show that our new gateway selection scheme can effectively exploit the available resources and achieve higher network throughput compared to random, fixed and grid-based schemes. Due to the space constraint, we defer these issues into the full version of this paper.

VII. CONCLUSION

In this paper, we investigate the problem of gateway selection for throughput optimization in multi-radio multi-channel wireless mesh networks. In contrast to the various methodologies in the literature, we not only explicitly model the delay overhead that is incurred during channel switching, and consider this delay-related issue in the design of our mechanism but also employ the most reliable interference model in our approach, e.g., physical interference model. To the best of our knowledge, it is the first time to take account switching overhead into the scenario of gateway selection in multi-radio multi-channel wireless networks under physical interference model. In this paper, we formulate the gateway selection scenario as a NP-hard optimization problem. Due to extremely high computational burden to generate an optimal solution, we also propose a new approximation algorithm for gateway selection using a cross-layer throughput optimization that can effectively exploit the available resources. Combining with a new interference-aware link-channel scheduling scheme we proposed in this work, we prove that the performance of our gateway selection scheme on the achieved network throughput is only a logarithmical factor far to the optimum in terms of the size of network. Simulation results demonstrate that our mechanism can effectively exploit the available resources and achieve much higher network throughput than random, fixed deployment and grid-based methods in the literature.

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