Link-Preserving Interference-Minimization Channel Assignment in Multi-Radio Wireless Mesh Networks

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Abstract

Using multiple channels with multiple radios per node in a wireless mesh network can potentially improve system capacity. This design requires the appropriate assignments of channels/radios to wireless backhaul links and creates a tradeoff between conflicting constraints and requirements. This study attempts to maximize the number of operative links, where a link is operative if radios at both ends of the link share a common channel (i.e., are link-preserving) and experience sufficiently low co-channel interference. These two criteria are conflicting in nature. A link-centric, channel-first radio resource assignment scheme that considers physical interference model and tight radio constraint is proposed. The proposed approach ensures link preservation and assigns channels to links based on the predicted upper bound and lower bound of the accumulated co-channel interference associated with particular assignments. Simulation results indicate that the proposed algorithm outperforms existing approaches in the number of operative links, particularly when only a few channels, or many radios, are available.

Keywords: channel allocation; wireless mesh network; interference; multi-radio

I. INTRODUCTION

A wireless mesh network (WMN) (Pathak & Dutta 2011, Benyamina et al. 2012) services to mobile stations equipped with wireless interfaces. A WMN enhances a wireless local area network (WLAN) by deploying dozens of mesh access points (MAPs), which provide wireless access service to mesh clients, over a large geographical area and linking them through a wireless backhaul network. This backhaul network, which may adopt a wireless transmission technology unlike that used by the wireless access links, enables multiple gateways to a wired network and provides multiple frame forwarding paths between any pair of MAPs.

Mesh points (MPs) are the basic units in the backhaul network, which forwards frames to other devices. An MP may also serve as an MAP if it allows wireless access by mobile users. An MP typically requires several wireless links, with one for each designated neighboring MP. Transceivers that operate on the same channel in close proximity cause co-channel interference, which degrades link capacity. A simple way to establish several links while avoiding capacity degradation is to equip each MP with multiple standalone wireless interfaces (radios) that utilize multiple non-overlapping channels in parallel. In this type of multi-radio, multi-channel WMN, assigning radio resource (channels and radios) to links is an optimization problem with various objectives that are defined with conflicting constraints and requirements. Despite this complexity, existing approaches share some common properties. For example, almost all existing approaches assume a limited number of radios and channels. Another common requirement is to preserve every designated link (i.e., the link-preserving requirement) or at least guarantee that the network remains connected after resource assignment (i.e., the connectivity requirement). A typical technique to satisfy the connectivity requirement is to use a default channel (Kyasanur & Vaidya 2005, Ramachandran et al. 2006, Skalli et al. 2007, Ko et al. 2007). However, meeting the link-preserving requirement may require channel switching (Tam & Tseng 2007, Chakchouk & Hamdaoui 2011) or other complicated techniques (Subramanian et al. 2008, Gardellin et al. 2011) to deal with the case when the number of links an MP must build exceeds the number of available radios or channels. The primary goal of radio resource assignment may be to minimize local interference (Ko et al. 2007), minimize overall interference (Subramanian et al. 2008), minimize maximum interference (Marina et al. 2010), maximize total operative links (Rajakumar et al. 2008), or maximize total network goodput (Raniwala et al. 2004, Jain et al. 2005). Previous researchers have proved that this problem is NP-hard or NP-complete (Raniwala et al. 2004, Jain et al. 2005, Subramanian et al. 2008, Marina et al. 2010) and proposed many heuristics to solve it.

A review of previous research suggests that the process of radio resource assignments can be formulated as finding a mapping from radios to channels/links (radio-centric) (Raniwala et al. 2004, Ramachandran et al. 2006, Skalli et al. 2007, Marina et al. 2010) or from links to channels/radios (link-centric) (Subramanian et al. 2008, Rajakumar et al. 2008). Assignments can be traffic-aware (Raniwala et al. 2004, Jain et al. 2005, Skalli et al. 2007) or traffic-independent (Ko et al. 2007, Rajakumar et al. 2008). The former approach assumes that different links bear different amounts of traffic while the latter approach does not involve this assumption. Existing approaches may assume overlapping (Ko et al. 2007) or non-overlapping channels (Ramachandran et al. 2006, Rajakumar et al. 2008), or different interference models (protocol or physical (Gupta & Kumar 2000)).

This study attempts to maximize the number of operative links, where a link is operative if the radios at the two ends of the link share a common channel (i.e., are link-preserving) and experience sufficiently low co-channel interference (meeting the interference constraint). These two criteria are conflicting in nature. However, a link is operative only if the link-preserving requirement is met, and it becomes inoperative only when it experiences sufficiently high interference. Therefore, this study considers only the link-preserving requirement and treats co-channel interference as a performance metric to minimize rather than a requirement to meet in allocating radio resource to links. Minimizing co-channel interference increases the number of operative links, which in turn increases the number of routing paths between any pair of MPs and can thus alleviate congestion by distributing traffic among multiple routing paths.

This study assumes a fixed number of non-overlapping channels and adopts the physical interference model. The number of radios allocated to each node is assumed fixed and known, and all radios are identical. This study also considers the *tight radio constraint*, in which the number of radios per node is less than both the number of available channels and the number of links incident on each node. This study proposes a traffic-independent, link-centric channel assignment algorithm that meets the link-preserving requirement with the goal of maximizing operative links.

This study's contribution. The following points present a summary of the unique features that set this study apart from existing studies on multi-channel, multi-radio channel assignment problems.

- This study proposes a coordination-free rule for the link-preserving requirement. The correctness of this rule has been proven.
- This study presents a greedy channel assignment strategy that estimates the upper-bound and lower-bound interference that may occur in an assignment. This information significantly helps decide which channel to use throughout the whole decision process because the worst-case and best-case performance of any particular decision can be predicted.
- This study adopts the physical interference model (Gupta & Kumar 2000), which is more general than the widely-adopted protocol interference model.

The remainder of this paper is organized as follows: Section II presents background information and related research. Section III presents a greedy channel assignment approach with a special treatment to deal with the link-preserving requirement. Section IV presents an evaluation of simulation results of the proposed approach with other alternatives. Section V concludes the paper.

II. PRELIMINARIES

A. Background

A WMN includes both a wireless access network and wireless backhaul network. This study assumes that the wireless access network uses a wireless technology or spectrum unlike that used in the wireless backhaul network (e.g., 802.11g and 802.11a). Thus, no communication in the access network interferes with that in the backhaul network. This study considers only channel assignments for the backhaul network and assumes all channels are non-overlapping (i.e., no interference from adjacent channels is expected). Other channel assignment schemes consider adjacent channel interference (Ko et al. 2007).

To help achieve a clear formulation of the channel assignment problem, this study formally defines three entities in WMNs: nodes, radios, and links. A *node* is an MP in the wireless backhaul network. A *radio* is a wireless interface that can operate on one channel at a time. A node can be equipped with multiple radios, allowing for parallel communications with several other nodes.

The term *link* is used ambiguously in previous studies. Most researchers consider only *physical links*. A physical link exists between two nodes when these two nodes are within transmission range of each other. This definition only considers the received signal strength. Therefore, this study defines *designated links* (generally paraphrased as virtual links (Raniwala et al. 2004, Skalli et al. 2007)), which are a given subset of physical links to be assigned channels. Many studies implicitly assume the identity between physical links and designated links, but this assumption is not always accurate.

Let N be the set of all nodes in a WMN. For each node $i \in N$, let R_i be the set of i's radios, let K_i be the set of channels available to i, and let L_i be the set of designated links incident on i which are to be assigned channels. Let (i,j) denote the physical link from some node i to another node j, and let D be the set of all designated links. In this case, $L_i = \{(i,j)|(i,j) \in D\}$. Define $f_i : L_i \rightarrow K_i$ as a function that assigns one channel to each designated link incident on node i. The goal of this study is to find f_i for each $i \in N$ to meet the following two conditions:

- *Link-preserving requirement.* This demands that the two end nodes of each designated link must allocate a common channel to this link. Formally,

  $$\forall i,j \in N : (i,j) \in D \Rightarrow f_i(i,j) = f_j(i,j). \tag{1}$$

  A designated link (i,j) for which (1) holds is a *committed link*. Let $C = \{(i,j)|(i,j) \in D \wedge f_i(i,j) = f_j(i,j)\}$ be the set of all committed links determined by a channel assignment. The link-preserving requirement demands that $D = C$ after assignment.
- *Interference constraint.* Interference experienced by each designated link must be sufficiently low. Committed links that meet the interference constraint are called *operative links*. Fig. 1 shows the relationship among these four types of links.

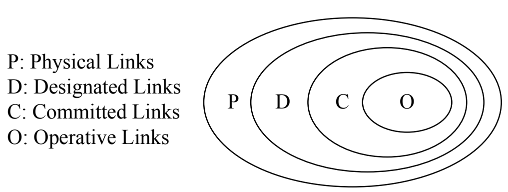

Fig. 1. Relationship among various types of links.

An alternative to the link-preserving requirement is *connectivity* requirement, which demands that the whole network must remain connected (not partitioned) despite the possible existence of some designated links that are not committed. Provided that the given set of designated links forms a connected network, the connectivity requirement is weaker than the link-preserving requirement because the latter implies the former, but not vice versa.

Concerning the interference constraint, this study assumes that a unidirectional transmission from i to j is successful only if the ratio of the received signal strength to the aggregated interference intensity from all other transmitters plus background noise (i.e., signal to interference plus noise ratio or SINR) exceeds some threshold t_s. SINR values can be obtained by theoretical modeling (Gupta & Kumar 2000) or field measurements. Let $F_i(k)$ be an indicator variable defined as

$$F_i(k) = \begin{cases} 1 & \text{if } k \in f_i(L_i), \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

Let $I_{i,j}(k)$ denote the SINR value of i's transmission received at node j when (i,j) operates on channel k. This study adopts the theoretical model by Gupta & Kumar (2000) and defines $I_{i,j}(k)$ as

$$I_{i,j}(k) = \frac{S_{i,j}}{\sum_{l \in N-\{i,j\}}(S_{l,j} \cdot F_l(k)) + N_a}, \tag{3}$$

where $S_{i,j}$ is the signal strength of i's transmission received at j and N_a denotes background noise. This study uses the Friis Free Space Model (Friis 1946) to compute the signal strength $S_{i,j}$, but other models or estimations can also be used.

Because this study investigates bidirectional links, the set of operative links after the assignment can be formulated as $O = \{(i,j)|(i,j) \in C \wedge$

$I_{i,j}(f_i(i,j)) \geq t_s \wedge I_{j,i}(f_j(i,j)) \geq t_s\}$. The goal of this study is to maximize $|O|$.

Channel allocations are typically subject to other constraints. Let $r_i = |R_i|$, $k_i = |K_i|$, and $l_i = |L_i|$ for each $i \in N$. Channel constraint assumes that k_i is limited while radio constraint places an upper limit on r_i. The tight radio constraint considered in this study states that $r_i < \min(k_i, l_i)$ for each i. This reflects a practice setting in which the number of radios each node has is usually less than the number of channels available to the node or the number of designated links incident on the node. The next section shows how the proposed approach treats the tight radio constraint.

B. Related Work

Researchers have proposed many approaches to the channel assignment problem in multi-radio, multi-channel WMNs. These approaches differ in their assumptions, constraints, and objectives. In traffic-aware methods, the objective can be to maximize overall system throughput or achieve a balanced traffic load subject to the link-capacity constraint (i.e., the total traffic load placed on a radio link must not exceed its capacity.) Traffic load information can help determine link priority in channel assignments, but it does not further complicate the problem. Thus, this study considers only traffic-independent approaches.

Previous methods commonly use two link interference models to estimate link interference: the *protocol model* and the *physical model* (Gupta & Kumar 2000). In the protocol model, a unidirectional transmission from i to j is considered successful if no other transmitters are located within some physical distance (which leads to the notion of *interference range*). Many researchers consider variants of this model that do not require physical distance information. For example, a link can be considered interfering with another if these two links share a common end (Kodialam & Nandagopal 2003) or one end of the first link is within some hops from one end of the second (Ko et al. 2007). Regardless of the exact definition, a common property associated with the protocol model is that the interference relation is Boolean, binary, and symmetric. Consequently, whether a link is operative can be checked by examining its interference relation with every other link in a pair-wise manner.

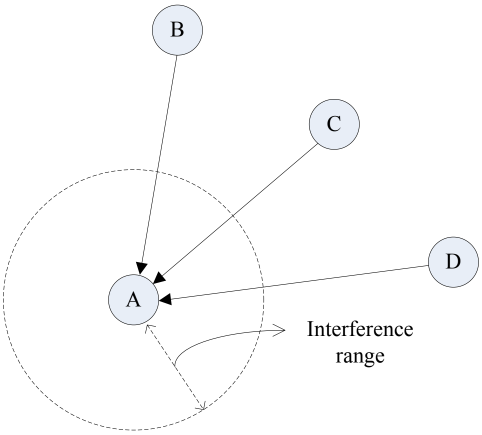

Fig. 2. An interference scenario that cannot be captured by the protocol model.

In the physical model, whether a link is operative is collectively determined by its relationship with all other links, and not by the presence or absence of a single neighboring link. The interference relation defined by this model is usually asymmetric, non-Boolean, and not binary. The SINR interference model adopted by this study is a physical model. The protocol model generally views interference from the MAC layer and above, and concerns phenomena such as transmission collision and bandwidth contention. In contrast, the physical model primarily considers physical-layer effects such as degraded signal quality and increased bit error rate. Most researchers follow the protocol model (Si et al. 2010) while this paper considers the Physical Model. The physical model is more general than the protocol model because the physical model is independent of the MAC layer and because the protocol model cannot capture some interference scenarios. For example, consider the scenario shown in Fig. 2, where three nodes B, C, and D can collectively interfere with the receptions of packets at Node A. However, none of these nodes alone interferes with Node A under the protocol model.[1]

Interference can be represented by a framework called a *conflict graph* (Jain et al. 2005), in which vertices represent links and edges represent the interference between links. The protocol model transforms the problem of seeking an interference-free channel assignment into a vertex coloring problem on the conflict graph. This problem and its variants

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[1] This example assumes the notion of interference range, but the conclusion also applies to other variants that assume binary interference relation.

are NP-hard (Raniwala et al. 2004, Jain et al. 2005, Subramanian et al. 2008, Marina et al. 2010). Conflict graphs can also be extended to represent interference in the physical model, where each edge is labeled with some number that quantifies the degree of interference associated with that edge.[2]

Tam & Tseng (2007) assumed that each MP has a single radio interface when multiple channels are available. These channels are utilized by dividing link-layer transmission time into fixed-size time slots and scheduling the transmission and reception slots to reduce possible co-channel interference among nearby transceivers. Combined with multipath routing, the proposed approach significantly improves end-to-end throughput. However, this approach demands network-wide tight time synchronization, which is not easy to achieve. The incurred channel switching delay also may not be neglected for some applications.

The simplest approach to multi-channel multiradio channel assignment is common-channel assignment (CCA) (assumed in Adya et al. 2004), which assigns Channel 1 to the first radio interface of each node, Channel 2 to the second radio interface of each node, and so on. This approach requires no coordination among nodes and retains network connectivity (when committed links are of concern). However, it also leads to a high degree of interference. Therefore, CCA usually serves as a baseline for performance comparison.

Ko et al. (2007) considered interference caused by overlapping channels and modeled it using the protocol model. They proposed a distributed algorithm to minimize local interference level subject to the channel constraint, the radio constraint, and the connectivity requirement. To guarantee network connectivity, each node must reserve a radio interface to operate on a default channel.

Some studies considered traffic-aware channel allocations. Gardellin et al. (2011) attempted to maximize minimum residual link capacity considering both traffic condition and physical-layer interference. The proposed approach consists of two phases. The first phase uses divide-and-conquer technique to reduce computational complexity of the problem while the second phase fixes potential dis-connectivity of network topology that may arise after the first phase. Chakchouk & Hamdaoui (2011) proposed a traffic-aware interference-free scheduling that uses channel switching to deal with the tight radio constraint. The objective of this work is to increase the capacity of active links (links with traffic loads).

Rajakumar et al. (2008) assumed the physical model and extended conflict graphs to represent the degree of interference between each link pair. They assigned a channel to a link if and only if the resulting interference is below a threshold. After channel assignment, all designated links that are not yet assigned channels are replaced by free-space optical links. They applied a generic algorithm to minimize the number of required optical links. However, this approach does not consider radio constraint, and fails to deal with the case when the number of channels assigned to a node exceeds the number of available radio interfaces.

Subramanian et al. (2008) adopted the protocol model and used conflict graphs to represent interference between link pairs. They modeled interference-free channel assignment as a node coloring problem in a conflict graph (which is NP-hand) and proposed a heuristic algorithm based on the tabu search (Hertz & de Werra 1987). The goal of this approach is to minimize the overall network interference subject to the link-preserving requirement with the channel constraint and the radio constraint. When the number of channels assigned to a node exceeds the number of radio interfaces available to a node, channels must be merged to meet the radio constraint. This is in contrast to Rajakumar et al. (2008).

The study by Marina et al. (2010) has constraints and requirements similar to Rajakumar et al. (2008). However, it differs from Rajakumar et al. (2008) in its goal, which is to minimize the maximum interference in the network. The authors showed that this problem is NP-hard, and proposed a heuristic approach called connected low interference channel assignment (CLICA) that assigns channels to radios in a node-by-node manner. Each node in this approach is associated with a priority that determines the order of this node in the assignment. The priority may be altered during the assignment procedure to meet the link-preserving requirement.

Yang et al. (2012) considered the case that not every MP is under the same administration. Therefore, MPs have the motivation to maximize their own profits without respecting overall system per-

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[2] For example, interference between a pair of links in (Padhye et al. 2005) is defined as the throughput degradation ratio of one link with respect to the other.

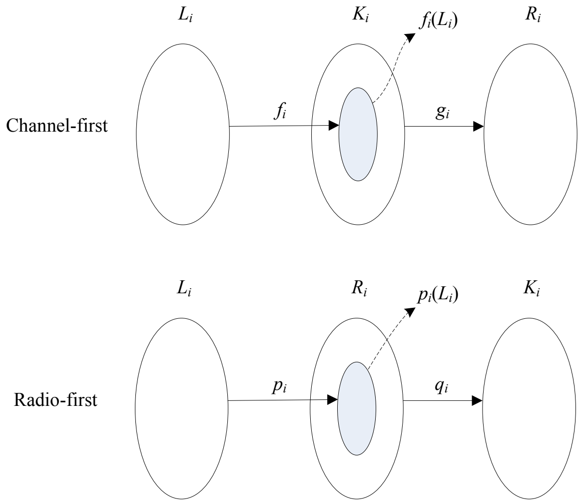

Fig. 3. Two possible mappings of link-centric channel assignments

formance. The authors proposed a game-theoretic approach to channel allocations in this setting. The proposed approach assumes an interference model that is defined on pairs of links (e.g., the protocol model).

III. The Proposed Approach

A. *On the Tight Radio Constraint*

Both radios and channels are essential radio resources for designated links to operate. A link-centric resource allocation can be modeled as a composition of two mappings (functions), depending on which resource (radio or channel) is assigned first. The first composition, $g_i \circ f_i$, corresponds to *channel-first* assignments, in which functions $f_i : L_i \to K_i$ and $g_i : K_i \to R_i$ are defined for each node i. The second composition, $q_i \circ p_i$, models *radio-first* assignments, in which $p_i : L_i \to R_i$ and $q_i : R_i \to K_i$ are also defined by assignments for each node i (Fig. 3).

Using the physical model, this study adopts the link-centric, channel-first assignment strategy. Therefore, it is necessary to define f_i and g_i for every node i. Neither channel switching nor the default-channel convention should be used in the solution. The goal is to maximize the number of operative links under the tight radio constraint while meeting the link-preserving requirement. Consider the following observations regarding the problem at hand:

- Radios are the scarcest resource under the tight radio constraint. Therefore, to fully utilize available radios, function $g_i \circ f_i$ must be onto, which implies that $g_i(f_i(L_i)) \equiv R_i$ or, equivalently, $|g_i(f_i(L_i))| = r_i$.
- The tight radio constraint states that $r_i < \min(k_i, l_i)$ for each i. If there is any f_i for which $|f_i(L_i)| > r_i$, then the mapping from $f_i(L_i)$ to R_i cannot be one-to-one and we must face the difficulty of letting these $|f_i(L_i)|$ channels share r_i radios. Although some techniques can cope with this condition (for example, channel switching (Bahl et al. 2004, So & Vaidya 2004)), we should preclude this condition to simplify the assignment problem.

These observations suggest that $f_i(L_i) \to R_i$ should be one-to-one and onto. Therefore, the proposed approach intentionally limits the number of channels that can be assigned to links of node i by r_i. That is,

$$\forall i \in N : |f_i(L_i)| = r_i, \tag{4}$$

which ensures that the mapping from $f_i(L_i)$ to R_i can be one-to-one for each i. To make this mapping onto as well, each channel in $f_i(L_i)$ should be assigned a different radio. The exact mapping from $f_i(L_i)$ to R_i does not matter in terms of interference because all radios are identical. However, the mapping may have effects on the link-preserving requirement, as the following discussion shows.

B. *On The Link-Preserving Requirement*

Recall that to make $f_i : L_i \to K_i$ one-to-one and onto for all node i, every radio of a node must be assigned to a different channel. However, this condition alone cannot ensure the link-preserving requirement. Consider the scenario shown in Fig. 4. Suppose that nodes d and j both have two radios, and have already been allocated channel sets $\{1, 2\}$ and $\{3, 4\}$, respectively, for their links. Thus, there will be no available radios/channels for assigning the link (d, j).

The key point is this: we should limit not only *the number of* channels that can be allocated to each node (as (4) specifies), but also *the range of* allocatable channels. Based on the range constraint, the following theorem shows that the link-preserving requirement can be guaranteed.

Theorem 1: Assume that every radio of the same node is assigned to a different channel. If each node i limits the set of channels that it can choose to

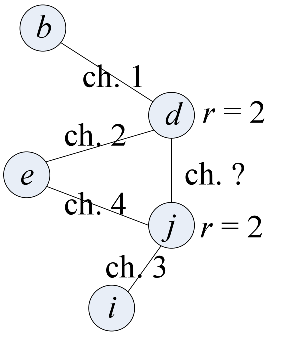

Fig. 4. A scenario where the link-preserving requirement is not met.

$K'_i = \{c_1, c_2, \cdots, c_u\}$, where

$$u = \min_{(i,j) \in D} \{r_i + r_j - 1\}, \tag{5}$$

then every designated link becomes a committed link.

Proof: Suppose, by way of contradiction, that every node limits the available channel set to that indicated by (5) but there exists some designated link (i, j) that is not committed. Let $m = (r_i + r_j - 1)$, $K'_i = \{c_1, c_2, \cdots, c_u\}$, and $K'_j = \{c_1, c_2, \cdots, c_v\}$. By definition, $|K'_i| = u \leq m$, $|K'_j| = v \leq m$ and $K'_i \cup K'_j \subseteq \{c_1, c_2, \cdots, c_m\}$. Because every radio of the same node is assigned to a different channel, node i must choose r_i out of u channels from the set $\{c_1, c_2, \cdots, c_u\}$ and node j must choose r_j out of v channels from the set $\{c_1, c_2, \cdots, c_v\}$. Let C_i and C_j be the sets of channels chosen by i and j, respectively. Thus, $|C_i| = r_i$ and $|C_j| = r_j$. Because (i, j) is not a committed link, it implies that $C_i \cap C_j = \phi$. By the inclusion-exclusion principle

$$\begin{aligned} |C_i \cup C_j| &= |C_i| + |C_j| - |C_i \cap C_j| \\ &= r_i + r_j - 0 \\ &= r_i + r_j. \end{aligned} \tag{6}$$

On the other hand, since $C_i \subseteq K'_i$ and $C_j \subseteq K'_j$, we have

$$|C_i \cup C_j| \leq |K'_i \cup K'_j| \leq m = r_i + r_j - 1, \tag{7}$$

which contradicts (6), completing the proof. ■

Figure 5 shows an example of applying this rule to a given WMN.

The method closely related to the proposed approach is the Tabu-based approach (Subramanian et al. 2008), which is also link-centric. The Tabu-based approach includes two phases. The first phase assigns channels to links with the goal of minimizing interference but without worrying about the radio constraint. The second phase processes all nodes in which the radio constraint is violated after the first phase, adopting a channel-merging procedure that may cause chain reactions to other nodes. In contrast, the proposed approach simply *prevents* any violation of the radio constraint when assigning channels to links.

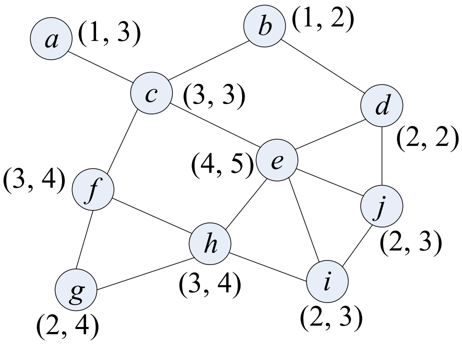

Fig. 5. An example of applying the link-preserving rule to a WMN. The number pair (r, u) associated with each node indicates the number of radios the node is given (r) and the maximum channel number the node can use (u) indicated by (5).

C. *On Interference Minimization*

This subsection presents a link-centric, channel-first channel assignment algorithm with the objective of maximizing the number of resulting operative links. The proposed approach assigns channels and radios to links on a link-by-link basis. Theorem 1 indicates that the link-preserving requirement is met provided that the constraint specified by (5) is always respected. The validity of this theorem has nothing to do with the order in which channels/radios are assigned to links. However, this order does affect the result of assignments. If different links have different traffic loads, the proposed approach can seek an optimal assignment order that maximizes overall throughput. This means the proposed approach can be easily modified to be load-aware. This study does not assume any load information and attempts to minimize resulting interference. The proposed approach is a greedy design in the sense that among all possible channel assignments, it first considers the one that leads to the highest SINR. The only problem is that it is necessary to estimate the resulting SINR for a particular channel assignment.

It is only possible to roughly estimate, and not accurately measure, the resulting SINR for a particular assignment because in general only partial information is available for an accurate measurement at the time of the assignment. The computation of $I_{i,j}(k)$ considers interference from all other nodes l for which $F_l(k) = 1$, as indicated by (3). Whereas $F_l(k) = 1$ implies the assignment of channel k to node l, $F_l(k) = 0$ at some particular moment during the assignment process only means that k has *not yet* been assigned to l. The eventual value of $I_{i,j}(k)$ can be degraded if l is subsequently assigned channel k. Therefore, an assignment based on $I_{i,j}(k)$ is *optimistic* because it ignores this possibility, and the exact SINR of (i, j) on channel k can be less than $I_{i,j}(k)$ after the channel assignment is completed.

To address this concern, this study also adopts a pessimistic estimation of link SINR that accounts for all potential interference. Let $G_i(k)$ be a variable indicating whether channel k has been or *can be* assigned to node i. This variable is defined as follows:

$$G_i(k) = \begin{cases} 1 & \text{if } k \in K'_i \text{ and } (F_i(k) = 1 \text{ or } \sum_k F_i(k) < r_i), \\ 0 & \text{otherwise.} \end{cases} \quad (8)$$

Intuitively, $G_i(k) = 0$ only when channel k cannot be assigned to node i. A *pessimistic* estimation can be defined by

$$J_{i,j}(k) = \frac{S_{i,j}}{\sum_{l \in N-\{i,j\}} (S_{l,j} \cdot G_l(k)) + N_a}. \quad (9)$$

This definition represents the SINR of (i, j) under the assumption that all other links not yet assigned channels will take channel k.

$I_{i,j}(k)$ (resp. $J_{i,j}(k)$) is generally different from $I_{j,i}(k)$ (resp. $J_{j,i}(k)$). When considering bidirectional links, take

$$N_{i,j}(k) = \min\{I_{i,j}(k), I_{j,i}(k)\} \quad (10)$$

and

$$M_{i,j}(k) = \min\{J_{i,j}(k), J_{j,i}(k)\} \quad (11)$$

as quality metrics. $M_{i,j}(k)$ and $N_{i,j}(k)$ are the lower bound (or the worst-case) and the upper bound (or the best-case) of the SINR of bidirectional link (i, j) on channel k, respectively, when considering the allocation of k to (i, j). The exact SINR value, which can only be obtained after the whole assignment is completed, falls between these two extremes.

Given $\{N_{i,j}(k)\}$ and $\{M_{i,j}(k)\}$ for every link (i, j) on every available channel k, how should we determine the order of links in assigning channels? This can be problematic because the values of $N_{i,j}(k)$ and $M_{i,j}(k)$ may diverge. Initially, $\forall i, k : F_i(k) = 0$, so $\forall i, k : G_i(k) = 1$. Therefore, the maximal value of $N_{i,j}(k) - M_{i,j}(k)$ for all (i, j) occurs in the very beginning of channel assignment. As channels are assigned to links, the difference between $N_{i,j}(k)$ and $M_{i,j}(k)$ diminishes. For the last link $l(i, j)$ in assignments, $N_{i,j}(k) = M_{i,j}(k)$ for all k.

Define $C_{i,j}(k)$ as follows for the priority of links in channel assignment. Formally,

$$C_{i,j}(k) = \left(\frac{\alpha - \beta}{\alpha}\right) M_{i,j}(k) + \left(\frac{\beta}{\alpha}\right) N_{i,j}(k), \quad (12)$$

where α is the number of designated links and β is the number of links that have already been assigned channels. Among all links that have not yet been assigned channels, the proposed approach selects the one that has the highest $C_{i,j}(k)$ value and assigns it channel k.

The rationale behind (12) is that $N_{i,j}(k)$ and $M_{i,j}(k)$ do not always have the same importance to (i, j). When most links are not yet assigned channels ($\beta \ll \alpha$), the worst-case estimation, $M_{i,j}(k)$, is given more weight than the best-case estimation $N_{i,j}(k)$ to reflect the concern of risk because there is still a lot of uncertainty in the future. Conversely, when most links have been assigned channels ($\beta \approx \alpha$), the worst-case estimation is given less weight than the best-case estimation. This setting attempts to maximize the best-case performance, which is hopeful because few links remain unassigned.

Recall that this approach adopts the link-centric, channel-first assignment strategy. This channel assignment rule defines the $f_i : L_i \to K_i$ function for each node i. For a complete solution, it is necessary to define the $g_i : K_i \to R_i$ function for each node i. That is, when allocating channel k to link (i, j), one dedicated radio at each node (i and j) is required to operate on the allocated channel. As a result of previous allocations, k may have already been allocated to node i or j, and have been assigned a radio. In this case, only the node for which k has not been previously allocated needs to arrange an available radio for k. It is also possible that all of i's or j's radios are already assigned to some channel other than k. In this case, simply skip the allocation of k to link (i, j). Link (i, j) can be assigned another channel in subsequent attempts. Algorithm 1 shows the detailed algorithm steps.

Algorithm 1 define_$f(N, D, K, \{r_i\}, \{S_{i,j}\})$

```
 1: for all $i \in N$ do
 2:     $u_i \leftarrow 0$    ▷ the number of $i$'s radios that have been used
 3:     Compute $K'_i$ as indicated by (5)
 4:     $F_i(k) \leftarrow 0$ for all $k \in K$
 5:     $G_i(k) \leftarrow 1$ for all $k \in K'_i$
 6:     $G_i(k) \leftarrow 0$ for all $k \in K - K'_i$
 7: end for
 8: $\Sigma \leftarrow \{(i,j,k) | (i,j) \in D \wedge k \in K'_i\}$
 9: $\alpha \leftarrow |D|$; $\beta \leftarrow 0$
10: while $\Sigma \neq \phi$ do
11:     for all $(i,j,k) \in \Sigma$ do
12:         Compute $M_{i,j}(k)$ and $N_{i,j}(k)$
13:         $C_{i,j}(k) \leftarrow \left(\frac{\alpha - \beta}{\alpha}\right) M_{i,j}(k) + \left(\frac{\beta}{\alpha}\right) N_{i,j}(k)$
14:     end for
15:     $(i,j,k) \leftarrow \arg\max_{(i,j,k) \in \Sigma}\{C_{i,j}(k)\}$
16:     if $(F_i(k) = 0 \wedge u_i = r_i)$ or $(F_j(k) = 0 \wedge u_j = r_j)$ then
17:         $\Sigma \leftarrow \Sigma - \{(i,j,k)\}$    ▷ skip channel $k$ for $(i,j)$
18:     else
19:         $f_i(i,j) \leftarrow k$; $f_j(i,j) \leftarrow k$    ▷ new definition
20:         if $F_i(k) = 0 \wedge u_i < r_i$ then    ▷ channel $k$ not yet used
21:             define_$g(i,k)$    ▷ assign channel $k$ to node $i$; refer to Algorithm 2
22:         end if
23:         if $F_j(k) = 0 \wedge u_j < r_j$ then    ▷ channel $k$ not yet used
24:             define_$g(j,k)$    ▷ assign channel $k$ to node $j$; refer to Algorithm 2
25:         end if
26:         $\beta \leftarrow \beta + 1$
27:         $\Sigma \leftarrow \Sigma - \{(i,j,k') | k' \in K'_i\}$    ▷ link $(i,j)$ done
28:     end if
29: end while
```

Algorithm 2 define_g(node i, ch k)

```
1: $F_i(k) \leftarrow 1$    ▷ channel $k$ is used by node $i$
2: $u_i \leftarrow u_i + 1$; $g_i(k) \leftarrow u_i$    ▷ assign a new radio to $k$
3: if $u_i = r_i$ then    ▷ $i$ has no more available radio
4:     for all $c \in \{k' | F_i(k') = 0\}$ do    ▷ so update $G_i$
5:         $G_i(c) \leftarrow 0$    ▷ $i$ will not use channel $c$
6:     end for
7: end if
```

The time complexity of the algorithm is dominated by the **for** loop between lines 11 and 14. Computing $M_{i,j}(k)$ or $N_{i,j}(k)$ (and thus $C_{i,j}(k)$) for a particular link (i,j) and channel k incurs a time cost of $O(|N|)$. Because the maximum size of Σ is $O(|D||K|)$, the **for** loop has an $O(|N||D||K|)$ time complexity. Therefore, the time complexity of the **while** loop enclosing the **for** loop is $O(|N||D|^2|K|^2)$, which also represents the time complexity of the algorithm. Some optimizations are possible. For example, instead of re-computing the interference from all other nodes for a particular link (i,j) and channel k every time the **for** loop is encountered, it is possible to add up all the interference changes caused by the previous assignment for each particular i, j, and k, and add this result to the original interference value. However, this optimization is not the primary focus of this algorithm.

IV. SIMULATION RESULTS

The simulations in this study compare the performance of the proposed algorithm with CCA (Adya et al. 2004), tabu-based (Subramanian et al. 2008), and CLICA (Marina et al. 2010). These approaches were chosen because they all meet the link-preserving requirement.[3] This common property ensures that comparisons can be made on a fair basis. This study also considers the possibility of assigning channels to links randomly subject to the constraint imposed by (5). This method, termed random when compared with others, meets the link-preserving requirement in Theorem 1, and has the potential to minimize interference because the channels in use are uniformly distributed.

All the algorithms compared here require a set of designated links as inputs. The counterparts all adopt the concept of transmission range to obtain a set of physical links and use this set for designated links. The proposed algorithm adopts the same assumption, but does not rely on it. The tabu-based and CLICA methods additionally require the setting of the interference range. In this case, our simulations assumed identical transmission and interference ranges as in Subramanian et al. (2008), Marina et al. (2010).

We varied the number of available channels k, the number of radio interfaces per node r, and the

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[3] This has been confirmed by our simulation results.

TABLE I
SIMULATION PARAMETER

Parameter	Value
Path loss model	Log-distance
Transmit power	15 dBm
Reference distance	1 m
Path loss at reference point	35 dB
Path loss exponent	3.0
Background noise	-95 dBm (Fu et al. 2008)

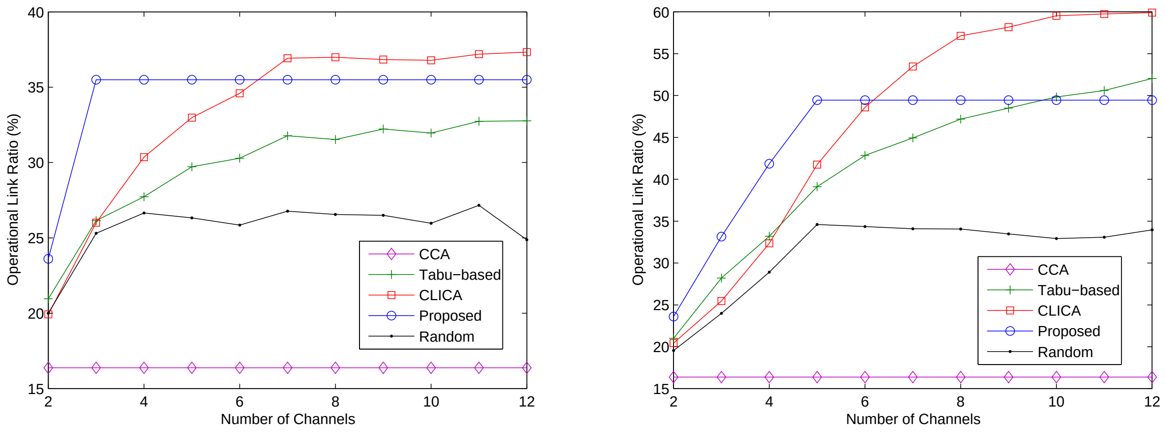
transmission range r_t in the simulations. Except for the last experiment, the transmission range was set to 25 m. For each transmitter-receiver pair, we use log-distance path loss model (Rappaport 2002) to calculate the received signal strength (RSS) given the distance between the transmitter and the receiver. After channel assignment is done, the RSS information together with background noise setting is then used to calculate the SINR of each link. Table I lists all related parameters.

This study investigates how many operative links can be yielded by different approaches. To this end, define *operative link ratio* (OLR) as the number of operative links divided by the number of total designated links. Concerning the interference constraint, OLR is affected by the setting of SINR threshold. The threshold value t_s in the simulations was set to 1 dB. Only when both ends of a link have a SINR value greater than t_s can the link be operative. The simulations involve 100 scenarios. In each scenario, 20 MPs were randomly placed in a 100×100 m^2 area. These scenarios served as our test cases, and the average of these cases was taken as the result.

First, r was fixed to observe how OLR changes with k. Fig. 6 shows the results with $r = 2$ and $r = 3$. The performance of CCA is irrelevant to k, which is justifiable because CCA performs identical channel assignment at all nodes, and at most one designated link counts between any pair of nodes. Other researchers have reported similar results (Marina et al. 2010). The proposed approach initially shows a linear increase. After a point, the availability of more channels does not further increase the OLR value, because the proposed algorithm places an upper bound on the number of usable channels (which is three when $r = 2$, and five when $r = 3$). Therefore, the proposed approach outperforms the CLICA and tabu-based methods only when $k \leq 6$. This trend changes when each node is provided with more radios. Fig. 7 shows the results when $r = 6$ and $r = 12$. When $r = 6$, the number of channels used by the proposed algorithm is limited to $(6 + 6 - 1) = 11$. Therefore, every channel is usable except for the case when $k = 12$ channels. This approach outperforms all counterparts except for the case of $k = 12$, in which the OLR value of the CLICA method is equal to ours. The superiority of our algorithm over its counterparts remains when r is increased up to 12. The performance of the random method is only better than that of the CCA method. The difference between the random approach and the proposed approach is the result of the proposed channel assignment algorithm.

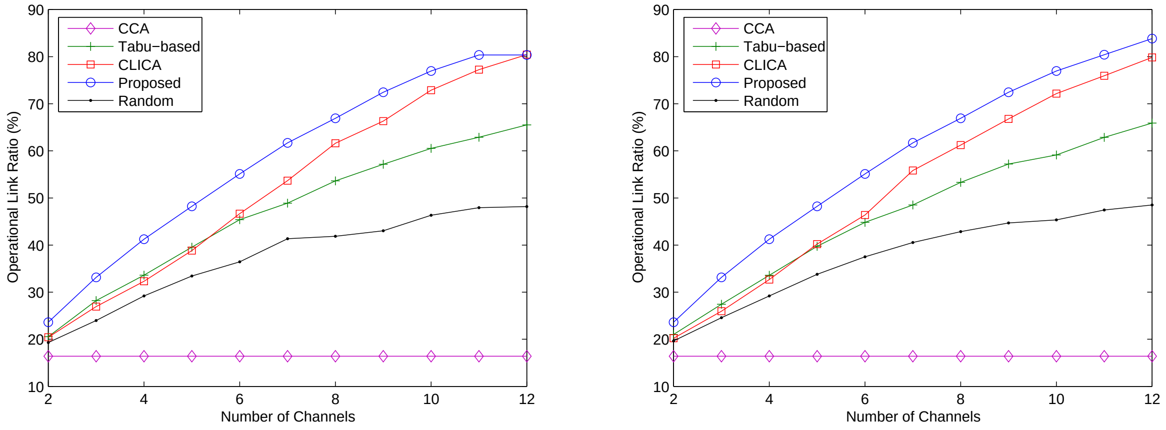
The next set of simulations fixed k to determine the relationship between r and OLR. When $k = 2$ or $k = 3$, more radios do not increase the OLR because of the lack of channel resource (Fig. 8), and the proposed approach performs the best. When the number of channels increases to six or 12, CLICA, the tabu-based approach, and the proposed approach all exhibit an increase in OLR with r initially, and a marginal improvement after the number of radios reaches some value (Fig. 9). In the case of six channels, the proposed approach performs the best. When 12 channels are available, the performance of the proposed approach is next to that of CLICA when $r \leq 6$. However, the proposed algorithm performs better than the others when $r \geq 7$.

The transmission range was also varied to alter the density of the designated links to determine how the performance of channel assignment schemes changes with the density of designated links. We fixed r to a typical value 3, and set k to 5 or 12. As Fig. 10 shows, the OLR values in all methods decreased as the transmission range increased. This trend is reasonable because a larger transmission range leads to a higher density of designated links, and thus, greater interference among transceivers. Consequently, fewer designated links become operative. The proposed algorithm and CLICA have comparable performance in this condition, and comprise the leading group. CLICA performs better than the proposed approach when there are enough channels ($k = 12$). However, the proposed approach outperforms CLICA when a limited number of channels is available ($k = 5$). The tabu-based method has a higher OLR compared with the random and CCA methods when the density of designated links is low, but its performance declines sharply with the link density. When the transmission range increases to



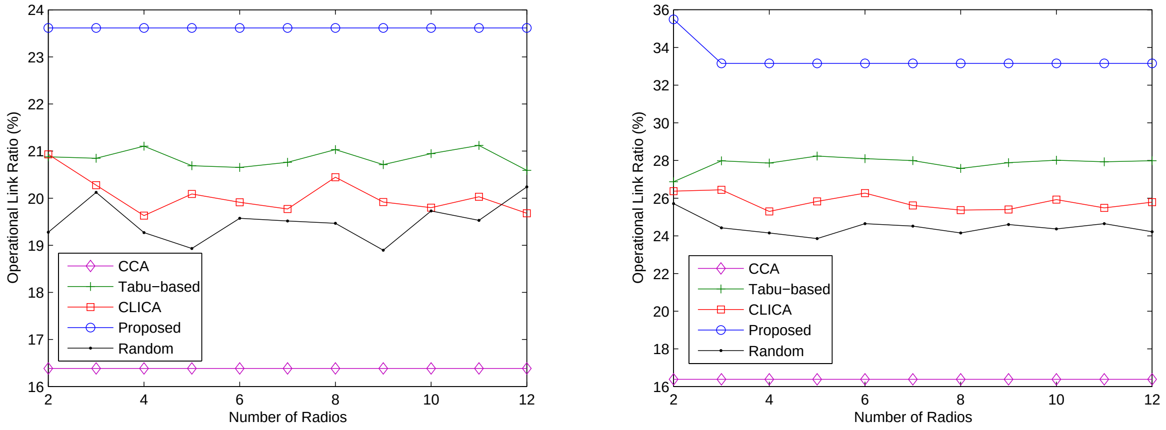
(a) (b)

Fig. 6. OLR versus the number of channels with (a) $r_i = 2$ and (b) $r_i = 3$ for all node i.



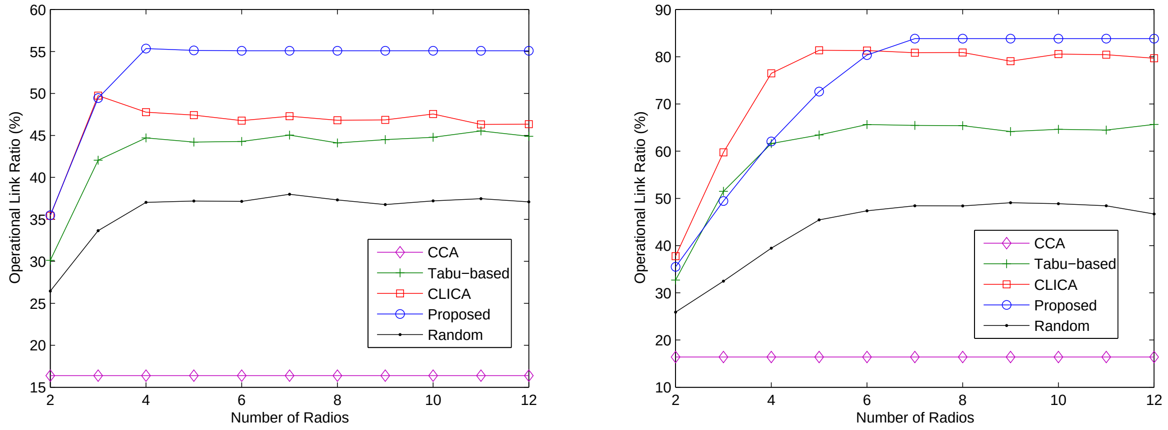
(a) (b)

Fig. 7. OLR versus the number of channels with (a) $r_i = 6$ and (b) $r_i = 12$ for all node i.



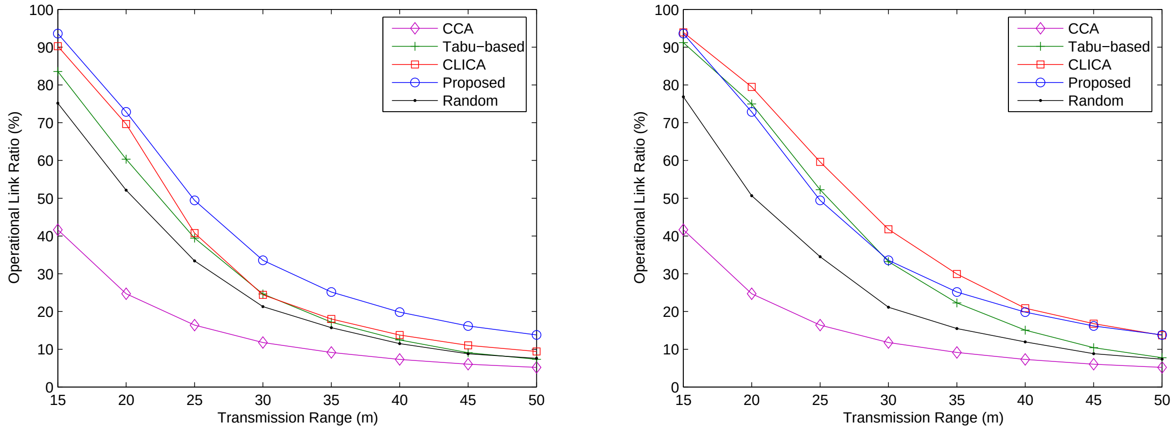
(a) (b)

Fig. 8. OLR versus the number of radios with (a) 2 channels and (b) 3 channels.



(a) (b)

Fig. 9. OLR versus the number of radios with (a) 6 channels and (b) 12 channels.



(a) (b)

Fig. 10. OLR versus transmission range with three radios (a) $k = 5$ (b) $k = 12$.

TABLE II
PERFORMANCE COMPARISONS IN TERMS OF OLR

Number of Radios	Number of Channels	
	Few	Many
Few	Ours $>$ Tabu-based $\geq$ CLICA	CLICA $>$ Ours $=$ Tabu-based
Many	Ours $>$ Tabu-based $>$ CLICA	Ours $>$ CLICA $>$ Tabu-based

50 m, the tabu-based OLR is close to that of the random or CCA method.

Table II presents a summary of the simulation results. This table does not include the CCA and random methods because these two methods are not recommended. This table shows that the proposed algorithm can increase the number of operative links when only a few channels or sufficiently many radios are provided. Its performance remains acceptable when many channels but only a few radios are available.

V. CONCLUSIONS

This study proposes a link-centric, channel-first radio resource assignment strategy that considers the physical interference model, tight radio constraint, and link-preserving requirement. This proposal for the link-preserving requirement under a tight radio constraint is simple because it prevents possible violation of the radio constraint during channel assignment rather than resolving violations after they occur. The proposed greedy channel assignment algorithm selects channels based on the predicted upper bound and lower bound of interference. The time complexity of the proposed approach is $O(|N||D|^2|K|^2)$, where N, D, and K are the set of all nodes, the set of all designated links, and the set of available channels, respectively. This time complexity is not low. Simulation results confirm the efficiency of this design in terms of operative link ratio. Compared with prior schemes, the proposed approach produces the highest number of operative links, particularly when only a few channels or many radios are available. When many channels but only a few radios are available, the proposed approach exhibits inferior performance because the proposed link-preserving rule may not fully utilize all available channels.

REFERENCES

Adya, A., Bahl, P., Padhye, J., Wolman, A. & Zhou, L. (2004), A multi-radio unification protocol for IEEE 802.11 wireless networks, *in* 'Proc. First Int'l Conf. on Broadband Networks', pp. 344–354.

Bahl, P., Chandra, R. & Dunagan, J. (2004), SSCH: Slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks, *in* 'Proc. 10th Int'l. Conf. on Mobile Computing and Networking', pp. 216–230.

Benyamina, D., Hafid, A. & Gendreau, M. (2012), 'Wireless mesh networks design: A survey', *IEEE Communications Surveys & Tutorials* **14**(2), 299–310.

Chakchouk, N. & Hamdaoui, B. (2011), 'Traffic and interference aware scheduling for multiradio multichannel wireless mesh networks', *IEEE Trans. on Vehicular Technology* **60**(2), 555–565.

Friis, H. T. (1946), 'A note on a simple transmission formula', *Proceedings of The Institute of Radio Engineers* **34**(5), 254–256.

Fu, B., Bernáth, G., Steichen, B. & Weber, S. (2008), Wireless background noise in the Wi-Fi spectrum, *in* '4th Int'l Conf. on Wireless Communications, Networking and Mobile Computing'.

Gardellin, V., Das, S. K., Lenzini, L., Cicconetti, C. & Mingozzi, E. (2011), 'G-PaMeLA: A divide-and-conquer approach for joint channel assignment and routing in multi-radio multi-channel wireless mesh networks', *J. Parallel Distrib. Comput.* **71**(3), 381–396.

Gupta, P. & Kumar, P. R. (2000), 'The capacity of wireless networks', *IEEE Trans. on Information Theory* **46**(2), 384–404.

Hertz, A. & de Werra, D. (1987), 'Using tabu search techniques for graph coloring', *Computing* **39**(4), 345–351.

Jain, K., Padhye, J., Padmanabhan, V. N. & Qiu, L. (2005), 'Impact of interference on multi-hop wireless network performance', *Wireless Networks* **11**(4), 471–487.

Ko, B.-J., Misra, V., Padhye, J. & Rubenstein, D. (2007), Distributed channel assignment in multi-radio 802.11 mesh networks, *in* 'Proc. IEEE WCNC', pp. 3978–3983.

Kodialam, M. & Nandagopal, T. (2003), Characterizing achievable rates in multi-hop wireless networks: The joint routing and scheduling problem, *in* 'Proc. 9th Int'l. Conf. on Mobile Computing and Networking', pp. 42–54.

Kyasanur, P. & Vaidya, N. H. (2005), Routing and interface assignment in multi-channel multi-interface wireless networks, *in* 'Proc. IEEE WCNC', pp. 2051–2056.

Marina, M. K., Das, S. R. & Subramanian, A. P. (2010), 'A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks', *Computer Networks* **54**(2), 241–256.

Padhye, J., Agarwal, S., Padmanabhan, V. N., Qiu, L., Rao, A. & Zill, B. (2005), Estimation of link interference in static multi-hop wireless networks, *in* 'Proc. 5th ACM SIGCOMM Conf. on Internet Measurement'.

Pathak, P. H. & Dutta, R. (2011), 'A survey of network design problems and joint design approaches in wireless mesh networks', *IEEE Communications Surveys & Tutorials* **13**(3), 396 –428.

Rajakumar, V., Smadi, M. N., Ghosh, S. C., Todd, T. D. & Hranilovic, S. (2008), 'Interference management in WLAN mesh networks using free-space optical links', *Journal of Lightwave Technology* **26**(13), 1735–1743.

Ramachandran, K., Belding-Royer, E., Almeroth, K. & Buddhikot, M. (2006), Interference-aware channel assignment in multi-radio wireless mesh networks, *in* 'Proc. IEEE INFOCOM'.

Raniwala, A., Gopalan, K. & cker Chiueh, T. (2004), 'Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks', *ACM Mobile Computing and Communications Review* **8**(2), 50–65.

Rappaport, T. S. (2002), *Wireless Communications: Principles and Practice*, 2nd edn, Prentice Hall.

Si, W., Selvakennedy, S. & Zomaya, A. Y. (2010), 'An overview of channel assignment methods for multi-radio multi-channel wireless mesh networks', *J. Parallel Distrib. Comput.* **70**(5), 505–

524.

Skalli, H., Ghosh, S., Das, S. K., Lenzini, L. & Conti, M. (2007), 'Channel assignment strategies for multiradio wireless mesh networks: Issues and solutions', *IEEE Communications Magazine* **45**(11), 86–93.

So, J. & Vaidya, N. H. (2004), Multi-channel MAC for ad hoc networks: Handling multi-channel hidden terminals using a single transceiver, *in* 'Proc. 5th ACM Int'l Symposium on Mobile Ad Hoc Networking and Computing', pp. 222–233.

Subramanian, A. P., Gupta, H., Das, S. R. & Cao, J. (2008), 'Minimum interference channel assignment in multiradio wireless mesh networks', *IEEE Trans. on Mobile Computing* **7**(12), 1459–1473.

Tam, W.-H. & Tseng, Y.-C. (2007), Joint multichannel link layer and multi-path routing design for wireless mesh networks, *in* 'Proc. IEEE INFOCOM', Anchorage, AK, pp. 2081–2089.

Yang, D., Fang, X. & Xue, G. (2012), Channel allocation in non-cooperative multi-radio multichannel wireless networks, *in* 'Proc. IEEE INFOCOM', Orlando, Florida USA.