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HIQP: A HIDDEN NODE AND INTERFERENCE AWARE CHANNEL ASSIGNMENT SCHEME FOR MULTI-RADIO MULTI-CHANNEL WIRELESS MESH NETWORKS

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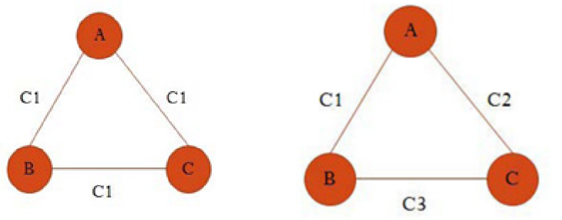
Abstract. *Carrier sense interference and hidden terminal problem are two critical factors, which limit the performance of wireless mesh networks. In order to increase the throughput of the network, multi-radio and multi-channel technology has been put forward to address this problem, since more channels can be used simultaneously to avoid collisions. In this paper, we propose "HIQP", a new scheme for hidden node and interference aware channel assignment, in which both hidden terminal problem and carrier sense interference are taken into consideration. This scheme is put forward in the link layer instead of network layer, which is a pre-determined approach. Our simulation results show that this optimum channel assignment scheme which has the least carrier sense interference and hidden terminal problem will be proposed before the establishment of network infrastructure.*
Keywords: WMNs, Hidden terminal problem, Carrier sense interference, Channel assignment, Pre-determined

1. **Introduction.** Wireless Mesh Networks (WMNs) have attracted a lot of attention due to the wide coverage, convenient access and robustness. They are multi-hop wireless networks which are composed of wireless mesh routers (MRs) and mesh end devices. Since the capacity of single-radio mesh networks is seriously affected by the nature of half-duplex of the wireless medium [1], multi-radio and multi-channel wireless mesh networks are widely noticed [2, 3]. In multi-radio multi-channel WMNs, how to assign the appropriate channels to appropriate radios to maximize the throughput of network is a key problem. A simple way to realize multi-radio and multi-channel is to make use of static channel assignment. However, with the increased number of wireless APs, the adjacent AP might use the same channel as well, which will cause conflictions [4, 5, 18] mainly resulting from two major problems, Carrier Sense Interference and Hidden Terminal Problem [5, 16, 17, 18]. The former problem is caused by interferences among nodes within the same carrier sense range. The problem will happen when a pair of nodes on a path communicates towards a common destination, which is called intra-flow interference, or among nodes on adjacent paths involved in different flows, which is called inter-flow interference [7]. The



(a) (b)

FIGURE 1. Single radio and single channel (a). Only one link can be used at one time; multi-radio and multi-channel (b). Three links can be used at the same time because they use different channels.

latter problem occurs when a node is visible from a wireless access point (AP), but not from other nodes communicating with the AP [8]. In this paper, we explore our model in the link layer and try to find the relations of the collisions between links according to carrier sense interference (CS) and hidden terminal problems (HD) and investigate an optimal channel assignment which has the fewest collisions. To the best of our knowledge, our work is the first to incorporate the hidden terminal problems in channel assignment for multi-radio multi-channel WMNs and to predetermine the network to avoid carrier sense interference and hidden terminal problem as much as possible. Intuitively, when we reduce the effects of carrier sense interference and hidden node interference together, the throughput will be increased a lot. Based on this idea, we state the motivated examples to explain the importance of research on channel assignment in multi-radio multi-channel WMNs.

1.1. **Motivation examples.** Generally, there are two motivating examples, which are shown as follows:

1. Single radio and single channel, which is shown in Figure 1(a). There are 2 characteristics in this case:
   - Three nodes (A, B, C) use the same channel C_1.
   - Only one link is allowed to be used simultaneously.

   The total capacity[1] equals the capacity of one channel.
2. Multi-radio and multi-channel, which is shown in Figure 1(b). The characteristics of this channel model are as follows:
   - Three nodes (A, B, C) and three channels (C_1, C_2, C_3).
   - Every node has two radios.
   - More than one orthogonal channels can be used simultaneously.

   The total capacity equals 3 times of the capacity of one channel.

According to the description of above two examples, we can obtain that the capacity of WMNs can be improved significantly with multi-radio and multi-channel.

1.2. **Contributions.** In this paper, our main contributions are summarized as follows:

- We consider the collisions resulting from both carrier sense interference and hidden terminal perspective and introduce a tunable parameter β to balance the collisions between carrier sense interference and hidden terminal problem to get the best channel assignment scheme.

[1] Network capacity is the maximum capacity of a link or network path to convey data from one location in the network to another.

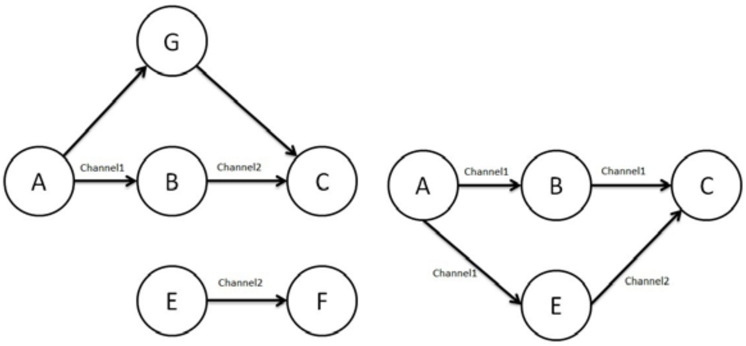
- We come up with an approach to predetermining the establishment of the networks which have the least collisions caused by carrier sense interference and hidden terminal problems.
- We validate the effectiveness of our proposed channel assignment scheme with extensive simulations. Both random topological networks and grid networks are evaluated.

1.3. **Paper organization.** The rest of this paper is organized as follows. Section 2 introduces the related work. Section 3 presents the problem statement. Our proposed approach is explored in Section 4. We evaluate the proposed approach with simulations in Section 5. Section 6 concludes this paper.

2. **Related Work.** Many algorithms have been proposed to improve the channel throughput. In summary, there are three kinds of optimal models for channel assignment: 1) Minimizing the interference of network; 2) Increasing the bandwidth of link; 3) Increasing the bandwidth of dataflow from point to point. The last two methods are performed in network layer and only meet the capacity of the network (Bandwidth), and the first one is an optimal plan working in link layer. Most previous work mainly focused on the carrier sense interference when proposing a channel assignment model. But the past recent years' researches [9, 10] show that carrier sense interference had been over estimated. In fact, the degradation resulting from carrier sense interference is not as serious as previous understanding. The literature [7] shows the hidden terminal problem, actually, has much more severe effects on the performance degradation than the carrier sense interference. The existing literature usually ignores that the hidden terminal problem is an important factor which needs to be considered when designing the channel assignment. Besides, fewer researches care about establishing networks before consideration of collisions. In our opinion, predetermined network is quite important because potential collisions should be avoided in advance.

An integer linear programming (ILP) model, proposed by A. Das et al. [11], tries to maximize the number of links being active simultaneously based on the assumption that each node has the same number of radios. Kyasanur et al. [12] studied multi-radio mesh networks, assuming that the network can switch interface from one channel to another dynamically without considering the traffic characteristics. Draves et al. [13] investigated multi-hop multi-radio mesh networks and introduced WCETT which is implemented in Multi-Radio Link-Quality Source Routing (MR-LQSR), where all nodes were assumed to be stationary. The channel assignment can be predetermined as well. Their results show that classical shortest path routing is not appropriate when multiple radios are deployed. Kim et al. [15] proposed a genetic algorithm-based dynamic channel allocation scheme. The goal of their paper is to maximize throughput and to minimize outage at the same time by seeking optimal channel allocation for a new call with the aim of minimizing interference to an existing call due to channel allocation for a new call. To achieve this goal, the dynamic channel allocation scheme was proposed to find the best combination from all calls, channels and cells when new call requests channel allocation. However, it needs exponential search spaces and becomes a NP-hard problem. Dase et al. [14] proposed a Multiple Access Control (MAC) protocol for multiple radios, using an extra busy tone interface. However, the paper does not show the number of radios which should be used. Das et al. [19] minimized total network interference to solve the problem of assigning channels to communication links in the network. However, they did not consider the interference brought in by both carrier sense interference and hidden terminal problem. D. Hammash et al. [7] took both carrier sense interference and hidden terminal problem into account and proposed a HIAM-Based routing protocol, with which routing stability and throughput can be higher and control packet overhead can be lower than existing approaches. However, they do not consider avoiding collisions before the establishment of the network firstly. Xie et al. [18] proposed LWDCA, a distributed static channel allocation algorithm based on the weight of link-load and link-potential interference degree for WMNs. Their algorithm not only can adapt the states of uniform or non-uniform distributed traffic, but also can increase network throughput and improve network performance. Unfortunately, they also ignored the collisions caused by hidden terminal problem. To the best of our knowledge, most related work only investigated carrier sense interference for channel assignment, but we incorporate both the hidden terminal problem and the carrier sense interference in our channel assignment.

3. **Preliminaries and Problem Statement.** In this section, we first explain the carrier sense interference and hidden terminal problem with some scenarios. Further, we show that the throughput, and interference caused by hidden terminal problem is more serious than that caused by carrier sense. Finally, the problem statement is given.



(a) Inter-flow interference (b) Intra-flow interference

FIGURE 2. Example of carrier sense interference. If link AD and link AB use the same channel, they cannot transmit data at the same time.

3.1. **Carrier sense.** As what has been mentioned, carrier sense interference is mainly caused by inter-flow and intra-flow interference. Figure 2 illustrates the examples of inter-flow and intra-flow interference. Inter-flow interference is shown in Figure 2(a). If two paths flows, *A*-*B*-*C* and *E*-*F*, exist at the same time, since both path *B*-*C* and path *E*-*F* are assigned channel 2 and *B* is within the carrier sense range of *E*, collisions will happen in this case. For better performance, path *A*-*G*-*C* should be used instead of path *A*-*B*-*C*. Figure 2(b) describes intra-flow interference. In this situation, both flows from *A* to *B* and *B* to *C* are assigned channel 1, which results in that flow from *A* to *B* and flow from *B* to *C* cannot exist simultaneously. Therefore, to avoid the collision, path *A*-*E*-*C*

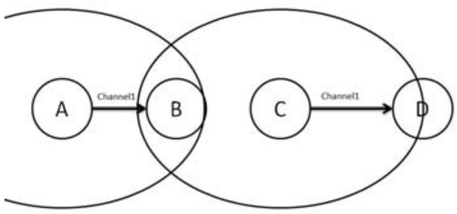


FIGURE 3. Example of hidden terminal problem. If link AD and link AB use the same channel, they cannot transmit data at the same time.

is better, because flows from A to E and E to C are assigned channel 1 and channel 2, respectively. Both flows work at the same time and carrier sense interference is avoided.

3.2. **Hidden terminal problem.** Hidden terminal problem is shown in Figure 3. Node A transmits data to B while C transmits data to D. Node A is not aware of the flow from A to B because C is out of the carrier sense range of node A. Since both links use the same channel, when C transmits data to D, transmission from A to B will be seriously affected by C. Collisions, transmission latency as well as packet losses may happen. In the view of path A to B, path C to D is the hidden link.

3.3. **Challenge.** Since both carrier sense interference and hidden terminal problem exist in the WMNs, we have to design a novel channel assignment scheme with consideration of them to facilitate the improvement of capacity of the network.

3.4. **Problem statement.** In this section, we first give the formalism of a network, and then we present the problem description by the form of input, objective and constraints.

Definition 3.1. *A network can be modeled as an undirected, bilateral communication graph* $G = (S \cup \{GW\}, E)$*. Here* GW *denotes the gateway. Given a host(node)* u *and a host(node)* v*, there is a edge* (u, v) *in* E *if and only if* $r_u \geq dis(u, v)$ *and* $r_v \geq dis(u, v)$ *where* r_u *is the radio range of host* u*,* $dis(u, v)$ *is the Euclidean distance between host* u *and host* v*. In this case,* $v \in S_N(u)$ *if and only if* $u \in S_N(v)$*,* $S_N(u)$ *indicates the neighbor set of host* u *in an undirected bilateral graph.*

In this paper, we mainly study the grid network. Hence, the problem is formally described as follows:

Input: A topology of a grid network G that consists of a gateway and a number of hosts, and the number of orthogonal channels *(C)* and the number of radios *(R)*.

Objective: Assign C channels to a number of sender hosts (including the source hosts and the forwarding hosts on the routing paths from the source hosts to the gateway) to maximize the network throughput.

Constraints: In multi-radio WMNs, there are two limitations on channel assignment.

1. Number of channels. Each link is assigned for a channel.
2. Number of radios on each node should be more than the number of channels.

$$N(Channel) \leq N(Radio), \text{ i.e., } C \leq R$$

If a channel meets the above two limitations, then it is a "feasible" channel. Since we may have many assignment plans, optimization of channel assignment is to select the best channel assignment from the "feasible" channels.

With better and more efficient channel assignment, we can minimize the collisions and maximize the throughput of the network in terms of carrier sense interference and hidden nodes problem. With multi-radio and multi-channel, transmission simultaneously can be realized and collisions can be avoided as much as possible. The target of this paper is to maximize the total throughput of the network by having optimal channel assignment to reduce collisions, in which both hidden node problem and carrier sense interference are considered.

This problem is inherently NP-complete. In next section, we will propose a novel scheme HIQP to solve this problem.

4. **Proposed Approach.** With our model, different kinds of schemes of channel assignment will be proposed. Each scheme will have different characteristics, e.g., throughput, interference caused by hidden terminal problem and carrier sense interference, packet loss. To find out the best scheme of channel assignment, we consider different channel assignment schemes and decide which one is the best. We make the assumption that the throughput only depends on the collisions from carrier sense interference and hidden terminal problem without the effects like packet loss rate, jitter, and delay and so forth.

Since it is difficult to avoid hidden terminal problem and carrier sense interference completely, what can be done is to minimize the total collisions to maximize the throughput of the network. Our approach is to keep the number of hidden terminal nodes smaller so that hidden terminal problem has fewer effects. And we also try to eliminate the carrier sense interference so that a trade-off between the CS nodes and HD nodes is made. Hence, we introduce a tunable parameter, $\beta \in [0, 1]$, to balance the effects caused by CS interference and hidden terminal problem. We assume an intuition that more CS nodes and less HD nodes will lead to higher capacity compared with that of more HD nodes and less CS nodes, even though we hope both the number of CS nodes and HD nodes can be decreased. If more CS nodes and less HD nodes contribute to the interference, the total capacity will be increased.

Our proposed model consists of two parts. The first part is CS interference and the latter part shows the effect of hidden terminal problem. We use β to adjust the total interference. When β changes to a certain value, the total collisions should be the fewest.

Definition 4.1. *Interference*

$$\begin{aligned}\Omega =& \frac{1}{L}\sum_{i=1}^{L}\beta\phi_i^{(CS)} + \frac{1}{L}\sum_{i=1}^{L}(1-\beta)\phi_i^{(HD)} \\ =& \frac{1}{L}\left(\beta\sum_{i=1}^{L}\sum_{j=1}^{L}I_{ij}^{'(CS)} + (1-\beta)\sum_{i=1}^{L}\sum_{j=1}^{L}I_{ij}^{'(HD)}\right)\end{aligned} \tag{1}$$

where β is a tunable parameter, L is the total number of links, $\phi_i^{(CS)}$ is the carrier sense interference, $\phi_i^{(HD)}$ is the hidden node interference. $I_{ij}^{'(CS)}$ is the CS nodes-based link collision matrix, $I_{ij}^{'(HD)}$ is the HD nodes-based link collision matrix.

Definition 4.2. *Node-Link Matrix*

$$S_{ij} = \begin{cases} 1, & v_i \textit{ is the vertex of } e_j, \\ 0, & \textit{otherwise.} \end{cases} \tag{2}$$

Definition 4.3. *CS Node-Based Potential Link Collision Matrix*

$$I_{ij}^{(CS)} = \begin{cases} 1, & e_i \textit{ is the neighboring link of } e_j, \\ 0, & \textit{otherwise.} \end{cases} \tag{3}$$

Definition 4.4. *HD Node-Based Potential Link Collision Matrix*

$$I_{ij}^{(HD)} = \begin{cases} 1, & e_i \textit{ is the 2-hop neighboring link of } e_j, \\ 0, & \textit{otherwise.} \end{cases} \tag{4}$$

Definition 4.5. *Link-Channel Assignment Matrix*

$$A_{jk} = \begin{cases} 1, & \textit{Channel } k \textit{ is assigned to } e_i, \\ 0, & \textit{otherwise.} \end{cases} \tag{5}$$

Minimize

$$\Omega = \frac{1}{L}\sum_{i=1}^{L}\beta\phi_i^{(CS)} + \frac{1}{L}\sum_{i=1}^{L}(1-\beta)\phi_i^{(HD)}$$
$$= \frac{1}{L}(\beta\sum_{i=1}^{L}\sum_{j=1}^{L}I_{ij}^{'(CS)} + (1-\beta)\sum_{i=1}^{L}\sum_{j=1}^{L}I_{ij}^{'(HD)})$$

Subject to:

$$0 \le 2A'_{ik} - \frac{1}{P}\left(\sum_{j=1}^{L} S_{ij}A_{jk}\right) < 2$$
$$\forall P > L, 1 \le i \le N, 1 \le k \le K$$

$$I_{ij}^{'(CS)} = (\sum_{k=1}^{K} A_{ik} \bullet A_{jk}) \bullet I_{ij}^{(CS)} \qquad I_{ij}^{'(HD)} = (\sum_{k=1}^{K} A_{ik} \bullet A_{jk}) \bullet I_{ij}^{(HD)}$$

$$\sum_{k=1}^{K} A_{jk} = 1, \forall 1 \le j \le L \qquad \sum_{k=1}^{K} A'_{jk} \le R_i, \forall 1 \le j \le N$$

$$\mathrm{A}_{jk} = 0 \text{ or } 1, \forall 1 \le j \le \mathrm{L}, 1 \le k \le \mathrm{K}$$
$$\mathrm{A}'_{ik} = 0 \text{ or } 1, \forall 1 \le i \le \mathrm{L}, 1 \le k \le \mathrm{K}$$

FIGURE 4. Proposed model

Definition 4.6. *Node-Channel Assignment Matrix*

$$A'_{jk} = \begin{cases} 1, & \textit{Channel } k \textit{ is assigned to } v_i, \\ 0, & \textit{otherwise.} \end{cases} \tag{6}$$

Definition 4.7. *CS Nodes-Based Link Collision Matrix*

$$I_{ij}^{'(CS)} = \begin{cases} 1, & e_i \textit{ is conllided with } e_j, \\ 0, & \textit{otherwise.} \end{cases} \tag{7}$$

Definition 4.8. *HD Nodes-Based Link Collision Matrix*

$$I_{ij}^{'(HD)} = \begin{cases} 1, & e_i \textit{ is conllided with } e_j, \\ 0, & \textit{otherwise.} \end{cases} \tag{8}$$

Figure 4 shows our proposed model in this paper. Obviously, the proposed model is a heuristic-based integer quadratic programming (HIQP) model. HIQP model is composed of objective function and some constraints of optimal channel assignment.

- **Objective function**: The optimal object Ω is to optimize an optimal parameter β in order to minimize the CS node-based interference and HD node-based interference.
- **Constraints**: Basically, the constraints satisfy the requirements of feasible channel.
  1. $0 \le 2A_{ik}^{i} - \frac{1}{P}\left(\sum_{j=1}^{L} S_{ij}A_{jk}\right) < 2$ indicates a relationship among the S_{ij}, A_{jk} and A'_{jk}. If $\sum_{j=1}^{L} S_{ij}A_{jk} \ge 1$, due to $\sum_{j=1}^{L} S_{ij}A_{jk} \le L$, then A'_{ik}=1.
  2. $I_{ij}^{'(CS)} = \left(\sum_{k=1}^{K} A_{ik} \bullet A_{jk}\right) \bullet I_{ij}^{(CS)}$ and $I_{ij}^{'(HD)} = \left(\sum_{k=1}^{K} A_{ik} \bullet A_{jk}\right) \bullet I_{ij}^{(HD)}$ represent the correlations between the CS-based potential link collision matrix and CS-based link collision matrix, and HD-based potential link collision matrix and HD-based link collision matrix, respectively.
  3. $\sum_{k=1}^{K} A_{jk} = 1$ and $\sum_{k=1}^{K} A'_{jk} \le R$ are two basic limitations for channel assignment. In another word, each link is assigned for a channel. The number of radios on each node should be larger than the number of channels.

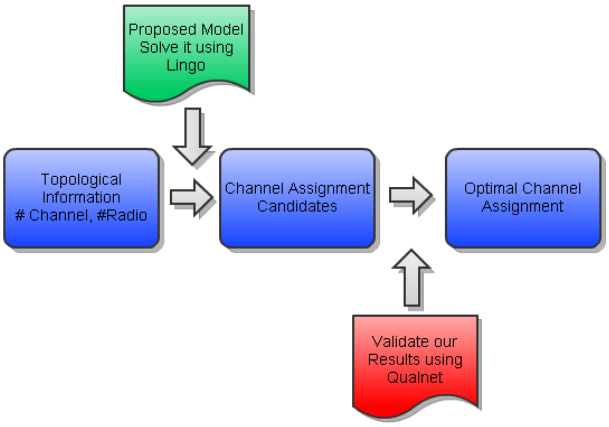


FIGURE 5. Evaluation framework. Make use of mathematics to get the channel assignment schemes, then simulate these schemes to select the scheme which has the highest throughput.

Based on above specific description of HIQP model, the working mechanism of HIQP model is to search the best channel assignment which satisfies the constraints and optimizes the objective function with various given tunable parameters. To obtain the optimal solutions of this model, Lingo 9.0 [2] is used.

5. **Experiment.** In this section, we investigate the correlation among number of radios on each node, number of channels and interference. It is assumed that the carrier sense interference range is equal to hidden terminal range. Then we adjust the value of β to analyze different schemes of channel assignment related to different β to find out the best scheme.

5.1. **Evaluation framework.** Our evaluation framework is composed of three modules and two implementation steps:

- Topological information of the network including the number of channels and the number of radios. This module is our input module.
- We obtain the channel assignment candidates using the proposed model. This module is our middle module.
- Optimal channel assignment. This is our output module.

As shown in Figure 5, we utilize the Lingo 9.0 to obtain the channel assignment candidates based on our proposed model. Furthermore, to extract our optimal channel assignment, we simulate them using Qualnet 5.0 [3] and compare the throughput of each channel assignment scheme.

5.2. **Experiment setup.** As mentioned above, in order to make use of the model, we use Lingo to simulate and get the target value from the module. With this module, we get different channel assignment schemes according to the changes of β. We classify different situations regarding different number of radios and channels. Since grid network is easy to analyze, we first simulate and analyze the grid network. After getting the correlation between the number of channels and collisions, we use Qualnet to simulate each channel assignment scheme and select the scheme which has the highest throughput as the final

[2]http://www.lindo.com/. Lingo is a comprehensive tool designed to make building and solving Linear, Nonlinear, Quadratic, Quadratically Constrained, Second Order Cone, Stochastic, and Integer optimization models faster, easier and more efficient.

[3]http://www.scalable-networks.com/products/qualnet/.

Simulation#	2			3	
β	0, 0.1, 0.2, …0.9, 1.0			0.3	
Network Type	4 times 4 grid	3 times 3 grid		4 times 4	random
Number of channels and radios	3 channels 3 radios	3 channels 3 radios	2 channels 3 radios	3 channels 3 radios	
Number of Nodes	16	9		16	
Distance between nodes	350 m				random
Radio Protocol	802.11b				
Routing Protocol	AODV				
Transmission range	375 m				
Flow Type	FTP				
Number of flows	4				
Starting time interval of flows	10s				
Simulation time	50s				
Average throughput	$(\sum_{i=1}^{4} Throughput\ of\ flow\ i)/4$				

FIGURE 6. Simulation parameters used in QualNet

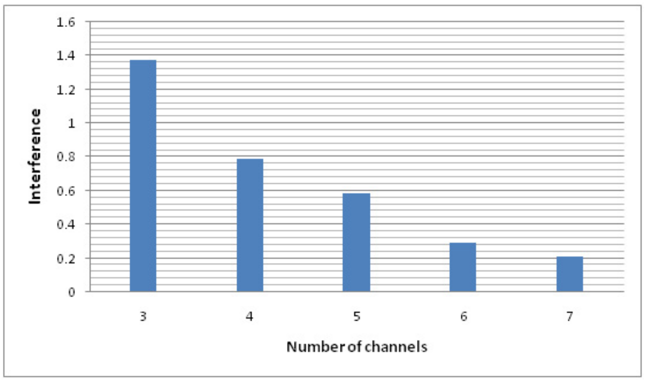


FIGURE 7. 4×4 grid network, $R = 3$. When the number of channels is larger, the value of interference is smaller. However, after the number of channels increases to more than 6, the changes of interference become smaller.

candidate. This final candidate is regarded as the pre-determined scheme. With this scheme we can make plans before the establishment of the network so that we do not need to modify the infrastructure of the network to address future potential problems like collisions. In addition, if efficient routing algorithm is used based on the final candidate, the performance of the network would be much better. After simulation in the grid network, we simulate the random network since random network is more practical in real world. Random node placement allows for fair number of hidden nodes and carrier sense interference. The simulation results have more practical value. Figure 6 describes the parameters we use for simulation in Qualnet.

5.3. **Experimental results.**

5.3.1. *The correlation between the number of channels and interference.* In this part, we change the number of channels and radios of 3×3 grid network and 4×4 grid network to get the relation between number of channels and interference as well as radios. Since we just want to know how the interference changes when the number of channels is changed without considering the effect brought in by β, we set the value of β is 0.5.

Figure 7 and Figure 8 show that when the number of radios is three, with the number of channels being increased, the interference of the 4×4 grid network will be decreased dramatically. The multi-line chart describes the same phenomenon for 3×3 gird network. The changes of the number of radios only have relatively small effects on the interference.

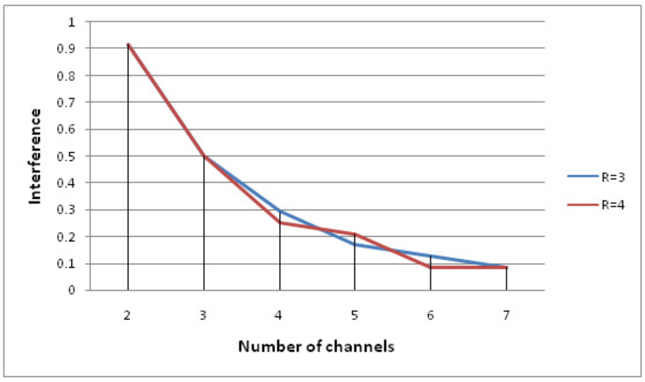
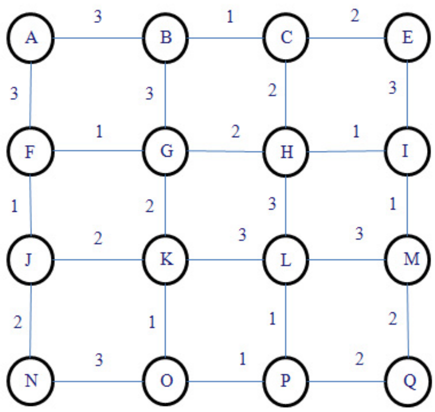


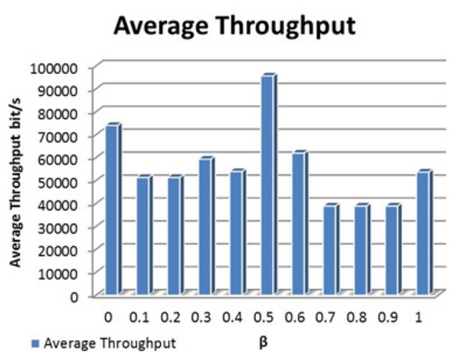
FIGURE 8. 3×3 grid network, $R = 3$ and $R = 4$. Interference will decrease when number of channels increases.

TABLE 1. Average throughput for 4×4 grid network when $C = 3$ and $R = 3$. When β is 0.5, the scheme has the highest throughput, thus this is the optimum channel assignment scheme.

β	0.0	0.1	0.2	0.3	0.4	0.5
Average Throughput (bit/s)	74082	51419.75	51419.75	59393.25	53990.75	95676.75
β	0.6	0.7	0.8	0.9	1.0	–
Average Throughput (bit/s)	62034	38949.75	38949.75	38949.75	53752.25	–



(a)

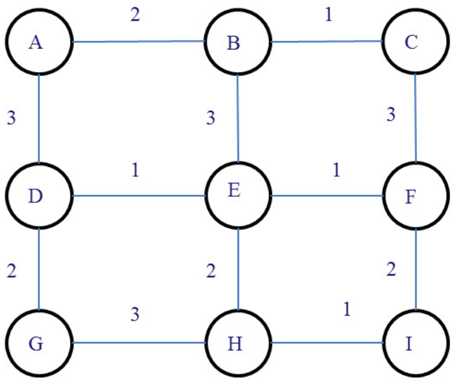


(b)

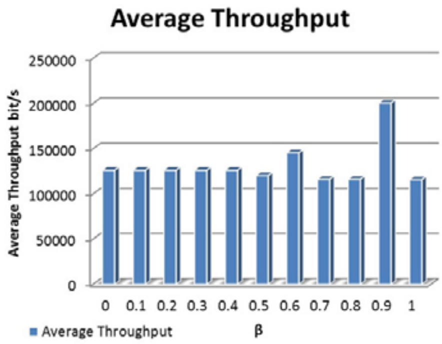
FIGURE 9. (a) Best channel assignment when β is 0.5. Compared with other schemes, this one has the highest throughput; (b) average throughput comparison under various β when $C = 3$ and $R = 3$. When β equals to 0.5, the throughput is the highest.

As what have been expected, more channels decrease the interference. However, this method has limited effects on the interference. As what can be observed from above charts, when the number of channels increase to more than 5, the decreased interferences become smaller and smaller, which means multi-channel and multi-radio has limitations to address channel assignment problem though it has obvious effects on this problem.

5.3.2. *Comparison experiments on throughput.* In this part, we simulate 4×4 grid network when $C = R = 3$ and 3×3 grid network when $C = R = 3$ as well as $C = 2$, $R = 3$ to make a comparison on how throughput changes when the number of channel changes.



(a)



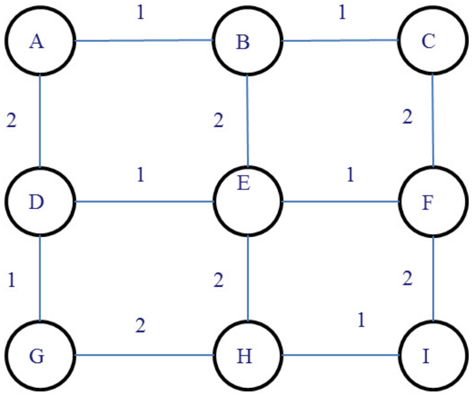
(b)

FIGURE 10. (a) Best channel assignment for 3×3 grid network when β is 0.9, number of channels and radios are both 3. Compared with other schemes, this one has the highest throughput; (b) average throughput comparison under various β when $C = 3$ and $R = 3$. When β equals to 0.9, the throughput is the highest.

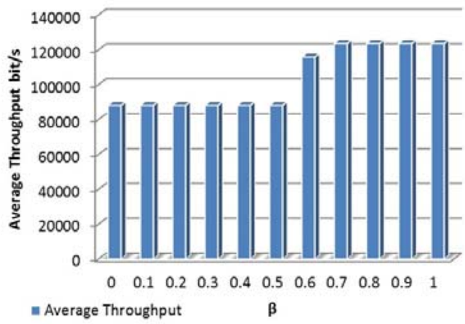
Figure 9(b) shows that average throughput comparison under various β when $C = 3$ and $R = 3$. It is easily to know that when $\beta = 0.5$, the average throughput is the highest, which means in this case the scheme of the channel assignment is the best. Figure 9(a) shows the best channel assignment for 4×4 grid network when $C = R = 3$ and Figure 10 shows 3×3 grid network when $C = R = 3$. To make a comparison for different number of channels, we simulate the 3×3 grid network which has two channels and three radios. The simulation results are shown in Figure 10(a) and Figure 11(b). According to Figure 10(b), when β is 0.9, the throughput will be the highest and therefore, under this β, Figure 10(a) shows the related optimum scheme. The results for 3×3 grid network are shown in Figure 11(b) and Figure 11(a). Figure 11(b) shows when β is equal to 0.7~1.0, the throughput can be the highest. Actually under these values of β, the model gives the same channel assignment schemes, which is shown in Figure 11(a). According to Figure 12, we can find that, generally, more number of channels means higher throughput, because more than one channel can be used at the same time to avoid some collisions.

5.3.3. *Performance comparison experiments with existing channel assignment schemes.* In this section, we compare our proposed scheme with existing channel assignment schemes in term of average throughput. We mainly compare the LWDCA algorithm [18], random algorithm, and our algorithm HIQP. LWDCA presents the weight of link-load and link-"potential" interference degree, and the construction method of weight-based chain. However, random algorithm is to assign the channels randomly with considering the factors of interference or capacity of the network. In the same way, we simulated 4×4 grid network when $C = R = 3$ and 3×3 when $C = R = 3$ as well as $C = 2$, $R = 3$ to make comparison about how performance are. Figure 13 shows the performance comparison results with existing channel assignment schemes (LWDCA, Random) in terms of average throughput. From Figure 13, we can easily draw a conclusion of our proposed HIQP, HIQP outperforms the other existing schemes in terms of average throughput, i.e., HIQP could improve the capacity of the network significantly.

5.3.4. *Comparison experiments on random networks and gird networks.* In this part, we use Qualnet to create nodes randomly instead of the perfect grid so as to observe the network performance in a more realistic environment. Since it is easy to imagine that



(a)



(b)

FIGURE 11. (a) Best channel assignment for 3×3 grid network when β is 0.7~1.0, number of channels is decreased to two. Number of radios is three. Compared with other schemes, this one has the highest throughput. (b) Average throughput comparison under various β when $C = 2$ and $R = 3$. When β is 0.7~1.0, the throughput is the highest.

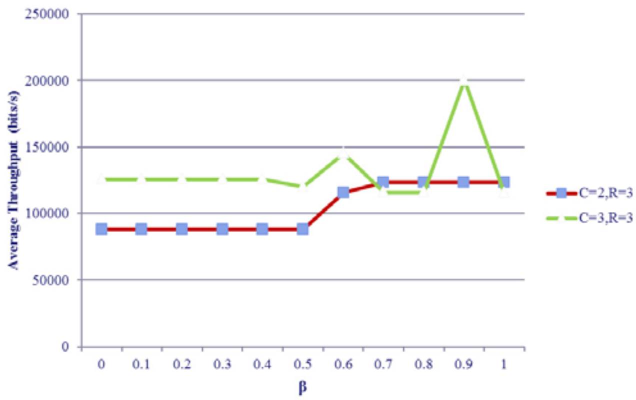
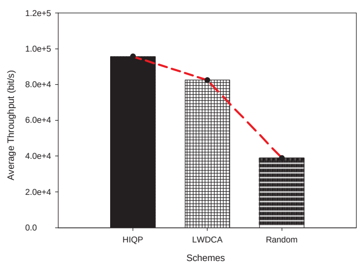
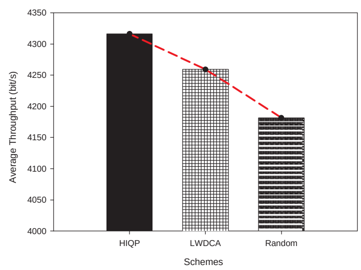


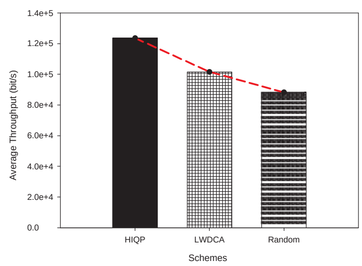
FIGURE 12. Throughput comparison between three-channel assignment and two-channel assignment schemes. Both of these two schemes have three radios, and the figure shows three-channel assignment has larger throughput.



(a) 4×4 grid network, $C = R = 3$, $\beta = 0.5$

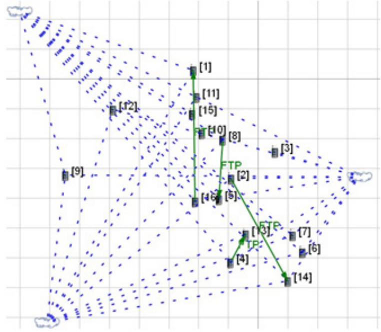


(b) 3×3 grid network, $C = R = 3$, $\beta = 0.9$

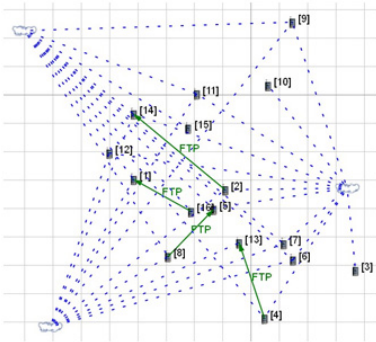


(c) 3×3 grid network, $C = 2$, $R = 3$, $\beta = 0.7$ 1.0

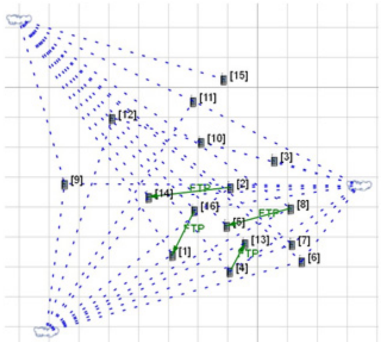
FIGURE 13. Performance comparison results with existing channel assignment schemes (LWDCA, random) in terms of average throughput



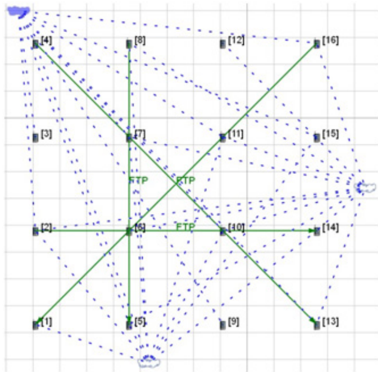
(a) Case 1: $\beta = 0.3$, $R = 3$, $C = 3$



(b) Case 2: $\beta = 0.3$, $R = 3$, $C = 3$



(c) Case 3: $\beta = 0.3$, $R = 3$, $C = 3$



(d) 4×4 grid network ($\beta = 0.3$, $R = 3$, $C = 3$)

FIGURE 14. Various random nodes placements and 4×4 grid network when $\beta = 0.3$, $R = 3$, $C = 3$

random network will have random throughput, this simulation only shows the changes of the throughput when the deployments of nodes and the distances between each pair of nodes are changed. We simulate three random node placement schemes under the condition that $\beta = 0.3$, 16 nodes, number of radios and number of channels are both three. We use 4×4 grid network to make a comparison. The three random assignment schemes are shown in Figure 14(a), Figure 14(b) and Figure 14(c). The 4×4 grid network is shown in Figure 14(d).

According to the simulation results, which are listed in Figure 15, it is difficult to make conclusions about the effects caused by random placements of nodes. However, the throughput of the random node placement scheme is much higher than the grid network scheme. Since we do not have enough samples to observe how the randomness of the nodes placement affects the throughput of the network, it is difficult to explain why the random networks have such higher throughput than the grid network. Probably, this phenomenon is caused by the fewer hidden terminal problem and carrier sense interference compared with that in the grid network.

5.4. **Discussion on β.** Experimental results demonstrate that all of the best channel assignment schemes have the highest throughput if and only if when $\beta \geq 0.5$. It is consistent with our basic intuition – *more CS nodes and less HD nodes will lead to higher capacity compared with that of more HD nodes and less CS nodes, even though we hope both the number of CS nodes and HD nodes can be decreased. If more CS nodes and less HD nodes contribute to the interference, the total capacity will be increased.* Therefore, we suggest the following important statement for pruning the channel assignment scheme candidates, that is, we only calculate the throughput and corresponding channel assignments when $\beta \geq 0.5$. In particular, when $\beta = 0$ and $\beta = 1$, i.e., hidden terminal

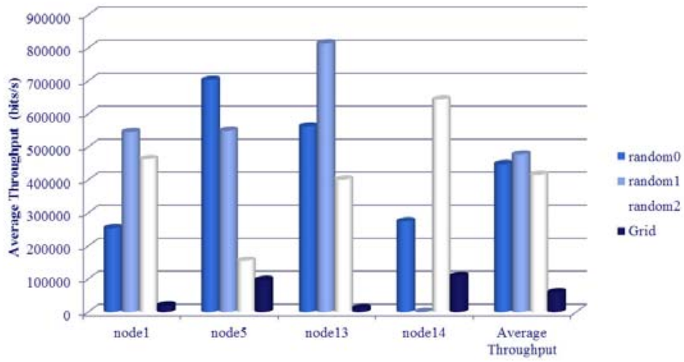


Figure 15. Throughput of random node placement schemes. Random schemes have much higher throughput than the grid network.

problem (carrier sense interference) is only considered, experimental results show that the average throughput under two special cases are worse than the average throughput with an optimal β.

6. Conclusions.

In this paper, we study the optimal channel assignment problem in multi-radio multi-channel wireless mesh networks. We propose *HIQP*, a hidden node and interference aware channel assignment scheme for Multi-radio Multi-channel WMNs. *HIQP* is to minimize the network interference by considering both hidden nodes problem and carrier sense interference. Simulation results indicate that optimal channel assignment should take account of average throughput so as to reduce the network interference further more. We investigate the correlation between the impact of radio and channel constraints. We also study the comparison analysis of various channel assignment schemes on random network and grid network. The optimum channel assignment scheme which has the fewest collisions can be pre-determined before the establishment of the network infrastructure.

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