Traffic and Interference Aware Scheduling for Multi-Radio Multi-Channel Wireless Mesh Networks

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Abstract—This paper proposes a scheduling scheme for wireless mesh networks (WMNs) that are capable of multiple channel access and equipped with multiple radio interfaces. The proposed scheme is interference and traffic aware in that it increases the overall achievable throughput of the network by eliminating interference between the wireless mesh routers, and maximizes the satisfaction ratios of all active sessions by accounting for the sessions’ data rate requirements. Simulation results show that the proposed scheme outperforms the Tabu-based scheduling scheme, and yields good tradeoffs between the achievable throughput of the network and the satisfaction ratios of the sessions.

Index Terms—multi-radio multi-channel access, channel assignment, link scheduling, wireless mesh networks.

I. INTRODUCTION

Wireless Mesh Networks (WMNs) are a new networking paradigm that can be deployed as a wireless backbone network [1], aiming at extending the coverage of traditional wireless access networks via wireless multi-hop connections. In this architecture, the fixed wireless mesh routers, which form a wireless backbone collect the traffic generated by the client nodes and relay it to other networks, such as Internet, cellular networks, Wi-Fi, WiMAX, etc. Nowadays, due to their low cost and ease of deployment and maintenance, WMNs are appealing to several applications, such as enterprise backbone networks, last mile broadband Internet access, high speed metropolitan area networks, building automation, remote monitoring and control, etc., and hence, they are foreseeable as one of the potential networking solutions to the bandwidth scarcity problem [2]. Unlike the case of ad hoc networks, energy consumption and mobility do not usually present a challenge to WMNs. Capacity limitation, however, presents a fundamental challenge to WMNs due mainly to the interference arising from the wireless nature of the environment as well as the scarcity of the radio/channel resources. The interference arising from the use of one single wireless channel in a multihop environment limits the number of data communications that can occur simultaneously in a given neighborhood, thereby decreasing overall network throughput. One emerging solution to this interference problem is to enable routers with multi-radio (MR), multi-channel (MC) access. For example, multi-channel access can be made possible through the use of the multiple non-overlapping channels that are provided by IEEE 802.11 standards. Although the promises of MR-MC networks are apparent, there still requires sophisticated scheduling algorithms that can effectively assign these available channels and radios to various links. In this paper, we propose a joint channel/radio assignment and time scheduling algorithm for MR-MC access capable WMNs that improves the overall achievable network throughput while accounting for data traffic requirements. The proposed scheduling scheme, referred to as TAIFS (Traffic-Aware, Interference-Free Scheduling), eliminates interference among the active links via a wise combination of time and frequency domains. In addition, TAIFS exploits the channel switching capability of the radio interfaces1 in order to increase the channel reuse, thus improving the network capacity even further. TAIFS is also traffic aware; i.e., given a set of active paths and active link loads, TAIFS distributes the time and channel resources among the active links in a way that maximizes the capacity of these links with respect to their traffic loads, thus making them meet the end-to-end bandwidth requirements as much as possible and consequently enhancing the overall achievable network throughput. Simulation results show that TAIFS outperforms Tabu Method [4] (a recently proposed scheduling scheme also for MR-MC networks) in terms of total achievable network throughput, end-to-end flow satisfactory ratio, and fairness. The remainder of this paper is organized as follows. Section II presents related works. Section III describes the system model. Section IV states and formulates the studied problem. Section V presents the proposed scheduling scheme. Section VI evaluates the performance of the proposed scheme, and compares it with the Tabu-based scheduling scheme. Section VII concludes the paper.

II. RELATED WORK

The apparent promises of MR-MC access networks have created significant research interests, resulting in numerous works ranging from performance optimization techniques to scheduling and channel assignment algorithms. Several studies have focused on characterizing the achievable throughput in MR-MC networks [5]–[7]. In [5], Kyasanur et al. derive lower and upper bounds on the capacity of static MC networks, and study the impact of multiple radios on such network capacity.

1The radio switching time is shown to be decreased to approximately 80 microseconds in commercial IEEE 802.11 interfaces [3].
The work in [6] derives necessary and sufficient conditions for the feasibility of rate vectors in MR-MC WMNs, and uses them to find upper bounds on the achievable throughput. In a recent work [7], Xie et al. have studied the feasibility of optimal channel assignment in MR-MC WMNs. They proved that the complexity of general channel assignment problems is exponential in the number of wireless links. On the other hand, they show that given a certain computing power (e.g., an off-the-shelf notebook PC), it is feasible to optimally solve channel assignment problems in small-scale and medium-scale commercial multi-radio WMNs. There has also been several research efforts that aimed at developing scheduling algorithms for MR-MC networks [4], [8]–[11]. Due to the NP-hardness of the scheduling problem, most of these reported algorithms are heuristic schedulers. In [8], Cheng et al. study the complexity of channel scheduling under the generalized physical interference model and under the generalized H-hops interference-free model, and prove the suitability of these two models for scheduling design in MR-MC networks. They also provide a polynomial-time approximation (PTAS) interference-free channel scheduling solution based on graph partitioning. In [9], Ramachandran et al. introduce the multi radio conflict graph, and a Breadth First Search based algorithm in order to achieve dynamic interference aware channel assignment. However, their scheme does not eliminate completely interference from the network nor does it consider traffic loads to improve the network performances. In [10], the authors use a network partitioning approach for channel scheduling. They proposed an algorithm, called MCCA, that aims at maximizing the network capacity through identifying the links that are most critical to carrying traffic and then protecting them against the interference. Although their approach is simple and resulting in polynomial time problem formulation, it is not flexible since all links in a partition are fixed to a common channel, and as a consequence, it cannot achieve optimal throughput. In [4], Subramanian et al. also address the problem of assigning channels to links in MR-MC WMNs. They propose a centralized Tabu-search based algorithm that assigns colors (i.e., channels) to the vertices of the contention graph (i.e., the links of the network graph). Their algorithm focuses on minimizing the network interference, and it resembles the Max-K cut problem. Although their scheme reduces interference significantly (closer to the lower bound on the amount of total network interference [4]), it assigns at most one channel per active link, which results in low network throughput. In [11], Bahandri et al. study the performances of a class of schedulers that uses a heuristic to make channel-to-link assignment in the presence of channels with heterogeneous rates without requiring an explicit exchange of queue/link rate information. This heuristic achieves some throughput gain by minimizing the incurred overhead, but it is not optimal, nor does it outperform other scheduling heuristics that use local information exchange [12].

In our work, we propose a scheduling scheme that (1) eliminates interference between the wireless routers forming the WMN, and (2) achieves a traffic-wise resource allocation in order to improve the network throughput. We compare our proposed scheme with the Tabu-search scheme [4], and show the importance of considering data traffic rate requirements as well as channel switching capabilities when designing scheduling algorithms. The proposed scheduling scheme uses binary integer programming BIP to maximize the capacity of the active links according to their traffic loads under both the protocol and physical interference models. It also exploits the radio-channel switching capability, which allows more spectral reuse, thus improving achievable throughput even further.

III. NETWORK MODEL

We consider a WMN modeled as a directed graph $G = (V, E)$, where $V$ denotes the set of all the nodes (mesh routers) in the network, and $E$ denotes the set of physical wireless links between pairs of nodes. Nodes are generated and placed randomly in a grid to form a WMN. We assume that all the nodes transmit with a fixed power $P$, and that there is a wireless link between two nodes when they are located within each other’s transmission range. That is, for all $(u, v) \in V^2$, $(u, v) \in E$ when $d_{uv} \leq r$, where $d_{uv}$ is the distance between nodes $u$ and $v$, and $r$ is node $u$’s transmission range.

We assume that each node is equipped with $m$ radio interfaces, and that there is a set $\Omega$ of $n$ orthogonal channels, each of which has a capacity $b$ (in Mbps). In this work, we consider that all nodes (i.e., mesh routers) are stationary, and that the WMN topology is infrastructure based with little to no topological changes. We consider a set $\Phi$ of simultaneously active sessions in the network, where each session $s_i \in \Phi$ is characterized by: Its source node $src(i)$, its destination node $dest(i)$, its required data rate $d_i$, and the path $P_i$ used to route session $s_i$’s traffic. Given the set of sessions (i.e., source-destination pairs, their data rates and their paths), we extract the active sub-graph $G'$ from the network graph $G = (V, E)$, where $G' = (V', E')$ is a weighted directed graph defined as:

- $E' = \{ e \in E : \exists s_i \in \Phi \text{ such that } e \in P_i \}$
- $V' = \{ v \in V : \exists e \in E' \text{ such that } e \text{ is incident to } v \}$
- $\forall e \in E'$, the weight $w(e)$ of link $e$ is the sum of all sessions’ required data rates whose paths contain $e$; i.e.,

$$w(e) = \sum_{s_i \in \Phi, P_i \ni e} d_i$$  \hspace{1cm} (1)

Links in the active subgraph $G'$ are directed according to the routing direction of active flows. It is important to mention that the focus of this work is on link scheduling and channel assignment algorithms rather than on routing techniques. Hence, we assume that routers use one of the existing routing algorithms for mesh networks (e.g., OLSR [13], [14]) to find optimal paths for all sessions. The proposed channel assignment and link scheduling scheme assumes that all paths are already chosen by means of the routing algorithm.

IV. PROBLEM STATEMENT AND FORMULATION

In this paper, we propose a traffic and interference aware link-scheduling scheme that dynamically assigns channels and time slots among different active links while maximizing the achievable sessions’ data rates. We assume that there exists a centralized server (e.g., a designated mesh router) in the network that has full knowledge of network topology,
radio/channel resource availability, and active sessions’ characteristics (i.e., source/destination, required data rate, and path). Note that because, by nature of WMNs, mesh routers can be safely assumed to be stationary (i.e., network topology does not change), and by assuming that the set of available channels and the number of radios remain unchanged over the course of sessions’ durations, we argue that having a centralized scheduler/server is effective. That is, given that the topology and the number of radios remain unchanged, the scheduler/server will have to periodically gather the sessions’ information, run the proposed joint channel and time scheduling algorithm, and advertise the scheduling solutions to all mesh routers, which they will then use in their communication. This schedule is updated by the server after a certain number of time frames (adjusted according to the design goals) and transmitted again (via a common channel) to the different nodes in the network. We also assume that the schedule update period is large enough compared to the broadcast delay and the channel switching delay, so that the schedule change is performed seamlessly and the communication between the active nodes continue smoothly without interruption, independently of the scheduling operations. In the remainder of this section, we will start by modeling and stating the different radio and interference constraints, and then define the criteria under which TAIFS performs.

A. Radio and Interference Constraints

In order to carry out a direct communication, two nodes need to be within each other’s transmission range, and have at least one of their radio interfaces tuned to a common channel. A link $e$ is said to be active if it has data traffic to carry; i.e., if it belongs to at least one of the sessions’ paths. When $e$ is active, it needs to be assigned at least one channel $k$. Thus, for every $(e, k) \in E' \times \Omega$, we introduce the binary variable $x^k_e$, and define it as:

$$x^k_e = \begin{cases} 1 & \text{if link } e \text{ is assigned channel } k \\ 0 & \text{Otherwise} \end{cases}$$

1) Interference Constraints: In this work, we consider two interference models: the protocol model and the cumulative model. In the protocol interference model, all links are assumed ideal, and the interference depends only on the distances separating the nodes [4], [5], [15]. In the cumulative interference model (also known as the physical interference model), the interference depends on distances, SINR levels, and other channel factors that affect signals’ strength, such as fading and path loss [15], [16]. The interference constraints under each of the two models are described next.

(i) The protocol Interference Model:

In our scheduling scheme, we are interested in maximizing the capacity of the active links only; i.e., the links that carry traffic loads. Given the active subgraph $G' = (V', E')$ defined in Section III, the contention graph $C(G')$ is defined as the undirected graph whose vertex set is $E'$ (i.e., active links), and whose edge set is all pairs $(u, v) \in E' \times E'$ such that $u$ interferes with $v$ or $v$ interferes with $u$. Fig. 1 shows an example of a network graph and its contention graph.

In this interference model [4], [5], [15], we assume ideal links and that the interference between nodes is mainly determined according to the distance separating them. We actually consider two types of interference constraints:

- **Interface-related Constraints**: state that any two links that share at least one of their vertices cannot use the same channel at the same time.
- **Pair-wise Interference Constraints**: state that in order for a transmission from node $i$ to node $j$ to be successful over the directed link $(i, j)$ using channel $k$, the following two conditions must hold:
  1) $d_{ij} \leq r$. That is, the receiver must be within the transmitter’s transmission range.
  2) $d_{ij} > r$ for every $l \in V'$ that is transmitting to any $h \in V'$ concurrently with $j$’s reception on the same channel $k$. That is, the receiver $j$ must be out of the range of interference caused by any other transmitter.

Therefore, by letting $I'(e) = \{e' \in E' : \text{Transmission over } e' \text{ interferes with Reception over } e\}$, one can write the interference constraints as:

$$x^k_e + x^k_{e'} \leq 1 \quad \forall (e, e') \in E' \times I'(e) \quad \forall k \in \Omega \quad (2)$$

(ii) The Cumulative Interference Model:

We now formulate the interference constraints under the cumulative model. We consider the Rayleigh fading channel model, which works well in urban/no-line-of-sight (NLOS) environments [18]. Let us assume that a link $e$ in the network transmits over channel $k$ with power $P^k_e$. Let $N_c$ denote the noise power measured at the receiver of link $e$. We also assume that the channel gain $G_{ee'}$ from the transmitter of link $e$ to the receiver of link $e'$ depends on the distance (between the transmitter and the receiver), and can be written as $G_{ee'} = K \cdot |l_{ee'}|^{-\alpha}$, where $\alpha > 2$ is the path loss exponent, and $|l_{ee'}|$ is the distance between the transmitter of the link

2. This contention graph model is similar to the one used in [17], and is used here to derive and formulate the different interference and radio constraints.

3. These constraints are also adopted by the IEEE 802.11 standard.
e' and the receiver of link e. A feasible schedule under the cumulative interference model is a set of activated links such that the minimum SINR requirements are satisfied. In our case, a schedule consists of a set of links that could be active over more than one channel at the same time. Hence, the above condition should be satisfied for each link-channel pair that is active over a given time slot. To model this, we use the activation decision variables $x_e^k$ in the SINR formula ($x_e^k$: indicates whether a link $e$ is active over a channel $k$). Thus the interference constraints can be written as:

$$\text{SINR}(e, k) \triangleq \frac{P_e^k G_{ee} F_e^k x_e^k}{\sum_{e' \neq e} P_{e'}^k G_{ee'} F_{e'}^k x_{e'}^k + N_e} > \beta_e x_e^k$$ (3)

where $F_e^k$ represents the fading coefficient of link $e$ and channel $k$, and $\beta_e$ is the SINR threshold at the receiver of link $e$. In the Rayleigh fading model, we assume that for every channel $k$, the fading state variables, $F_e^k$, are i.i.d. exponentially distributed random variables with unit mean. We also assume that the interference from other transmitters is much larger than the white Gaussian noise at the receivers, and therefore, we ignore the receiver noise in our analysis. Hence, Eq. (3) becomes:

$$\text{SINR}(e, k) \triangleq \frac{P_e^k G_{ee} F_e^k x_e^k}{\sum_{e' \neq e} P_{e'}^k G_{ee'} F_{e'}^k x_{e'}^k} > \beta_e x_e^k$$ (4)

Note that SINR here is a random variable. Therefore, for practicality reasons and since we do not know the fading states ahead of time (i.e. before the actual transmission occurs), Eq. (4) is replaced by Eq. (5) (given hereafter), which uses the average value of SINR, denoted by $\overline{\text{SINR}}$, and written as:

$$\text{SINR}(e, k) = \frac{E[P_e^k G_{ee} F_e^k x_e^k]}{E[\sum_{e' \neq e} P_{e'}^k G_{ee'} F_{e'}^k x_{e'}^k]}$$

Hence, the interference constraints under the cumulative interference model are:

$$\text{SINR}(e, k) = \frac{P_e^k G_{ee} x_e^k}{\sum_{e' \neq e} P_{e'}^k G_{ee'} x_{e'}^k} > \beta_e x_e^k \quad \forall e \in E', \forall k \in \Omega$$ (5)

In the particular case, where all the links use the same power level $P$ for transmission, the cumulative interference constraints become:

$$\text{SINR}(e, k) = \frac{G_{ee} x_e^k}{\sum_{e' \neq e} G_{ee'} x_{e'}^k} > \beta_e x_e^k \quad \forall e \in E', \forall k \in \Omega$$ (6)

2) Radio Constraints: Given that every node is equipped with $m$ radio interfaces, a node can at most communicate on $m$ different channels at a given time. By letting $E'(i) = \{ e \in E' : e \text{ incident to } i \in V' \}$, these radio constraints can be written as:

$$\sum_{k \in \Omega} x_e^k \leq m \quad \forall i \in V'$$ (7)

Similar interface constraints and interference models have already been used in the literature [15], [16]. However, it is important to reiterate that this paper does not propose an interference model. The main contribution of this paper rather lies in: (i) the formulation of the scheduling problem in the case of a Rayleigh fading environment, (ii) the construction of an interference-aware frequency and time schedule with respect to the spatial traffic distribution (Phase I of TAIFS), and (iii) the exploitation of interface switching capability to increase the channel reuse and further improve the network throughput (Phase II of TAIFS).

B. Session Satisfaction Ratio

TAIFS increases the achievable network throughput by eliminating interference among the active links in the WMN while satisfying the data rate requirements of active sessions as much as possible; i.e., while maximizing the satisfaction ratios of active sessions, which are defined next. Recall that a link $e \in E'$ could be used to communicate traffic belonging to multiple different sessions, where again each session $s_i$ is associated with a data rate requirement $d_i$. Hence, every link $e$ is assigned an aggregate data demand $w(e)$ as defined by Eq. (1). Let $w = [w(e)]_{e \in E'}$ be the vector representing all aggregate data demands on all active links. For all $e \in E'$, the total data rate that can be achieved on link $e$ per frame (a frame is a set of time slots that repeat periodically; i.e., schedule length) is:

$$c(e) = \frac{\sum_{t=1:n_{ts}} \sum_{k \in \Omega} x_{e,t}^k \times b}{n_{ts}}$$ (8)

where $b$ is the capacity of one channel, $n_{ts}$ is the total number of time slots per frame, and

$$x_{e,t}^k = \begin{cases} 
 1 & \text{if link } e \text{ is assigned channel } k \text{ at time slot } t \\
 0 & \text{otherwise}
\end{cases}$$

Under the physical interference model, the link throughput $c(e)$ can be expressed as:

$$c(e) = \frac{\sum_{t=1:n_{ts}} \sum_{k \in \Omega} x_{e,t}^k \times b(e,k)}{n_{ts}}$$

where $b(e,k)$ is the channel capacity given by Shannon Formula, $b(e,k) = b \log_2(1+SINR(e,k))$, and $SINR(e,k)$ is the signal to interference plus noise ratio for link $e$ over the channel $k$ as defined by Eq. (3). For every $e \in E'$, we now define the per-session satisfaction ratio $sr(e)$ of link $e$ as:

$$sr(e) = \frac{c(e)}{w(e) \times n_{sa}(e)}$$

where $n_{sa}(e)$ is the number of sessions carried out over link $e$, and for every session $s_i \in \Phi$, the session satisfaction ratio $sr_i$ as:

$$sr_i = \min_{e \in F_i} sr(e)$$

V. TRAFFIC-AWARE INTERFERENCE-FREE SCHEDULING

TAIFS operates in two main phases. The first phase performs a joint channel and time scheduling by solving a binary integer program (BIP) whose objective is to maximize the capacity of active links according to their traffic loads subject to interference and radio constraints. The output of this phase is a set of active links, each assigned one time slot and a number of channels. The second phase is a heuristic
that checks the possibilities of increasing the spectrum usage further by assigning more time slots and channels to active links whenever possible (i.e., without violating radio and interference constraints) while privileging the links with the least satisfaction ratios.

A. TAFIS Phase I: Traffic-Aware BIP-Based Scheduling

We will start by formulating our problem of traffic and interference aware channel assignment as a binary integer program (BIP). The outcome of this BIP is a subset of links that are assigned channels in a way that they can be active at the same time without interfering with each others. We present a BIP for each of the two studied interference models.

1) BIP Formulation for Channel Assignment:

(i) Case 1: Using the Protocol Interference Model

In this model, we assume that all links are ideal; i.e., the probability of transmission success on link e over channel k (given that both the radio and interference constraints are met) is \( P_{\text{success}}(e, k) = 1 \). Thus, the channel assignment program can be formulated as:

\[
\max \sum_{k \in \Omega} \sum_{e \in E'} w(e) \times x_{e}^{k}
\]

BIP(1):

\[
\begin{align*}
\sum_{k \in \Omega} \sum_{e \in E'} & \ x_{e}^{k} \leq 1 \quad \forall k \in \Omega, \forall e \in E', \forall e' \in I'(e) \\
\sum_{e \in \Omega} & \ x_{e}^{k} \leq m \quad \forall i \in V' \\
\end{align*}
\]

\( x_{e}^{k} \in \{0, 1\} \quad \forall k \in \Omega, \forall e \in E' \)

The above BIP assigns as many channels as possible to active links while giving priority to those with higher traffic loads under interference (Eq. 2) and radio (Eq. 7) constraints.

(ii) Case 2: Using the Cumulative Interference Model

We now consider the physical interference constraints introduced in the previous section, and account for the link reliability. In this model, transmitted signals are likely to attenuate and decay, thereby increasing the chances of the receiver not being able to decode its intended signal (\( P_{\text{success}}(e, k) \neq 1 \)). Using Eq. (4), one can define the transmission failure probability for a link e using channel k as \( \text{Prob}(\text{SNIR}(e, k) \leq \beta_e x_e^{k}) \); i.e.,

\[
P_{\text{out}}(e, k) = \text{Prob}(P_{e}^{k} G_{e,e} F_{e}^{k} x_{e}^{k} \leq \beta_e x_e^{k} (\sum_{e' \neq e} P_{e'}^{k} G_{e,e'} F_{e'}^{k} x_{e'}^{k})))
\]

The expression of \( P_{\text{out}}(e, k) \) could be derived from the following result [19]:

**Result:** Suppose \( z_1, z_2, ..., z_n \) are independent exponentially distributed random variables with means \( E[z_i] = 1/\lambda_i \). Then we have:

\[
\text{Prob}(z_1 \leq \sum_{i=2}^{n} z_i) = 1 - \prod_{i=2}^{n} \frac{1}{1 + \lambda_i/\lambda_1}
\]

Now given that for every channel k, the random variables, \( F_{e}^{k}, e = 1,..., |E'| \), are independent and exponentially distributed with \( E[F_{e}^{k}] = 1, \forall k \in \Omega \), one can write

\[
P_{\text{out}}(e, k) = 1 - \prod_{e' \neq e} \frac{1}{1 + (\frac{\beta_e P_{e}^{k} G_{e,e} x_{e}^{k}}{P_{e}^{k} G_{e,e} x_{e}^{k}})}
\]

The probability \( P_{\text{success}}(e, k) \) of transmission success of link e over channel k can be expressed as \( 1 - P_{\text{out}}(e, k) \). Or,

\[
P_{\text{success}}(e, k) = \prod_{e' \neq e} \frac{1}{1 + (\frac{\beta_e P_{e}^{k} G_{e,e} x_{e}^{k}}{P_{e}^{k} G_{e,e} x_{e}^{k}})}
\]

Thus, the channel assignment per time slot optimization problem can be formulated as a MINLP:

\[
\max \sum_{k \in \Omega} \sum_{e \in E'} w(e) \times x_{e}^{k}
\]

\[
\text{SNIR}(e, k) = \frac{P_{e}^{k} G_{e,e} x_{e}^{k}}{\sum_{e' \neq e} P_{e'}^{k} G_{e,e} x_{e'}^{k} + x_{e}^{k}} \quad \forall k \in \Omega, \forall e \in E'
\]

This optimization program is equivalent to BIP(1). It aims at maximizing link capacity by increasing the number of channels assigned to each link according to its traffic demand, while taking into account the quality of the link modeled via \( P_{\text{success}} \). The first set of inequalities in this program (MINLP) corresponds to the physical interference constraints. The second set corresponds to the radio interface constraints. The third set corresponds to the power constraints, stating that the transmission power of any link must not exceed \( P_0 \). Finally, the last set of inequalities corresponds to the channel-to-link assignment indicator variable, which can only take the value of zero or one. This new optimization program is a MINLP (Mixed Integer Non Linear Program), which aims at optimizing not only the channel-to-link assignment, but also the transmission power allocated for every active link-channel pair. Power allocation variables appear in both expressions of \( P_{\text{success}}(e, k) \) and \( \text{SNIR}(e, k) \). When all links are assumed to transmit at the fixed power \( P \), the probability of transmission success becomes

\[
P_{\text{success}}(e, k) = \prod_{e' \neq e} \frac{1}{1 + (\frac{\beta_e G_{e,e} x_{e}^{k}}{G_{e,e} x_{e}^{k}})}
\]

and MINLP becomes a binary integer program, termed BIP(2):

\[
\max \sum_{k \in \Omega} \sum_{e \in E'} w(e) \times \prod_{e' \neq e} \frac{1}{1 + (\frac{\beta_e G_{e,e} x_{e}^{k}}{G_{e,e} x_{e}^{k}})} \times x_{e}^{k}
\]

\[
\text{SNIR}(e, k) = \frac{G_{e,e} x_{e}^{k}}{\sum_{e' \neq e} G_{e,e} x_{e'}^{k} + x_{e}^{k}} > \beta_e x_e^{k} \quad \forall k \in \Omega, \forall e, e' \in E'
\]

\[
\sum_{k \in \Omega} \sum_{e \in E'} x_{e}^{k} \leq m \quad \forall i \in V' \\
\]

\( x_{e}^{k} \in \{0, 1\} \quad \forall k \in \Omega, \forall e \in E' \)

Note that we can use the same heuristic that we developed for solving the problem of joint scheduling and channel assignment under the interference protocol model to solve the above physical interference model based formulation. It suffices to solve BIP(2) in the first algorithm (that we will present in the next paragraph) instead of solving BIP(1).

2) TAFIS Phase I Description: Since BIP(1) and BIP(2) perform the same task, namely channel assignment, but with respect to two different interference models, we will use the “unique” notation BIP to refer to any of them. Because solutions to the BIP presented above may be such that some active links may not be assigned any channels due to resource (channels and radio interfaces) limitations, we propose to proceed iteratively in order to ensure that all active links
are scheduled. In the first iteration, the set of all the active links (i.e., \( E' \)) is injected as an input to BIP (either BIP(1) or BIP(2)). After solving this BIP, there will be two disjoint sets: a set \( E_1 \) of these active links that have been assigned channels; i.e., \( E_1 = \{ e \in E' : \exists k \in \Omega, x^k_e = 1 \} \) and a set \( E_2' \) of all these unassigned active links; \( E_2' = E' \setminus E_1 \). In the second iteration, BIP is solved again, but while considering \( E'_2 \) instead of \( E' \) as the set of active links (those active links that were not assigned any channels during the first iteration). After solving this second BIP, there will also be two disjoint sets: a set \( E_2 \) of all active links that are assigned channels during the second iteration; i.e., \( E_2 = \{ e \in E'^2 : \exists k \in \Omega, x^k_e = 1 \} \) and a set \( E'_3 \) of all the unassigned active links; \( E'_3 = E'^2 \setminus E_2 \). These iterations continue until all the active links in \( E' \) are each assigned at least one channel. Once this is done, each set \( E_i \) obtained during iteration \( i \) will be assigned a time slot, during which all links in \( E_i \) are scheduled to carry traffic during that time slot. These iterations constitute the first phase of TAIIFS, and are summarized in Algorithm 1. In this algorithm, \( SM \) represents a 3-dimensional schedule matrix, containing information about the time and channel assignment for the whole set of active links after execution of TAIIFS Phase I.

**Algorithm 1 TAIIFS Phase I: BIP based Scheduling**

1. **Input:** \( G' = (V', E'), \Omega, w, CM \): The set of constraints.
2. **Output:** \( n_{ts} \): Number of time slots per time frame, \( SM \): Time and Channel assignment matrix.
3. \( A \leftarrow E' \)
4. \( n_{ts} \leftarrow 0 \)
5. Initialize \( SM \) to zero matrix
6. while \( A \neq \emptyset \) do
7. Solve BIP
8. \( S \leftarrow \{ e \in A : \exists k \in \Omega, x^k_e = 1 \} \)
9. \( A \leftarrow A \setminus S \)
10. Update \( SM \) and \( CM \)
11. \( n_{ts} \leftarrow n_{ts} + 1 \)
12. end while

**B. TAIIFS Phase II: Traffic-Aware Link-Capacity Improvement**

The first algorithm described above partitions the set \( E' \) of all active links into disjoint subsets, each of which consists of multiple non-interfering links that can be active concurrently during a time slot. Each of these links is assigned a number of channels that it can use during that time slot. We now propose a heuristic that aims at increasing the number of active links that can be scheduled during each of the time slots determined by Algorithm 1. Basically, the heuristic tries to further increase the data rate \( c(e) \) that every link \( e \) can achieve, while prioritizing the links with the lowest satisfaction ratios. The heuristic works as follows. First, it uses the outcome of Algorithm 1 (run during TAIIFS Phase I) to calculate the satisfaction ratio \( sr(e) \) of every active link \( e \). Recall that the algorithm allocates one time slot and assigns a number of channels for every link \( e \). Second, the heuristic ranks these links according to their increasing order of their satisfaction ratios. The rationale behind this ordering is to give a privilege to links that are the farthest from satisfying their data rate requirements. Once this preparation phase is done, the heuristic picks the "neediest" link \( e_c \) among all links, and for every time slot \( T_j \) that chronologically follows the time slot \( T_i \) that has been assigned to \( e_c \) in Phase I, it computes the set of channels over which link \( e_c \) could be activated during \( T_j \) without causing any interference. Among these channels, only the channels that, once assigned to \( e_c \), do not violate the radio constraints are then kept. We denote this set of channels by \( \Gamma(e_c, T_j) \). If \( \Gamma(e_c, T_j) \neq \emptyset \), channels from this set are assigned to \( e_c \) on a per-channel-by-channel basis until \( floor(sr(e_c)) = 1 \) or until all channels in \( \Gamma(e_c, T_j) \) are assigned to \( e_c \). The steps needed to perform this check operation (i.e. check whether a link \( e_c \) can be activated in time slot \( T_j \) and determine the set of channels \( \Gamma(e_c, T_j) \) it will use during that time slot, if possible) is given by Algorithm 2.

**Algorithm 2 TAIIFS PHASE II: check module**

1. **Input:** \( e_c \): candidate link, \( T_j \): candidate time slot, \( L(T_j) \): set of links active during \( T_j \).
2. **Output:** \( \Gamma(e_c, T_j) \): set of channels to be assigned to \( e_c \) in \( T_j \).
3. \( A \leftarrow L(T_j), \Gamma(e_c, T_j) \leftarrow \emptyset, exit = 0 \)
4. while \( (A \neq \emptyset) \) and \( (exit = 0) \) do
5. Pick \( l \in A \)
6. if \( (e_c \text{ interferes with } l) \) or \( (l \text{ interferes with } e_c) \) then
7. \( \Gamma(e_c, T_j) \leftarrow \Gamma(e_c, T_j) \setminus CH(l, T_j) \)
8. if \( \Gamma(e_c, T_j) \neq \emptyset \) then
9. \( exit = 1 \)
10. end if
11. end if
12. \( A \leftarrow A \setminus \{l\} \)
13. end while
14. if \( \Gamma(e_c, T_j) \neq \emptyset \) then
15. Check channels in \( \Gamma(e_c, T_j) \): remove those violating radio constraints when assigned to \( e_c \) during \( T_j \)
16. end if

Note that in Algorithm 2, \( L(T_j) \) (the set of links active in time slot \( T_j \)) and \( CH(l, T_j) \) (the set of channels used by link \( l \) in time slot \( T_j \)) are deduced from the \( SM \) matrix. After the check module related to the activation of link \( e_c \) in slot \( T_j \) is performed, if \( floor(sr(e_c)) < 1 \), then we move to the next time slot \( T_{j+1} \) and apply the check module for link \( e_c \) and time slot \( T_{j+1} \). We keep performing the same operations until \( floor(sr(e_c)) = 1 \) or until the end of the frame is reached; i.e., all the time slots that follow \( T_i \) are scanned. The steps of the whole heuristic run during TAIIFS Phase II are summarized and provided in Algorithm 3.

Now that we have presented the two phases of our scheme in detail, we will next show how TAIIFS (i) eliminates interference between wireless routers, (ii) increases spectral reuse, and (iii) improves network throughput.

By design, TAIIFS assigns channels/time slots to active links in such a way that they do not interfere with each other. In fact, in the first phase of our scheme the active are scheduled iteratively. In each iteration, a set of links are assigned some channels over which they can be active during a given time
Algorithm 3 TAIFS Phase II: Network Capacity Improvement

1: Input: $E'_{sorted}$: Array of links in $E'$ sorted according to their capacities, $T_{sorted}$: Array of time slots assigned to links in $E'_{sorted}$, $n_{ts}$, SM: The schedule matrix, sr: The link satisfaction ratio vector.


3: for counter = 1 : $|E'_{sorted}|$ do
4:   $e_c$ ← $E'_{sorted}[counter]$
5:   $T_i$ ← $T_{sorted}[counter]$
6:   $T_j$ ← $T_{i+1}$
7:   while ($T_j \leq n_{ts}$) and(floor(sr($e_c$)) < 1) do
8:      $\Gamma(e_c, T_j)$ ← check module($e_c, T_j, L(T_j)$)
9:      if $\Gamma(e_c, T_j) \neq \emptyset$ then
10:         Update SM
11:         Update (sr($e_c$))
12:      end if
13:      $T_j$ ← $T_{j+1}$
14: end while
15: end for

The number of channels assigned per link is proportional to the link’s traffic load. As a consequence, links participating in forwarding traffic of more than one session (thus representing potential bottlenecks) are given higher priority and assigned more channels. Hence, the per session achievable throughput will be increased compared to the case where every link is assigned only one channel independently of the traffic load, as done in previous works: [9], [10], [20], [21].

In short, the proposed scheduling scheme improves the network throughput and the session satisfaction ratios by (i) considering the physical link reliability in Rayleigh fading environment, (ii) eliminating interference among active links, (iii) taking into account the spatial traffic distribution during the channel assignment process, (iv) allowing the use of multiple channels per link, and (v) privileging links with lower session satisfaction ratios.

VI. PERFORMANCE EVALUATION

We now evaluate the performances of TAIFS and compare them with those of Tabu Method [4]. We use the “session satisfaction ratio” metric as a means of evaluating the effectiveness of the studied schemes, which is defined as the ratio of the session’s achieved data rate to that of its required one.

For completeness, we first begin by providing a brief overview of the tabu based scheme. Tabu Method is a centralized channel assignment algorithm also designed for MR-MC WMNs. It consists of two main phases: In the first phase, it assigns channels (or colors) to vertices in the contention graph, where each vertex corresponds to one link in the active graph, but without taking radio interface constraints into account. It starts first from a random channel assignment, and then tries to improve this assignment iteratively by using the tabu-based search technique [22]. The goal of this phase is to minimize interference by achieving a graph vertex coloring that maximizes the number of edges that link vertices of different colors in the contention graph. Since the channel assignment obtained from the first phase may not satisfy the radio interface constraints, during the second phase, Tabu Method applies a merge procedure repeatedly to eliminate these constraint violations.

A. Simulation Method and Setting

We implemented both TAIFS and Tabu Method in MATLAB. We used TOMLAB (linked with MATLAB) to solve the BIPs of TAIFS Phase I. TOMLAB offers a variety of tools to solve BIPs efficiently and reliably; the one that we used is based on the Branch and Cut algorithm [23]. We ran our simulations, analyzed them, and plotted our results also using MATLAB. In our simulations, we generated random MR-MC WMNs, each consisting of 50 mesh routers randomly deployed in a 1000m×1000m area. We also fixed the transmission range r of every node to 250m. We consider n wireless channels, and assume that every mesh router is equipped with m radio interfaces. For evaluation purposes, we varied n from 2 to 12 and m from 2 to 6. For every generated network topology, we also generate $|\Phi| = 20$ sessions by randomly selecting 20 random pairs of source/destination nodes. MaxRate denotes the maximum data rate that a session can require. Session i’s data rate, $i = 1, 2, \ldots, |\Phi|$, is set to $i \times \text{MaxRate}/|\Phi|$. The total traffic load $T_{MaxRate}$ equals then

$$T_{MaxRate} = \frac{(|\Phi| + 1)\text{MaxRate}}{2}$$

It is known that BIPs are NP-hard problems. However, there exists some fast operation research approaches/heuristics implemented in Tomlab/CPLEX (e.g., Branch and Cut) that
can provide fast and accurate enough solutions to BIPs. For example, for the case of our simulations (a network with 50 nodes and 12 channels) the CPU time for computing the BIP based schedules is around few milliseconds. This computation time could be further decreased if computation is performed by more powerful computing machines/servers. In the following subsections, we will present the performances of our scheme in terms of satisfaction ratio improvement.

### B. Performance Behaviors

Figs. 2 and 3 show the average session satisfaction ratio when both the number of channels and the number of radios are varied respectively for MaxRate = 10Mbps and MaxRate = 60Mbps. We can see that, for both cases of MaxRate, the average session satisfaction ratio has the same trend: It increases as the number of channels and/or radio interfaces increases. We notice that when the number of radios per node equals 2, an increase in the number of channels has little to no impact on the achieved per session satisfaction ratio. Likewise, when the number of channels equals 2, an increase in the number of channels slightly improves the average session satisfaction ratio. However, when n gets closer to 12, an increase in the number of radios incurs a significant improvement in the achieved session satisfaction ratio; this can be seen from the steep slope of the obtained curves.

On the other hand, by varying MaxRate, we can clearly see the impact of total traffic load on the performances. For instance, when MaxRate = 10Mbps, the total traffic load is \( T_{10} = 105Mbps \), and we can achieve up to 80% per session satisfaction ratio. While, when MaxRate is increased to 60Mbps (i.e., total traffic load \( T_{60} = 630Mbps \)), we can only achieve up to 15% of the required data rate. This gives us good insights on the capacity of our network during the WMN planning phase. In other words, given a set of resources and sessions’ rate requirements, we can determine the average session satisfaction ratio guaranteed by our scheduling scheme.

### C. Performance Comparison

We now compare session satisfaction ratios of TAIFS with those of Tabu Method. Since Tabu Method does not eliminate the interference completely, we consider that the obtained link capacity with this scheme is \( c(e) = \frac{b}{d(c)+1} \). Hence, what we measure for the Tabu Method is an upper bound rather than the actual achievable performance.

Figs. 4 and 5 show the average session satisfaction ratios under both schemes for two different values of MaxRate: 10Mbps and 60Mbps. Observe that the session satisfaction ratio realized under our scheme is double the one realized under Tabu-scheme. In addition, notice that the variation of the number of radio interfaces affects the performances of our scheme; by looking at the satisfaction ratios depicted via the 3 curves shown in Fig. 4, we can see that when \( n \) is greater than 6 channels, adding 2 more radio interfaces increases the

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**Fig. 2.** Impact of the number of channels and radios on the average satisfaction ratio for \( \text{MaxRate} = 10Mbps \)

**Fig. 3.** Impact of the number of channels and radios on the average satisfaction ratio for \( \text{MaxRate} = 60Mbps \)

**Fig. 4.** Session satisfaction ratio: \( \text{MaxRate} = 10Mbps \)

**Fig. 5.** Session satisfaction ratio: \( \text{MaxRate} = 60Mbps \)
satisfaction ratio level by about 20%. With Tabu Method, on the other hand, as \( m \) increases from 4 to 6, the achieved session satisfaction ratio level increases slightly and tends to stabilize around the value of 35%.

Tabu Method performs even poorly when \( \text{MaxRate} \) is increased to 60Mbps. In fact, Fig. 5 shows that when \( n = 6 \) and \( m = 6 \), our scheme performs three times better than Tabu Method. The figure also shows that for a given value of \( \text{MaxRate} \), the best session satisfaction ratio realized under our scheme is around 15% versus 7% for Tabu Method. We also notice that when \( m = 6 \), with \( n \) greater than 12 channels, TAIFS achieves much better satisfaction ratio; the curve is still far from stabilizing at a fixed bound/value for \( n = 12 \).

Figs. 6, 7, and 8 depict satisfaction ratios of all sessions sorted in their decreasing order according to their traffic loads from the session that has the highest traffic load to the one that has lowest traffic load when \( n = 2 \), \( n = 6 \), and \( n = 12 \) respectively. In these figures, the x-axis presents the sessions sorted from session \( s_1 \) (with the highest traffic demand \( d_1 = 10\text{Mbps} \)), session \( s_2 \) (with the second highest demand \( d_2 = 9.5\text{Mbps} \)), to session \( s_{20} \) (with the lowest traffic demand \( d_{20} = 0.5\text{Mbps} \)). The y-axis represents sessions’ satisfaction ratios.

In our scheme, sessions with higher traffic demands (i.e. those which have smaller indexes) are given higher priorities during the channel allocation process by formulating the assignment problem as the maximization of a weighted sum, where the weights represent the different sessions’ data rate requirements/demands. The figures clearly show that in spite of this predilection in resource allocation, sessions \( s_1 \) to \( s_{10} \) have a bit lower satisfaction ratios than sessions \( s_{11} \) to \( s_{20} \). On the other hand, if we use the ratio \( SR_i/\text{MaxRate} \) as a fairness criterion, where \( i \in [1, 10] \) and \( j \in [11, 20] \), the obtained ratios come out closer to 1, which indicates that our scheme is also fair in terms of allocating rates among sessions. The same trend has also been observed under Tabu Method. However, our scheme achieves higher session satisfaction ratios.

In essence, these obtained results show that our proposed scheme, TAIFS, outperforms the TABU based scheme in terms of sessions’ satisfaction ratios. Although Tabu Method minimizes the interference in the network, it does not make an efficient use of the available resources (i.e. channels vs. time). Unlike Tabu Method, TAIFS can assign active links more than one channel per time slot. In addition, TAIFS allows links to switch across different channels during different time slots, thereby utilizing the available spectrum and radio resources more efficiently.

VII. Conclusion

This paper proposes an interference-free, traffic-aware scheduling scheme for MR-MC WMNs. Our scheme uses binary integer programming to assign channels and time slots to active links while accounting for sessions’ traffic loads. Results show that our scheme increases throughput and sessions’ satisfaction ratios by (i) eliminating interference and (ii) taking into account the spatial traffic distribution. Results also show that our proposed scheme outperforms Tabu-based scheduling scheme in terms of session satisfaction ratios.

References


