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 interfaces[1] 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.

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[1]The 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 can not 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 Ω 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 Φ of simultaneously active sessions in the network, where each session $s_i \in \Phi$ is characterized by: Its source node $sce(i)$, 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' = $\{ e \in E : \exists s_i \in \Phi$ such that $e \in P_i \}$
- V' = $\{ v \in V : \exists e \in E'$ such that e 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.,

$$w(e) = \sum_{s_i \in \Phi : P_i \ni e} d_i \tag{1}$$

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_e^k, and define it as:

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

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

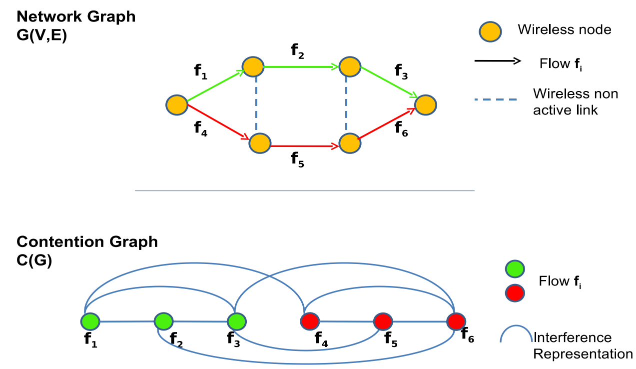

Fig. 1. An example of network graph and its contention graph.

u interferes with v or v interferes with u[2]. 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**[3]: state that any two links that share at least one of their vertices can not 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) $d_{lj} > r$ 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 $I'(e) = \{e' \in E' : \text{Transmission over e' interferes with Reception over e}\}$, one can write the interference constraints as:

$$x_e^k + x_{e'}^k \leq 1 \quad \forall (e, e') \in E' \times I'(e) \ \ \forall k \in \Omega \tag{2}$$

(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_e^k. Let N_e 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 $G_{ee'} = K. \mid l_{ee'} \mid^{-\alpha}$, where $\alpha > 2$ is the path loss exponent, and $\mid l_{ee'} \mid$ 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:

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

where F_e^k represents the fading coefficient of link e and channel k, and β_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 for $e = 1, \ldots, |E'|$, 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:

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

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 $\overline{SINR}$ and written as:

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

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

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

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

$$\overline{SINR(e,k)} = \frac{G_{ee}.x_e^k}{\sum_{e' \neq e} G_{ee'}.x_{e'}^k} > \beta'_e.x_e^k \quad \forall e \in E'; \forall k \in \Omega \quad (6)$$

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

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

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 $\mathbf{w} = [w(e)]_{e \in E'}$ 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:

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

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

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

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

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

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 $\mathbf{sr}(e)$ of link e as:

$$\mathbf{sr}(e) = \frac{c(e)}{w(e) \times n_s(e)}$$

where $n_s(e)$ 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:

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

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. TAIFS 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 $P_{success}(e,k) = 1$. Thus, the channel assignment program can be formulated as:

$$\text{BIP(1):}\quad \begin{aligned} &\max_{x_e^k} \sum_{k\in\Omega}\sum_{e\in E'} w(e)\times x_e^k \\ &x_e^k + x_{e'}^k \leq 1 \quad \forall k\in\Omega, \forall e\in E', \forall e'\in I'(e) \\ &\textstyle\sum_{k\in\Omega}\sum_{e\in E'(i)} x_e^k \leq m \quad \forall i\in V' \\ &x_e^k \in \{0,1\} \quad \forall k\in\Omega, \forall e\in E' \end{aligned}$$

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 ($P_{sucess}(e,k) \neq 1$). Using Eq. (4), one can define the transmission failure probability for a link e using channel k as $Prob(SINR(e,k) \leq \beta_e.x_e^k)$; i.e.,

$$P_{out}(e,k) = Prob(P_e^k G_{ee} F_e^k x_e^k \leq \beta_e x_e^k (\sum_{e'\neq e} P_{e'}^k G_{ee'} F_{e'}^k x_{e'}^k))$$

The expression of $P_{out}(e,k)$ 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:

$$Prob(z_1 \leq \sum_{i=2:n} z_i) = 1 - \prod_{i=2:n} \frac{1}{1+\lambda_1/\lambda_i}$$

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

$$P_{out}(e,k) = 1 - \prod_{e'\neq e} \frac{1}{1 + (\frac{\beta_e.P_{e'}^k.G_{ee'}.x_{e'}^k}{P_e^k.G_{ee}})}$$

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

$$P_{success}(e,k) = \prod_{e'\neq e} \frac{1}{1 + \frac{\beta_e.P_{e'}^k.G_{ee'}.x_{e'}^k}{P_e^k.G_{ee}}} \tag{9}$$

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

$$\begin{aligned} &\max_{x_e^k, P_e^k} \sum_{k\in\Omega}\sum_{e\in E'} w(e)\times P_{succes}(e,k)\times x_e^k \\ &\overline{SINR(e,k)} = \frac{P_e^k.G_{ee}.x_e^k}{\sum_{e'\neq e} P_{e'}^k.G_{ee'}.x_{e'}^k} > \beta'_e.x_e^k \quad \forall k\in\Omega, \forall e\in E' \\ &\textstyle\sum_{k\in\Omega}\sum_{e\in E'(i)} x_e^k \leq m \quad \forall i\in V' \\ &P_e^k \leq P_0 \quad \forall k\in\Omega, \forall e\in E' \\ &x_e^k \in \{0,1\} \quad \forall k\in\Omega, \forall e\in E' \end{aligned}$$

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 $P_{success}$. 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 $P_{success}(e,k)$ and $SINR(e,k)$. When all links are assumed to transmit at the fixed power P, the probability of transmission success becomes

$$P_{success}(e,k) = \prod_{e'\neq e} \frac{1}{1 + \frac{\beta_e.G_{ee'}.x_{e'}^k}{G_{ee}}}$$

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

$$\begin{aligned} &\max_{x_e^k} \sum_{k\in\Omega}\sum_{e\in E'} w(e)\times \prod_{e'\neq e} \frac{1}{1 + \frac{\beta_e.G_{ee'}.x_{e'}^k}{G_{ee}}} \times x_e^k \\ &\overline{SINR(e,k)} = \frac{G_{ee}.x_e^k}{\sum_{e'\neq e} G_{ee'}.x_{e'}^k} > \beta'_e.x_e^k \quad \forall k\in\Omega, \forall e, e'\in E' \\ &\textstyle\sum_{k\in\Omega}\sum_{e\in E'(i)} x_e^k \leq m \quad \forall i\in V' \\ &x_e^k \in \{0,1\} \quad \forall k\in\Omega, \forall e\in E' \end{aligned}$$

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) TAIFS 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., $E_1 = \{e \in E' \ : \exists k \in \Omega, x_e^k = 1\}$ 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., $E_2 = \{e \in E_2' : \exists k \in \Omega, x_e^k = 1\}$ 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 TAIFS, 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 TAIFS Phase I.

Algorithm 1 TAIFS Phase I: BIP based Scheduling

Input: $G' = (V', E')$, Ω, **w**, CM: The set of constraints.
Output: n_{ts}: Number of time slots per time frame, **SM**: Time and Channel assignment matrix.
$A \leftarrow E'$
$n_{ts} \leftarrow 0$
Initialize **SM** to zero matrix
while $A \neq \emptyset$ **do**
  Solve BIP
  $S \leftarrow \{e \in A : \exists k \in \Omega, x_e^k = 1\}$
  $A \leftarrow A \setminus S$
  Update **SM** and CM
  $n_{ts} \leftarrow n_{ts} + 1$
end while

B. TAIFS 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 TAIFS Phase I) to calculate the satisfaction ratio $\mathbf{sr}(e)$ 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 TAIFS PHASE II: **check module**

Input: e_c: candidate link, T_j: candidate time slot, $L(T_j)$: set of links active during T_j.
Output: $\Gamma(e_c, T_j)$: set of channels to be assigned to e_c in T_j.
$A \leftarrow L(T_j)$, $\Gamma(e_c, T_j) \leftarrow \Omega$, $exit = 0$
while $(A \neq \emptyset)$ and $(exit = 0)$ **do**
  Pick $l \in A$
  if (e_c interferes with l) or (l interferes with e_c) **then**
    $\Gamma(e_c, T_j) \leftarrow \Gamma(e_c, T_j) \backslash CH(l, T_j)$
    if $\Gamma(e_c, T_j) = \emptyset$ **then**
      $exit = 1$
    end if
  end if
  $A \leftarrow A \backslash \{l\}$
end while
if $\Gamma(e_c, T_j) \neq \emptyset$ **then**
  Check channels in $\Gamma(e_c, T_j)$: remove those violating radio constraints when assigned to e_c during T_j
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 $floor(\mathbf{sr}(e_c)) < 1$, 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 $floor(\mathbf{sr}(e_c)) = 1$ 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 TAIFS 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 TAIFS (i) eliminates interference between wireless routers, (ii) increases spectral reuse, and (iii) improves network throughput.

By design, TAIFS 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

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.
Output: **SM**: Time and Channel assignment matrix, **sr**: The link satisfaction ratio vector.
for $counter = 1 : |E'_{sorted}|$ **do**
  $e_c \leftarrow E'_{sorted}[counter]$
  $T_i \leftarrow T_{sorted}[counter]$
  $T_j \leftarrow T_{i+1}$
  while $(T_j \leq n_{ts}) and (floor(\mathbf{sr}(e_c)) < 1)$ **do**
    $\Gamma(e_c, T_j) \leftarrow$ **check module**$(e_c, T_j, L(T_j))$
    if $\Gamma(e_c, T_j \neq \emptyset)$ **then**
      Update **SM**
      Update $(\mathbf{sr}(e_c))$
    end if
    $T_j \leftarrow T_{j+1}$
  end while
end for

slot while meeting the interference and radio constraints. The second phase of our scheme conserves the "interference-free" property. Indeed, in this phase, we only activate link e in some slot $T_j > T_i$ if and only if there exists some channel k such that if link e transmits in slot T_j over channel k it will not interfere with the other links which are already active in T_j, and the radio constraint is not violated by this activation. Hence, the schedule obtained after phase II is also interference-free. However, we should mention that in our work we did not consider external interference originating from other wireless networks co-located with the WMN.

On the other hand, TAIFS improves spectral reuse during both phases. In the first phase, spectral reuse is increased by assigning the same channel to multiple, non-interfering links that can be active during the same time slot. Channel reuse is further increased in the second phase. In fact, note that in the first phase, if a link e is activated in time slot T_i, $(i < n_{ts})$, e is not considered for activation in time slot T_j $(\forall j, i+1 \leq j \leq n_{ts})$. In the second phase we study the possibility of activating link e in time slots different from the time slot it has been initially assigned during phase I. Thus, in phase II, by increasing the number of slots in which a link is activated, we increase not only the link capacity, but also the channel reuse (i.e. the number of users per channel at a given time).

As far as network throughput is concerned, in our scheduling scheme, the channel-to-link assignment is performed with respect to the link's current traffic load as shown BIP. Thus, 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 $1000m \times 1000m$ 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 $i \times MaxRate/|\Phi|$. The total traffic load $T_{MaxRate}$ equals then

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

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

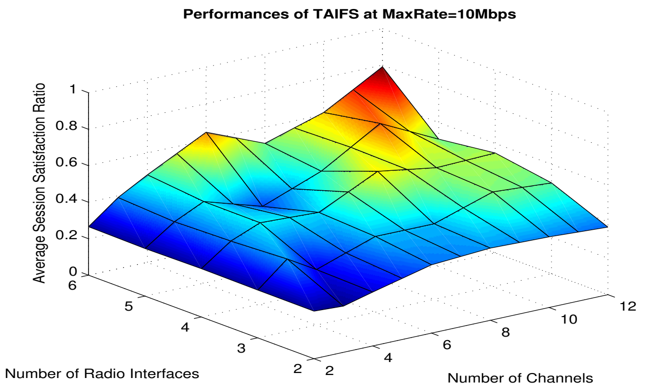

Fig. 2. Impact of the number of channels and radios on the average satisfaction ratio for $MaxRate = 10Mbps$

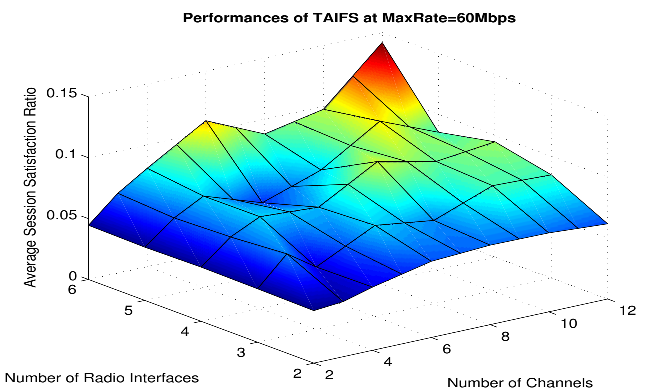

Fig. 3. Impact of the number of channels and radios on the average satisfaction ratio for $MaxRate = 60Mbps$

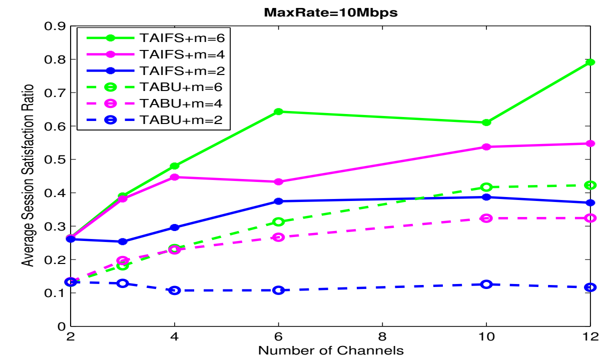

Fig. 4. Session satisfaction ratio: $MaxRate = 10Mbps$

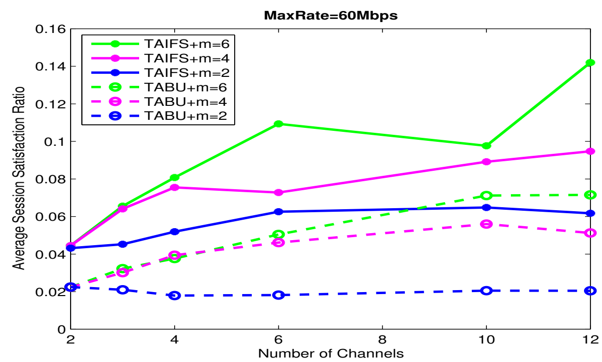

Fig. 5. Session satisfaction ratio: $MaxRate = 60Mbps$

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 m 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 n equals 2, an increase in the number of radios 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 $c(e) = \frac{b}{|I'(e)|+1}$. 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

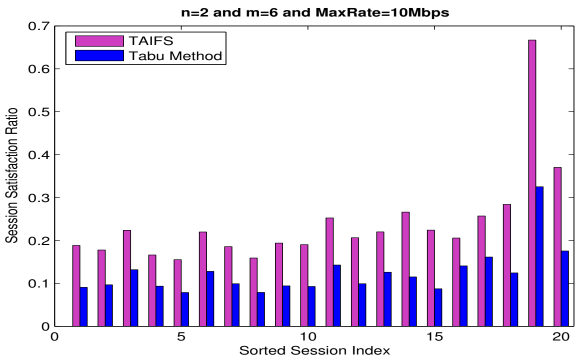

Fig. 6. Session satisfaction ratios: $n = 2$ and $m = 6$

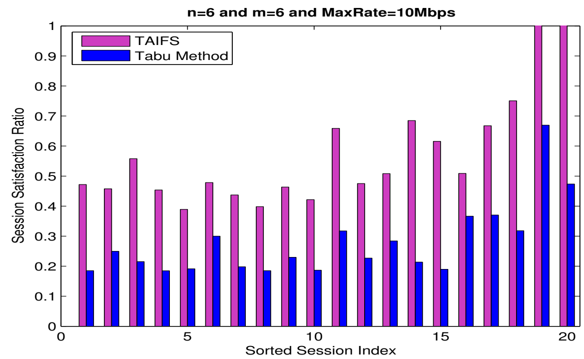

Fig. 7. Session Satisfaction Ratios: $n = 6$ and $m = 6$

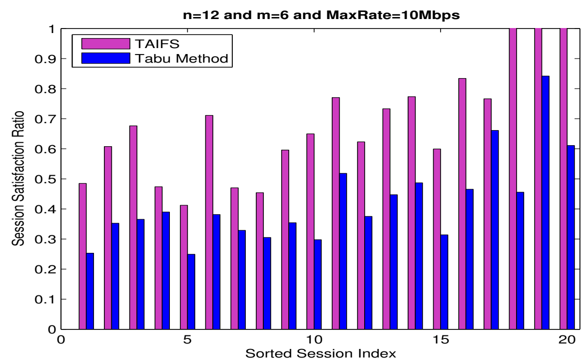

Fig. 8. Session satisfaction ratios: $n = 12$ and $m = 6$

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 $MaxRate$ 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 $MaxRate$, 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 $d_1 = 10Mbps$), session s_2 (with the second highest demand $d_2 = 9.5Mbps$), to session s_{20} (with the lowest traffic demand $d_{20} = 0.5Mbps$). 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/SR_j 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

[1] I. F. Aykilidz and X. Wang, "A survey on wireless mesh networks," in *IEEE Communications Magazine*, 2005.

[2] *FCC, Spectrum Policy Task Force (SPTF), Report of the Spectrum Efficiency WG, November*, 2002.

[3] P. Bahl, R. Chandra, and J. Dunagan, "Ssch: Slotted seeded channel hopping for capacity improvement in ieee 802.11 ad-hoc wireless networks," in *ACM MobiCom*, 2004.

[4] A.P. Subramanian, H. Gupta, S.R. Das, and J. Cao, "Minimum interference channel assignment in multiradio wireless mesh networks," *IEEE Transactions on Mobile Computing*, vol. 7, no. 12, December 2008.

[5] P. Kyasanur and N. H. Vaidya, "Capacity of multi-channel wireless networks: Impact of number of channels and interfaces," in *ACM MobiCom*, 2005.

[6] M. Kodialam and T. Nandagopal, “Characterizing the capacity region in multi-radio multi-channel wireless mesh networks,” in *ACM Proceedings of MOBICOM*, 2005, pp. 73–87.
[7] W. Xie, Y.J. Zhang, M.L. Sichitu, L. Fu, and Y. Yao, “Feasibility of optimally assigning channels by exhaustive search in commercial multi-radio wireless mesh networks,” *Telecommunication Systems*, 2010.
[8] W. Cheng, X. Cheng, T. Znati, X. Lu, and Z. Lu, “The complexity of channel scheduling in multi-radio multi-channel wireless networks,” in *IEEE INFOCOM*, April 2009.
[9] K.N. Ramachandran, E.M. Belding, K.C. Almeroth, and M.M. Buddhikot, “Interference-aware channel assignment in multi-radio wireless mesh networks,” in *IEEE INFOCOM*, 2006.
[10] S. Avallone and I.F. Akyildiz, “A channel assignment algorithm for multi-radio wireless mesh networks,” in *ICCCN*, 2007, pp. 1034–1039.
[11] V. Bahandri and N.H. Vaidya, “Scheduling in multichannel wireless networks,” *Distributed Computing and Networking*, 2010.
[12] X. Lin and S. Rasool, “A distributed joint channel assignment, schedling and routing algorithm for multi-channel ad hoc wireless networks,” in *IEEE INFOCOM*, 2007.
[13] D. S. J. De Couto, D. Aguayo, J. Bicket, and R. Morris, “A high-throughput path metric for multi-hop wireless routing,” in *Proceedings of ACM Mobicom*, 2003.
[14] `www.olsr.org`.
[15] P. Gupta and P. R. Kumar, “The capacity of wireless networks,” *IEEE Trans. on Information Theory*, March 2000.
[16] L. Fu, S.C. Liew, and J. Huang, “Effective carrier sensing in csma networks under cumulative interference,” in *IEEE INFOCOM*, March 2010.
[17] K. Jain, J. Padhye, V. Padmanabhan, and L. Qiu, “The impact of interference on multi-hop wireless network performance,” in *ACM Proceedings of MOBICOM*, 2003.
[18] D. Chizhik, J. Ling, P. W. Wolniansky, R. A. Valenzuela, N. Costa, and K. Huber, “Multiple-input-multiple-output measurements and modeling in manhattan,” *IEEE Journal on Selected Areas in Communications*, April 2003.
[19] S. Kandukuri and S. Boyd, “Optimal power control in interference-limited fading wireless channels with outage-probability specifications,” *IEEE Transactions on Wireless Communications*, January 2002.
[20] M.K. Marina and S.R. Das, “A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks,” in *The 2nd International Conference on Broadband Networks*, 2005, pp. 381–390.
[21] H. M. Ali, A. Busson, and V. Veque, “Channel assignment algorithms: A comparison of graph based heuristics,” in *The 4th ACM workshop on Performance monitoring and measurement of heterogeneous wireless and wired networks*, 2009.
[22] A. Hertz and D. de Werra, “Using tabu search techniques for graph coloring,” *Computing*, , no. 39, 1987.
[23] R.A. Stubbs and S. Mehrotra, “A branch and cut method for 0-1 mixed convex programming,” *Mathematical Programming*, 1999.