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Nodes organization for channel assignment with topology preservation in multi-radio wireless mesh networks

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ABSTRACT

The wireless mesh network is a new emerging broadband technology providing the last-mile Internet access for mobile users by exploiting the advantage of multiple radios and multiple channels. The throughput improvement of the network relies heavily on the utilizing the orthogonal channels. However, an improper channel assignment scheme may lead to network partition or links failure. In this paper we consider the assignment strategy with topology preservation by organizing the mesh nodes with available channels, and aim at minimizing the co-channel interference in the network. The channel assignment with the topology preservation is proved to be NP-hard and to find the optimized solution in polynomial time is impossible. We have formulated a channel assignment algorithm named as DPSO-CA which is based on the discrete particle swarm optimization and can be used to find the approximate optimized solution. We have shown that our algorithm can be easily extended to the case with uneven traffic load in the network. The impact of radio utilization during the channel assignment process is discussed too. Extensive simulation results have demonstrated that our algorithm has good performance in both dense and sparse networks compared with related works.

1. Introduction

The emerging wireless mesh network [1] is expected to play an important role in building the multi-hop wireless access networks in the future by merging other wireless networks together, such as the cell networks, ad hoc networks and sensor networks. Such a combined network can not only enhance the coverage range, but also increase the system throughput as well as the communication reliability. And the wireless mesh network is generally deployed in the last mile and expected to extend or enhance Internet access for mobile clients located at the edge of wired networks. Although the mesh networks work in the similar way as that in the ad hoc networks, nodes in the mesh networks generally keep stationary and are supplied with wired power. The mesh network is still a pioneering research field and becomes a hot-spot recently.

The broadcasting characteristic of the wireless communications leads to the co-channel interference on the adjacent links in the multi-hop wireless networks. For example, the well-known hidden terminal and exposed terminal problems show that two links can not transmit packets simultaneously if they close enough. Co-channel interference is the main factor that has reduced the network throughput compared with that in the wired networks. It is proposed to use multiple radios as well as

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multiple channels in the mesh networks to reduce the co-channel interference and improve the network throughput accordingly [2–3,5]. Each mesh router is equipped with several wireless network-interface cards (NICs or radios), and each radio can be assigned to one orthogonal channel. Two radios can communicate with each other if they are assigned the same channel and within the transmission of each other. The IEEE 802.11 b/a have provided 3/12 orthogonal channels. Compared the traditional single radio wireless network, the mesh network can reduce co-channel interference and improve network throughput by utilizing multiple radios and multiple channels, because nodes can transmit simultaneously if they use different orthogonal channels. However, the number of radios on the nodes is generally less than that of the available channels, and minimizing the interference is still one important research issue.

The objective of the channel assignment problem is to ensure the efficient utilization of the available orthogonal channels. For example, connectivity guarantee is generally considered as one key issue while providing reliable and robust routing, and lower co-channel interference means higher network throughput. Assuming that all nodes in the mesh network are assigned the same number of radios, it is obviously that the network connectivity is maximized in case that all nodes are assigned the identical set of channels (with the number of channels in the set same as that of the radios on the nodes). However, such a channel assignment scheme results in maximum co-channel interferences. Similarly, channel assignment with lower co-channel interference may lead to network partition or link failure.

Here we consider a strategy named as *topology preservation* [15] to balance between the network connectivity and co-channel interference. Topology preservation means that links in the original single channel network will also exist in the final multi-channel network topology after channel assignment. To preserve the original topology in the channel assignment can avoid the network partition and the links failure. Furthermore, the routing protocols which are fully researched in the single channel network can be applied to the mesh network without further modification. The topology preservation strategy provides compatibility among the traditional ad hoc networks, sensor networks, cell networks and the new emerging mesh networks. In fact, channel assignment with topology preservation makes the wireless mesh networks more applicable in the real-world scenarios. In this paper we aim at designing a channel assignment scheme with minimum interference while providing topology preservation.

There are some pioneering works on the channel assignment problem with topology preservation in the wireless mesh networks [2–4]. The basic ideas behind them are described as following. When all links in the original topology are preserved, they shall be organized into a set of groups in the channel assignment problem, in which one group represents one special channel. Note that different channels in the network are orthogonal and interference occurs only between links assigned with the same channel, i.e., links in the same group. The overall interference in the network can be obtained with the links in the same groups. In this way the minimum-interference channel assignment problem is in fact converted to a Max k-cut and Min k-partition problem. In this paper we call the channel assignment algorithms based on the above conversion as *links organization* algorithms.

Although links organization algorithms sound reasonable in the wired networks and in wireless networks with directional radios, but they have problems in the wireless network with omni-directional radios. Fig. 1 shows an example to illustrate the problem. There are four nodes in the network and the chain topology is shown in Fig. 1(1). Assuming that links (a, b) and (c, d) are assigned channel 1, and links (b, c) channel 2 (in Fig. 1(2)). With the links organization algorithms the overall interference is calculated in fact between links (a, b) and (c, d). However, it shall be noticed that radios on the mesh nodes are generally omni-directional and the speaking on the radio will be heard by all neighbors in the communications range, i.e., the speaking on channel 1 by node b will also be heard by node c. In fact, there is an additional link between node b and c on channel 1 after the channel assignment for links in Fig. 1(2), as illustrated in Fig. 1(3). Note that omni-directional radios are popular in the wireless mesh networks, and this example has shown that links organization algorithms are not suitable for the channel assignment problem with topology preservation.

Different from the previous links organization algorithms, our work aims at providing channel assignment solution by organizing the nodes accordingly to the available channels. There is a link $(i, j; k)$ between node i and j if they both are assigned channel k. As the example has illustrated in Fig. 1, nodes organization may result in a multi-graph while the links organization results in a simple-graph. It means that the nodes organization is more possible to improve the network connectivity compared with the links organization because there are feasibly several links between two nodes. However, the adding of new links into the network might increase the overall interference while preserving the original topology.

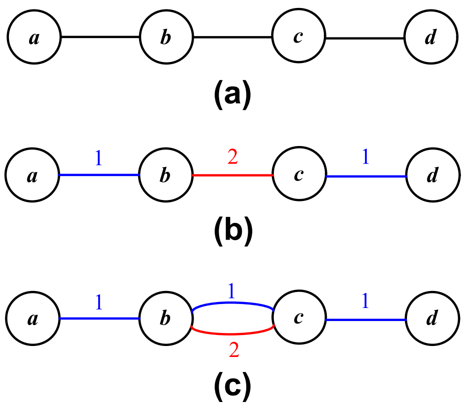


Fig. 1. An example to illustrate problems in the algorithms for links organization. (a) The original chain topology with four nodes. (b) The links organization result in which (a, b) and (c, d) are assigned channel 1, and links (b, c) channel 2. (c) The final topology with omni-directional radios in which there is an additional link between node b and c on channel 1.

So far as we know, our work is the first one mentioning nodes organization for the channel assignment with topology preservation in the wireless mesh networks. The channel assignment problem is proved to be NP-hard and to find the optimized solution in polynomial time is impossible. In this paper we have formulated a channel assignment algorithm named as DPSO-CA which is based on the discrete particle swarm optimization and can be used to find the approximate optimized solution. Although our algorithm is designed for the case with unified traffic load in the network, we also have shown that it can be easily extended to the case with uneven traffic load in the network. We have discussed the radio utilization in the channel assignment problem and its impact on the co-channel interference and network throughput.

The rest of this paper is organized as follows: we introduce the related work in Section 2 and present the problem formulation in Section 3. Section 4 introduces an approach based on the Particle Swarm Optimization (PSO) algorithm. In Section 5 we concern with the simulation result. Section 6 discusses the radio utilization and the uneven traffic load in the network and Section 7 is conclusion.

2. Related work

Optimal channel assignment in an arbitrary wireless mesh backbone is proven to NP-hard problem based on its mapping to the graph coloring problem [6,14]. The proposed channel assignment schemes can be partitioned into three main categories: dynamic, static, and quasi-static [7], which depends on how frequently the channel assignment is modified. The dynamic strategy allows channel switching among available channels according to the packet destination. With dynamic channel assignment, when two mesh nodes need to communicate with each other, they need to switch to the same channel. The key challenge in this case is how to coordinate the switching decisions. Switching one channel to another on a radio can bring about delay which can be in order of milliseconds. Therefore, dynamic channel assignment strategy with current commodity IEEE 802.11 hardware is difficult to realize and might not be practical [9]. While the static strategy assigns channels to radios either permanently, or for time intervals that are long with respect to the radio switching time. This is practical and can be easily extended to the quasi-static strategy by switching the channels in regular intervals. Quasi-static assignment strategies are attractive since they allow for simple coordination algorithms (as for the static assignment schemes) and also provide the flexibility.

The static channel assignment schemes can be further classified into two categories: common channel assignment and varying channel assignment [4]. In the common channel assignment scheme, all radios on all of the mesh nodes are assigned the same set of channels, in which the network connectivity is similar to that in the single-radio network. While providing connectivity guarantee, it leads to severe co-channel interference and channels are poorly utilized in case that the number of available channels is eventually larger than that of the radios because only a limited number of channels (equal to that of the radios) are used in the network. In the varying channel assignment scheme, radios in different nodes are assigned different sets of channels. The difference of the channel assignment for the radios may result in lower interference, but it shall be carefully designed to avoid network partition and links failure. Our paper has followed this strategy and proposed a solution based on the varying channel assignment scheme with the topology preservation.

Raniwala et al. [3] proposed a centralized load-aware channel assignment algorithm to find static channel assignment, but it required the load and routing information of the network and was hard to realize in a real network. It first estimates the total expected load on each virtual link by summing the load according to the traffic flow between the pairs of sources and destinations. The channel assignment is done in a greedily way for links in decreasing order of expected traffic load. Although this scheme presents a method for channel allocation that incorporates connectivity and traffic patterns, the assignment of channels on links may cause a ripple effect whereby already assigned links have to be revisited, thus increasing the time complexity of the scheme.

Marina et al. [14] proposed a polynomial time greedy heuristic, called Connected Low Interference Channel Assignment (CLICA). CLICA is a traffic independent channel assignment scheme which first computes the priority for each mesh node and then assigns channels based on the network topology as well as the conflict graph. However, the proposed algorithm might override the priority of a node to when the radio number constraints are violated. Although this scheme avoids link revisits compared with that in [3], it does not incorporate the different traffic patterns in the mesh networks.

The works in [15] extended the idea in [14] and proposed two link organization algorithms for the channels assignment with topology preservation. The first is based on a heuristic search technique called Tabu search, which was originally designed for graph coloring problems. The Tabu search starts with a random channel assignment for all links in the network. The channel assignment is further randomized by switching the channels of a certain number of neighbor links. And the Tabu search chooses the best one as the result of the first stage without taking into account the radio constraint. Therefore, the second stage is to start from the node with the maximum violations of the interface constraint, and combine the assignments of two radios that share the same channel so as to minimize the increase in conflicts. However, an iteration operation is required when the constraint on the radio number is violated. Iteration has increased the algorithm complexity as well as reduced the system performance. The second is a greedy heuristic inspired by the greedy approximation algorithm for Max k-cut problem in graphs by considering the radio consideration in the iteration. Cheng et al. had proposed an integer line programming solution as well as a heuristic algorithm for the channel assignment problem [29]. However, this paper did not utilize the entire available channel while preserving the original topology, and might lead to lower network throughput.

Das et al. [11] considered a fixed channel assignment which maximizes the number of bidirectional links that can be activated simultaneously and subject to interference constraints. Two mixed integer linear programming models for solving the fixed channel assignment problem with multiple radios were proposed with computational results on various grid topologies presented and discussed. However, these approaches are with exponential complexity and they are not scalable especially in networks with large number of nodes.

The authors of [10] presented an interference-aware channel assignment algorithm and protocol for multi-radio wireless mesh networks that address this interference problem. The proposed solution intelligently assigns channels to radios to minimize interference within the mesh network and between the mesh network and co-located wireless networks. This approach extended the conflict graph model further into multi-radio conflict graph (MCG) and assigned channels to radios instead of links and only considers the binding of a radio to a channel while ignoring the interface-channel binding.

Tang et al. [16] defined and presented an effective heuristic for the minimum INterference Survivable Topology Control (INSTC) problem which seeks a channel assignment for the given network such that the induced network topology is interference-minimum among all K-connected topologies. They also formulated the Bandwidth-Aware Routing (BAR) problem for a given network topology, which seeks routes for QoS connection requests with bandwidth requirements, and presented a polynomial time optimal algorithm to solve the BAR problem under the assumption that traffic demands are splittable. For the non-splittable case, a maximum bottleneck capacity path routing heuristic was presented.

Raniwala et al. [8] presented distributed algorithms that utilize only local traffic load information to dynamically assign channels and to route packets, and compared its performance against a centralized algorithm that performs the same functions. However, these works did not consider preserving the topology of the original network, and might lead to inefficient network management and routing in the applications of the mesh network. In [12], the authors defined specific mechanisms that can transform partially overlapped channels into an advantage, instead of a peril, and constructed simple analytical and empirical models of such interference occurring in IEEE 802.11 networks. A distributed algorithm with minimizing the network interference using overlapping channels was proposed. However, the network load was not considered in the algorithm.

Das et al. [19] addressed the static channel assignment problem for multi-channel multi-radio static wireless mesh networks, and focused on minimization of the average and maximum collision domain sizes. It was shown that the channel assignment problems are closely related to problems in combinatorial optimization such as Max k-cut and Min k-partition. Four metrics based on which mesh channel assignments and an algorithm to maximize the number of logical links that could be active simultaneously were proposed in this work. Sridha et al. [13] proposed a load-based scheme for assigning channels to the radios as well as a meta-heuristic based on genetic algorithms. However, the broadcasting characteristic of wireless communication was ignored in their works, which leaded to the wrong calculation on the overall interference in the network and may result in un-efficient channel assignment scheme. Subramanian et al. [20] applied the Lagrange relaxation method to obtain lower bounds as well as near-optimal feasible solutions for large size networks as well as a meta-heuristic based on genetic algorithms. They also proposed an integer linear programming to obtain bounds of optimal solution and evaluate the proposed algorithm by the usage of partially overlapping channels based on a conflict graph.

In this paper we aim at the minimum-interference channel assignment problem by organizing the nodes with the available channels while preserving the original topology. Different from all these previous works, our centralized channel assignment algorithm based on the discrete particle swarm optimization [30,31] is to find the approximate optimized solution by satisfying the radio number constraint as well at the topology preservation constraint. Although that the algorithm is designed for the network with unified traffic on the links. We also present that our algorithm can be easily extended to the case with uneven traffic load. All these show that our proposed algorithm is robust and efficient to the channel assignment problem in the wireless mesh networks.

3. Problem formulation

In this section, we formally describe in details the system model and the formulation of the channel assignment problem.

3.1. Network model

We consider a wireless mesh network in the plane with stationary wireless nodes, in which each node is equipped with a certain number of radios. It is assumed that all radios in the network operate in half-duplex mode with omni-directional antennas, and the transmission ranges are identical to all radios. The original topology of the wireless mesh network can be modeled as an undirected graph $G = (V, E)$, where V represents the set of mesh nodes and E the set of wireless links. There is a link (i, j) between i and j if both nodes are located within the transmission ranges of each other. Fig. 2 shows an example to illustrate a network topology composed of six nodes.

We also assume that all channels are orthogonal, meaning that the transmissions on different channel can be carried out simultaneously. The set of available channels is denoted by K. Without loss of generality, we denote $K = \{1, 2, \ldots, k_{max}\}$. Let R_i denote the number of radios and K_i the set of assigned channels for any given mesh node i.

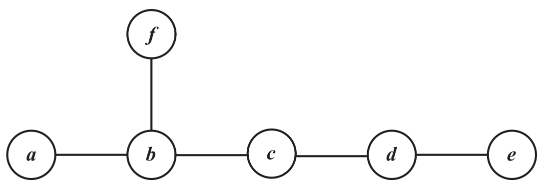


Fig. 2. An example of network with six nodes.

The final topology of the network after channel assignment can be denoted as $G' = (V', E')$, in which $V' = V$ and $(i, j; k) \in E'$ if and only if $k \in K_i \cap K_j$ and $(i, j) \in E$.

It should be mentioned that the radio number on the mesh nodes is generally less than that of the available channels. Generally, the final topology of the network after channel assignment is different from that of the original topology. This conclusion is obvious with two observation: (a) In case that two nodes are within their transmission ranges, there is a link between them on the original topology G; However, there is no link on G' between them if they are not assigned a common channel, which means the two nodes are disjointed; (b) More than one links can exist between two nodes in the final topology G' if they are assigned more than one common channels. Our work aims at preserving all the original links after the channel assignment. The definition of topology preservation is defined as below.

Definition 1 (*Topology Preservation*). The topology is preserved if and only if the original topology G and the final topology G' with the channel assignment satisfies the following constraint: for each $(i, j) \in E$, there exist at least one $k \in K_i \cap K_j$ and $(i, j; k) \in E'$.

3.2. Interference model

Interference is one key issue in the wireless mesh network and is selected as the optimization object in the work. Although the term interference is well-known in many papers, there is still no accurate model to define whether two links interfere with each other in the wireless communication. Several interference models have been proposed [2,16]. The famous interference model is called the physical model based on the signal to interference plus noise ratio (SINR), in which it is assumed that packet transmission is successful with high probability if the SINR is larger that the threshold while lower SINR is not used for transmitting. In fact, lower SINR results in high packet error ratios but it still can be used in transmitting. A protocol model is proposed [16] in which two links interfere with each other if their distance ratio is lower than a given threshold as $(1 + \Delta)$, where Δ models situations where a guard zone is specified to prevent a neighboring node from transmitting on the same channel. Tang et al. [2] proposed that two links (i, j) and (u, v) interfere with each other if one of the following distances $d_{i,u}$, $d_{i,v}$, $d_{j,u}$, $d_{j,v}$ is smaller than the interference range.

In this paper, we assume that a binary interference model, meaning that two links either or not interfere with each other. Obviously the protocol model in [16] and the model in [2] follow this assumption. In fact, our experiment follows the model of literature [2]. However, it should be mentioned that our channel assignment algorithm is not limited to that, and it can be applied to any binary interference model.

Definition 2 (*Potential Interference Number*). The potential interference number of link $(i, j) \in E$ is the number of links in set E which interfere with link e according to the binary interference model.

Definition 3 (*Interference Number*). The interference number of link $(i, j; k) \in E'$ is the number of links in set E' which interfere with link $(i, j; k)$ according to the binary interference model and have the same channel number k as link $(i, j; k)$.

3.3. Conflict graph

Conflict graph [17] has been used extensively to characterize the network interference in the wireless networks. For example it is widely adopted in those which convert the channel assignment problem in a Max k-cut problem or a Min k-partition problem. A conflict graph $G_c = (V_c, E_c)$ can be conduced from the original network topology $G = (V, E)$, in which $V_c = E$ and there is an edge between two vertices in E_c if they are in the interference range of each other in G. Fig. 3 illustrates the concept of conflict graph corresponding to original network graph in Fig. 2. It is showed that there are conflict edges $((a, b), (b, c))$, $((a, b), (c, d))$ and $((a, b), (b, f))$ in the conflict graph G_c, because the link (a, b) interferes with the links (b, c), (b, f) and (c, d) in the undirected graph G by assuming that the interference range is identical to the transmission range with the Tang [2] interference model.

Definition 4 (*Conflict Graph*). A conflict graph $G_c = (V_c, E_c)$ is conduced by $G = (V, E)$ with $V_c = E$ and $(e_1, e_2) \in E_c$ if e_2 interfere with link of e_1 in G.

3.4. Channel assignment problem

Given the topology of a wireless mesh network, the capacity of the network is heavy depending on the assignment of the available channels to links. One intuitive target of the channel assignment problem is to minimize the total interference numbers since the interference has described the conflicts in the wireless links. The total network interference in the network is defined as the number of pairs of wireless links that are interfering.

Definition 5 (*Total Interference Number*). The total interference number for the mesh networks is the sum of interference number of all links in E'.

However, it should be mentioned that the radio number on the mesh nodes is generally less than that of the available channels, and the number of distinct channels allocated to the links incident on any node should not excess

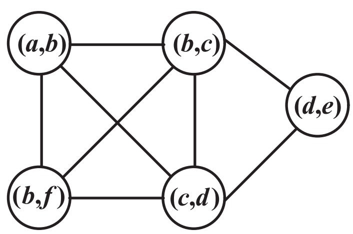


Fig. 3. An example of conflict graph corresponding to Fig. 2.

the number of radios on that node. As mentioned, R_i and K_i are used to denote the number of radios and the set of assigned channels for node i. The radio number constraint for the channel assignment can be formulated as follows:

$$|K_i| \leqslant R_i \tag{1}$$

It is desirable to have a channel assignment scheme whose corresponding topology has relatively low interference. The channel assignment for one node is a set of channels among the set K, which can be denoted as a non-empty subset of K. Let $P(K)$ be power set of K, we have the following definition for the channel assignment problem.

Definition 6 (*Channel Assignment Problem*). The channel assignment problem is to find the function $f : V \rightarrow P(K) \setminus \phi$ for graph G with topology preservation and the radio number constraint, so that the total interference number in the network is minimized.

4. Approach based on PSO algorithm

Particle swarm optimization (PSO) is a population based stochastic optimization technology which is developed by Dr. Eberhart and Kennedy [18], inspired by social behavior of bird flocking or fish schooling. PSO provides a population-based search for the optimization problem in which population individuals called particles change their position around with time in the multi-dimensional search-space according to simple formulae. Each particle adjusts its position according to its own experience, and the experience of its neighbors, making use of the best position encountered by it and its neighbor and continually updating the better positions found by the particles. A PSO system combines local search methods with global search methods, attempting to balance between the exploration and exploitation. It has been proved to be an effective global optimization approach and has been successfully applied in various areas, such as no-wait flowshop scheduling problem, neural network training, and traveling salesman problem and so on. The PSO algorithm has generally two updating formulas, i.e., velocity updating formula and position updating formula. The particle is updated by the following two best values. One is the best solution of the particle that it has achieved so far which is named as *pbest*. Another best value is a global best value in the population and it is named as *gbest*.

However, the feasible channel assignment for the wireless mesh network is discrete in the solution space, i.e., the channel number assigned for one mesh nodes is strictly an integer between 1 and k_{max}. So the particle cannot fly smoothly in the solution space, meaning that a new updating formula is required. In this paper, we have developed a discrete PSO algorithm for the channel assignment problem (DPSO-CA) by introducing the genetic operations into the iteration process. The position updating includes two different operations, namely, crossover operation and mutation operation. The particles use the crossover operation to improve their positions with information about the global and local best value, i.e., *gbest* and *pbest*, while the mutation operation to change the position randomly and avoid the local optimization problem. The detailed process of the DPSO-CA is described as following.

4.1. Encoding

Consider a wireless mesh network in which the node number is $n = |V|$ and the available channel number is k_{max}. The particle in this paper is used to represent one feasible channel assignment scheme for the wireless mesh networks, which is the combination of the channel assignment for radios on all nodes in the network. The position of particle i at time t can be denoted as:

$$X_i^t = (x_{i1}^t, x_{i2}^t, \ldots, x_{in}^t), \tag{2}$$

where x_{ik}^t denotes the channel assignment for node k at time t. Obviously, the position of the particle represents a feasible channel assignment for the mesh network. Each particle keeps track of its coordinates in the problem space and are associated with the best solution it has achieved so far, which is called *pbest* and denoted as:

$$pbest_i^t = (p_{i1}^t, p_{i2}^t, \ldots, p_{in}^t). \tag{3}$$

When a particle takes all the population as its topological neighbors, the best value is a global best and is called *gbest* and denoted as:

$$gbest_i^t = (g_{i1}^t, g_{i2}^t, \ldots, g_{in}^t). \tag{4}$$

The particle swarm optimization is in fact a series of changing the velocity of each particle toward its *pbest* and *gbest* by randomly changing the particle position in the iterations.

4.2. Population initialization

Our work aims at the minimum-interference channel assignment with topology preservation. To preserve the original links in the topology after channel assignment, two neighbor nodes shall be assigned at least one common channel. The initial value of the particle shall represent one feasible channel assignment result which satisfies the topology preservation as well as the radio number constraint. In our population initialization process, one radio on each mesh node is assigned to one special common channel, which can provide the necessary guarantee for the topology preservation. An example is illustrated in Fig. 4 to show the particle initialization process for the topology in Fig. 2, in which each node owns three radios. In this example one radio on each mesh node is selected and assigned to channel 2, while the other radios are assigned channels with a random selection from the rest available channels. For example, the channel assignment for node c is {1, 2, 8}. Note that each node shall be assigned with three different channels.

4.3. Crossover and mutation operation

As mentioned above, the position of each particle denotes a feasible solution for the channel assignment problem. It must be ensured that the modified position of the particles shall also satisfy the topology preservation as well

a	2	3	7
b	1	4	2
c	1	2	8
d	2	5	9
e	2	10	12
f	1	2	6

Fig. 4. Population initialization for Fig. 2 with radio number as 3.

as the radio number constraints too. In case that the channel assignment for radios on the same node is operated in fully independent way, the new position for the particle might conflict with these conditions. To convert such a position (which violates with the conditions) to a feasible position may increase the computation complexity or be impossible in some cases. In this paper we borrow the idea from genetic algorithm and introduce the mutation and crossover operations as following.

The *mutation operation* is used to change the particle position in a randomly way. The equation for the mutation operation is given below:

$$A_i^t = mutate\left(X_i^{t-1}, c_1\right) = \begin{cases} mutate\left(X_i^{t-1}\right), & r_1 < c_1 \\ X_i^{t-1}, & else \end{cases}. \tag{5}$$

where c_1 is a constant variable, and r_1 is a random number generated randomly between (0, 1).

The *crossover operation* is originated from the genetic algorithm and is used to modify the current particle position with information from the *pbest* or *gbest*.

$$B_i^t = crossover\left(A_i^t, pbest_i^{t-1}, c_2\right) = \begin{cases} Crossover\left(A_i^t, pbest_i^{t-1}\right), & r_2 < c_2 \\ A_i^t, & else \end{cases}. \tag{6}$$

$$X_i^t = crossover\left(B_i^t, gbest_i^{t-1}, c_3\right) = \begin{cases} Crossover\left(B_i^t, gbest_i^{t-1}\right), & r_3 < c_3 \\ B_i^t, & else \end{cases}. \tag{7}$$

where c_2 and c_3 are two constant variable, and r_2 and r_3 are two numbers generated randomly between (0, 1).

An example is shown to illustrate the mutation and crossover operations in Fig. 5. One channel of node *c*, i.e., 2, is mutated to another channel, i.e., 6. The node as well as the channel selection are both done in a randomly way, and the replacement shall satisfy the radio number constraint as well as the topology preservation constraint. In Fig. 5(b), the channel assignment for node *c* is changed from {1, 2, 8} to {1, 2, 6}, in which the final channel is learned from the randomly selected channel of *pbest*. And assignment for node *f* is changed from {1, 2, 6} to {1, 2, 12}, in which the channel 12 is learned from *gbest*.

4.4. Fitness function

Note that the particle shall modify its position according to the current best position as well as the global best position. A parameter named as fitness value is necessary to measure the value of these positions, and fitness function is the formula that can be used to calculate the fitness value. Since that the objective of our channel assignment

a	2	3	7
b	1	4	2
c	1	2	8
d	2	5	9
e	2	10	12
f	1	2	6

→

2	3	7
1	4	2
1	**6**	8
2	5	9
2	10	12
1	2	6

(a) Mutation operation.

pbest

a	1	4	4
b	3	1	11
c	4	**6**	1
d	7	1	9
e	3	10	1
f	1	12	11

2	3	7
1	4	2
1	**6**	8
2	5	9
2	10	12
1	2	**12**

gbest

3	1	7
6	4	3
8	3	9
2	5	3
3	8	7
11	3	**12**

(b) Crossover operation.

Fig. 5. Operation example for topology of Fig. 1.

problem is to minimize the total network interference, it is reasonable to use the network interference number as the fitness value directly. And the accordingly fitness function can be denoted as $I(f)$.

$$I(f) = \sum_{(i,j)} \text{interference number of link}(i,j). \quad (8)$$

4.5. Algorithm overview

The pseudo code for the DPSO-CA algorithm is described with Table 1.

Lemma 1. *Let pn be the particle number, iter be the iteration times, E be the set of links in the original topology, n and K be the node and radio number. The time complexity of the DPSO-CA is* $O(|E| * |E|) + O(iter * pn * n * K)$.

Proof. In the first step of the proposed DPSO-CA, we need to build the *Gc* in which each link is either or not the interference link of any given link, and the time complexity is $O(|E| * |E|)$. The time complexity for step 2 is O(1). In step 3, the particle initialization is $O(pn * n * K)$. In step 4, each node calculates its fitness value with the time complexity as $O(n * K * |E|)$, and to find the best particle is $O(n)$. In step 6, the crossover operation is done with $O(pn * n * K)$ for each particle. In step 7, the mutation process is done with $O(pn * n * K)$ for each particle too. And steps from 4 to 7 run *iter* times. In this way, the total time complexity of the DPSO-CA is $O(|E| * |E|) + O(1) + O(pn * n * K) + O(n) + iter * (O(pn * n * K) + O(pn * n * K)) = O(|E| * |E|) + O(iter * pn * n * K)$. □

5. Experimental results

In this section, we study the performance of our designed algorithm for the channel assignment problem compared with other works by experiments. The mesh networks are built with the varying number of nodes, channels and radios. Two sets of random network, namely, sparse and dense networks, are generated by randomly placing 25 or 50 mesh nodes in the square meters area 1000 m × 1000 m. The transmission range is assumed to be 250 m. The average node degree is about 4.88 in the sparse network and 7.48 in the dense network. The interference model follows the literature [16], i.e., two links $e_1 = (i, j)$ and $e_2 = (u, v)$ interfere with each others if one of the following distances, $d_{i,u}$, $d_{i,v}$, $d_{j,u}$, $d_{j,v}$, is smaller than the interference range. The interference range is assumed to be equal to the transmission range. When the node position and the transmission range are given, there is an edge between two nodes if their distance is no larger than the transmission range. And then graph G is built as well as the conflict graph G_c. In this paper we assume the mesh nodes are equipped with the same number of radios.

Here we use two metrics to illustrate the performance of the algorithm, namely, the fractional network interference and network throughput, which are first proposed in [15]. The fractional network interference is defined as the ratio of overall interference number and the overall potential interference number in the network, which can be used to measure the final interference after the channel assignment. In the network with uniform traffic and channel capacity, the available bandwidth of one link is in fact determined by the number of links interfering. We use the following Equation to calculate the available bandwidth on link *e*.

$$Capacity(e) = 1/(1 + \text{interference number of } e). \quad (8)$$

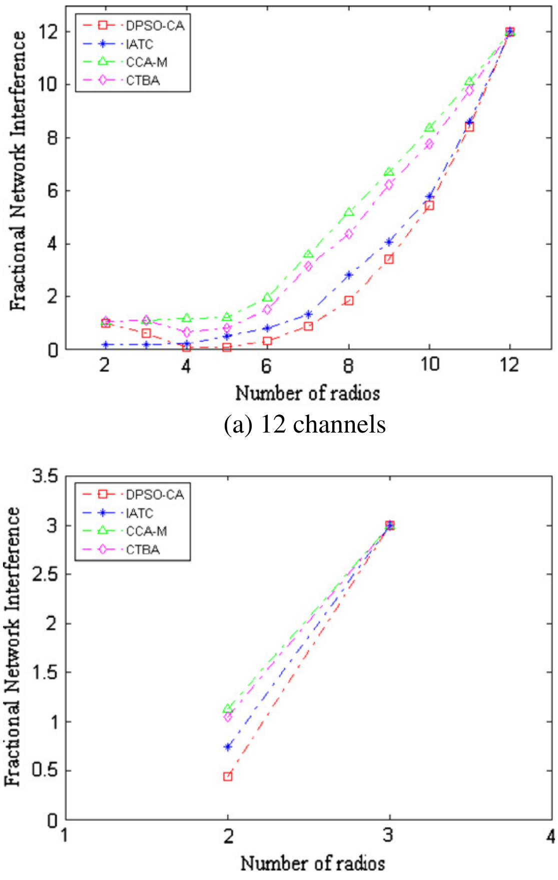
Then the network throughput can be calculated as the sum of capacity of all links in the network. Note that there might be several links on different channels between two adjacent nodes.

In order to evaluate the DPSO-CA algorithm proposed in this paper, we compare it with the centralized Tabu-based algorithm CTBA [15] as well as the heuristic IATC algorithm in [16]. The main idea behind the CTBA is to convert the channel assignment problem to the Max *k*-cut problem, and it has two steps: the first is to assign the channel to the conflict graph Tabu-list with random channel switch on the links, and the second is to iteratively merge the channels on nodes with more channels than the radio number. The IATC is to assign channels to links while maintaining the network connectivity. In the simulation, the connectivity requirement for the network is assumed to be 1-connected. Readers are guided to [16] for details about the algorithm. We also intended to compare our works with the heuristic CCA algorithm in [29]. However, the CCA did not utilize all the available radios of the mesh network which is generally impracticable, and in the simulation we use a modified version CCA-M by simply assigned the available radios to the un-used channels. These algorithms are implemented using MATLAB program on a PC (1 CPU, 2.00 GHz, 1.00 GB RAM) under the Windows XP operating system.

Fig. 6a shows that DPSO-CA has smaller fractional network interference compared with that of CTBA and CCA-M in all cases. For example, in the case that there are 12 channels and 5 radios, the fractional network interferences for the DPSO-CA, CTBA and CCA-M are 0.0719/0.8106/1.204 accordingly. The reduction ratios of the DPSO-CA are about 91.1% and 94.0% compared with CTBA and CCA-M. In case that there are 12 channels and 2 radios,

Table 1
The pseudo code of DPSO-CA.

Discrete PSO algorithm for channel assignment problem (DPSO-CA)
Input: topology $G = (V, E)$, $K = \{1, 2, \ldots, k_{max}\}$, R_i ($i \in V$).
Output: the channel assignment result K_i for each $i \in V$.
1. Build the conflict graph $G_c = (V_c, E_c)$ with the original graph G as well as the given binary interference model;
2. Initialize the population size and the generation number;
3. Initialize the value for all particles;
4. Calculate the fitness value of each particle; Calculate *pbest* of each particle and select the *gbest* from all particles;
5. Do step 6 and 7 for each particle:
6. Crossover the current position with *pbest* as well as *gbest*;
7. Mutate the current position;
8. If termination condition is not satisfied, return to step 4;
9. Set the *gbest* as the final solution, and calculate K_i, $i \in V$ accordingly to *gbest*.



(a) 12 channels

(b) 3 channels

Fig. 6. Fractional network interference in sparse network with 25 nodes.

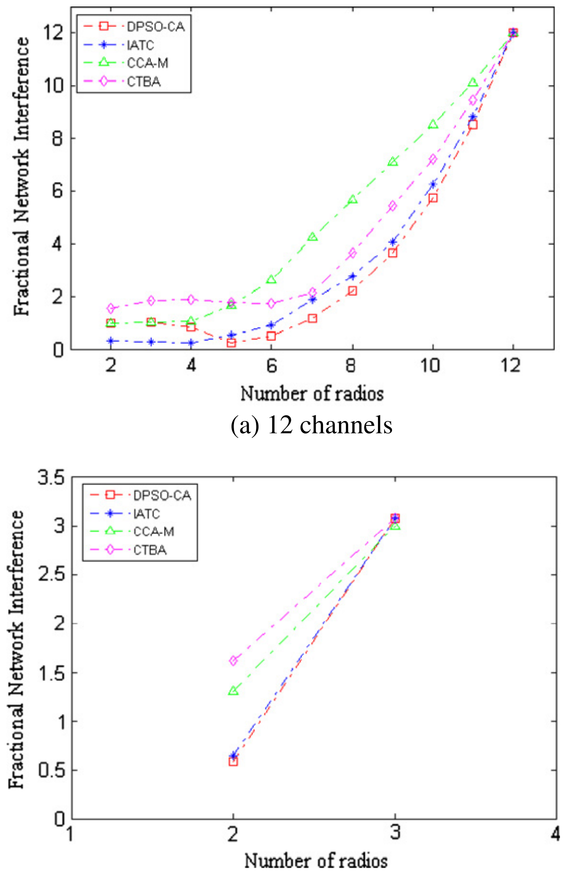
it is hard to find a feasible channel assignment scheme with the topology preservation. However, our DPSO-CA still gets 6.9% reduction compared with CTBA and CCA-M. The defect of CTBA might lie in its two-step operation mechanism: Although its first step can find a good solution, but the second step leads to interference increase by merging links violating the radio number constraint. Meanwhile, each particle in our DPSO-CA represents a feasible solution satisfying both the topology preservation and the radio number constraint. And this rule is also obeyed when particles fly in the solution space. It means that descendent particles generally have lower interference compared with their ancestors. And the final result of our DPSO-CA is expected to better than that of CTBA.

In the case that there are 12 channels and 2 radios, the DPSO-CA runs worse that IATC with an increasing ratio of 541%. Note that IATC is designed to provide connectivity guarantee instead of topology preservation, and in our simulation only 1-connectivity is required for the IATC. It is obvious that IATC can reduce more links compared with our DPSO-CA because the topology preservation is a harder constraint compared with the 1-connectivity. However, with the increasing of radio number, our DPSO-CA runs better than IATC. For example, in case that there are 12 channels and 5 radios, the fractional network interferences for DPSO-CA and IATC are 0.0719/0.5156 accordingly. The reduction ratio of DPSO-CA is about 86.1% compared with IATC. It shows that increase of radio number is helpful to improve the channel variation of the particles which lead to better results.

Fig. 6b shows the cases with three channels in the network. Note that the radio number is generally less than that of available channels. The conclusions similar to that of Fig. 6a can also be obtained.

Fig. 7 draws the experimental results in the dense networks (50 nodes). There are more nodes in the same deploying scenario and more links are added in the network topology. It also can be seen that our DPSO-CA runs better than CTBA and CCA-M in all scenarios. For example, in case that there are 12 channels and 5 radios, the fractional network interference is 0.2534/1.7637/1.6386 with DPSO-CA, CTBA and CCA-M separately. The reduction ratios of DPSO-CA are about 85.6% and 84.5%. In case that there are 12 channels and 2 radios, the reduction ratios are 34.6% and 0.5%.

In case that there are 12 channels and 2 radios, the DPSO-CA runs worse that IATC with an increasing ratio of 228%. However, with the increasing of the radio number, our DPSO-CA also runs better than IATC. For example, in case that there are 12 channels and 5 radios, the fractional



(a) 12 channels

(b) 3 channels

Fig. 7. Fractional network interference in dense network with 50 nodes.

network interferences for DPSO-CA and IATC are 0.2534/0.5264. The reduction ratios of DPSO-CA are about 51.9% accordingly.

Throughput is an important criterion to measure the performance of the channel assignment algorithm. The links share a common channel in the wireless communications, and the available bandwidth for a given link is determined by its interference links as well as the traffic load on them. In case that the traffic is unified in the network, the shared bandwidth for a given link can be obtained by Eq. (8) with the assumption that the link bandwidth is identical, and the network throughput is considered as the sum of link throughput.

Fig. 8 shows that DPSO-CA algorithm has larger network throughput than CTBA and CCA-M in the sparse network. For example, in case that there are 12 channels and 5 radios, the network throughput is 36.0/29.7738/30.7263 with DPSO-CA, CTBA and CCA-M separately. The increasing ratios of DPSO-CA are about 20.9% and 17.2%. In case that there are 12 channels and 2 radios, the network throughput is 8.7094/7.2110/8.0842 with the DPSO-CA, CTBA and CCA-M separately. The increasing ratios of the DPSO-CA are about 20.8% and 7.7%.

An interesting observation from Fig. 8b is that with the radio number increasing from 2 to 3, the network throughput has decreased with DPSO-CA. We can also find this trend in Fig. 8a with radio number increasing from 7 to 12. A possible explanation is as following. The radios have to select one among the same set of channels. It is more possible for two radios to choose a common channel in case that the radio number is too large. The overall interference number increases and the network throughput decreases accordingly. The similar conclusion can also be found in Fig. 9.

6. Discussion

In this section we have discussed the radio utilization problem on the mesh nodes and the case with uneven traffic in the network.

6.1. The radio utilization

Compared with the single-radio single-channel wireless networks, the mesh networks benefit from the usage of multiple radios on the mesh nodes. However, there is a link between two radios if they are assigned the same channel and within the transmission range of each other. If the channel assigned for one radio is different from that of

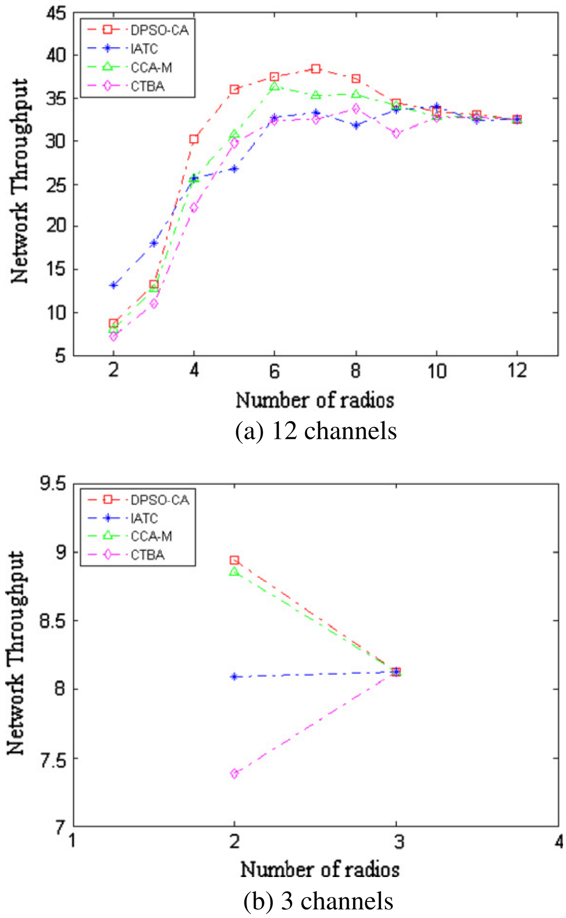


Fig. 8. Network Throughput in dense network with 25 nodes.

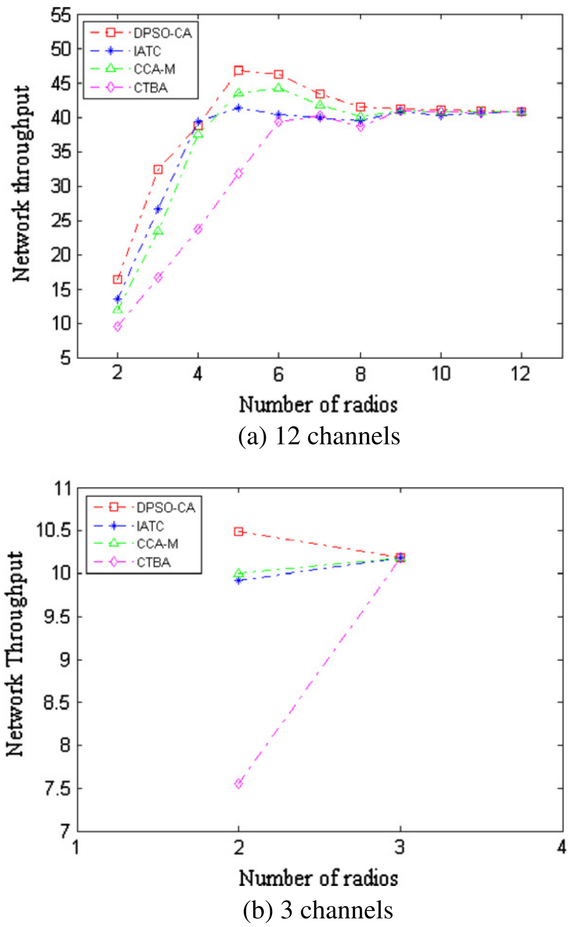


Fig. 9. Network Throughput in dense network with 50 nodes.

all other radios in the transmission range, the radio is un-utilized since no other radio it communicates with. Such a case shall be avoided so as to utilize all radios available. This problem is first discussed and named as the *radio utilization problem* in this paper.

The utilization of all radios in the network is expected to improve the network throughput while providing connectivity guarantee. In fact, we find that the case occurs that some radios are un-utilized in the DPSO-CA, CTBA as well as the IATC algorithm. For example, in the population initialization process of the DPSO-CA, we randomly select one channel for the radios. Such a channel assignment is considered as a feasible solution since it provides topology preservation and satisfies the radio number constraint. However, the radio utilization is not checked since the assignment is operated in random mode and the selected channel is not guaranteed to be used by neighbor radios.

Then we shall answer questions such as how to utilize the radios and how much benefit we can obtain from it. For the first question, we propose to modify our DPSO-CA algorithm by adding a new step at the end of the algorithm which is described as following.

Step 11: Check the utilization of radios for each node in sequence. If one radio is found un-utilized, the channel assignment for this radio is changed by randomly selected one available channel which is used by at least one neighbor and un-used by the node itself.

We extend our simulations and compared the initial DPSO-CA with the modified version (Step 11 is added) with criteria as the fractional interference number as well as the network throughput. As we can observe from Fig. 10, the increasing ratios of fractional interference number for the case using radio utilization are all no smaller than one in all situations compared with the initial DPSO-CA. This conclusion is expected because the radio utilizing will increase the overall interference number by changing the radio from a seldom used channel to a channel used by at least one neighbor radios.

In the sparse network with 25 nodes, we observe a significant increase of the network throughput in case that radio number is 4 or 5. However, with the radio number increasing, the impact has reduced directly. Furthermore, the network throughput changes within a limited range in the dense networks with 50 nodes. It might demonstrate that the radio utilization may be help in sparse network with radio number moderate. And its impact on the increasing ratio is just small enough in case that the radio number is close to that of the channel numbers.

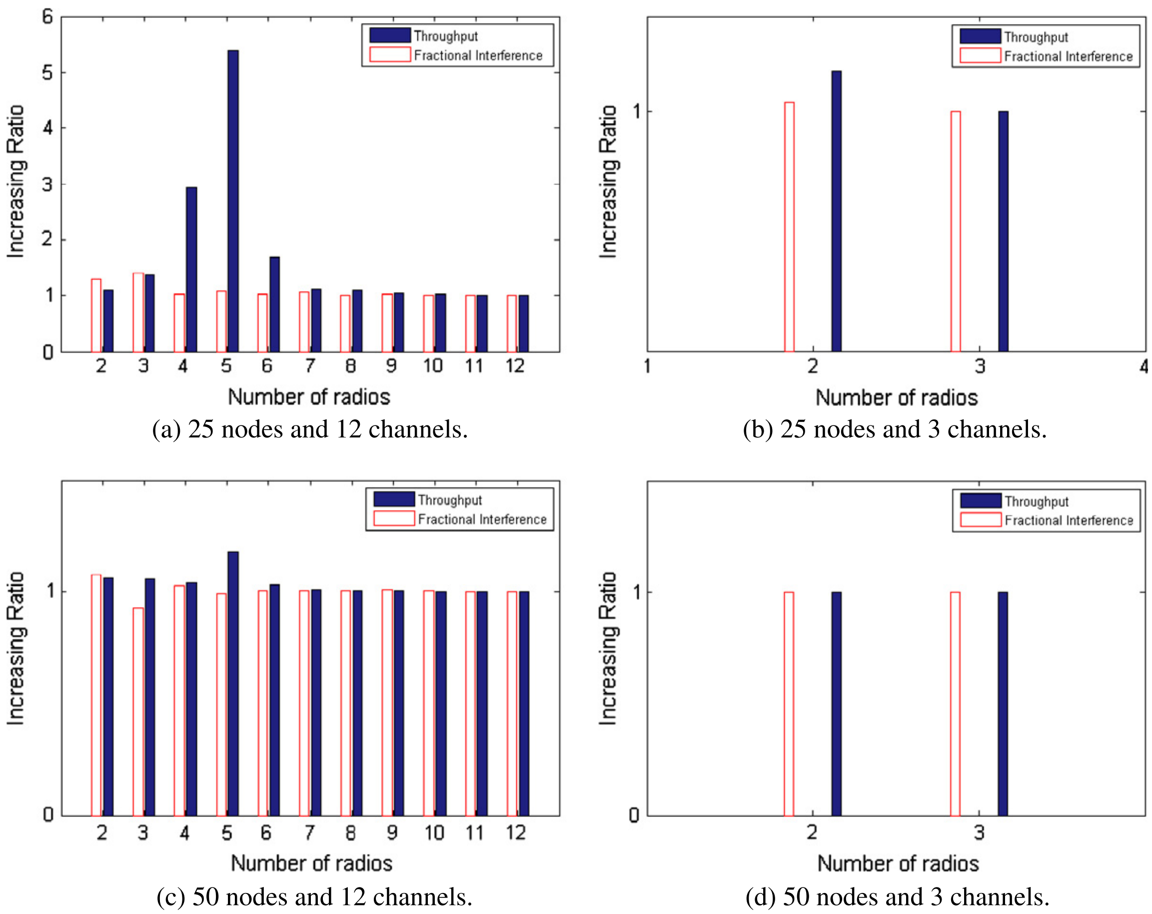


Fig. 10. Impact of radio utilization on the network throughput and fractional interference number.

6.2. The case with uneven traffic in the network

The broadcasting characteristic of wireless communications and the accordingly co-channel interference are the main factors that influence the network throughput in the wireless networks compared with that in the wired networks. The co-channel interference in the channel assignment problem is generally considered as the optimizing target used in many research works. In case that the traffic load in the network is unified on all links in the network, the network performance can be measured by the overall interference number. Our work follows this intuition and provides solutions to minimizing the overall interference number.

However, the wireless mesh network is expected to provide last-mile Internet access for mobile users. Traffic load is generated between end-users and the Internet gateways. The mesh node can aggregates the incoming data flow from end-users in the corresponding area, and forwards the data to the gateway. Packets originated from the Internet to the mobile user can be delivered in the reverse direction. Such application scenario has shown that the traffic load is generally uneven on the links in the mesh network. In such a case the channel assignment problem is a little different from that in the previous sections. For example, assuming that link e_1 is the potential interference link of e_2, they in fact do not interfere with each other even though they are assigned the same channel in the special case that the traffic load on either link is zero. This example has illustrated that we shall consider the traffic load on the links while assigning algorithms for the channel assignment problem.

Given the sets of source and destination nodes and the bandwidth requirement of the pairs, the traffic distribution on the links in the network is determined by the routing strategy used by the source and destination nodes. A single-path routing will try to find one path and all traffic loads is carried on the selected path. For example, shortest path routing (SPR) is generally used in the wired/wireless networks, in which hop count is considered as the metric for routing path selection. Shortest path routing is also compatible to the case that there are several gateway nodes in mesh networks. However, the shortest path is not guaranteed to provide the bandwidth requirement and other single-path routing protocols can be found in [16,21–23]. Another strategy is to use multiple paths among the source and destination nodes [25–28]. There are two obvious benefits with the multiple-path routing, i.e., load balancing and bandwidth guarantee. In case that one link is over-loaded, this strategy can select several paths to provide the required bandwidth. However, the multiple-path routing is more complicated and leads to high overhead in the network. Recently, a lot of research works have tried to combine the routing with the channel assignment problems together [6,8,24]. At the first glance, the idea sounds reasonable because it tries to optimize the network throughput in a unified framework. However, such work results are too complicated and cannot contribute to the application scenario. In this work, the routing strategy is isolated from the channel assignment problem which is more sophisticated and easy to realize.

In case that the routing protocol is given, the traffic load on the links can be obtained by summarizing the traffic contribution of each pair of source and destination nodes in the network. Let $w(i, j)$ be the normalized traffic on link e. The wireless mesh network can be modeled as a weighted graph $G = (V, E, W)$, where W is the set of weights for the links. The previous minimum-interference channel assignment problem is just converted into a *weighted* minimum-interference channel assignment problem. The definition of the potential interference number as well as the interference number in Section 3 can be modified as following.

Definition 2a (*Potential Interference Number*). The potential interference number of link $(i, j) \in E$ is the sum of weights of links in set E which interfere with link e according to the binary interference model.

Definition 3a (*Interference Number*). The interference number of link $(i, j; k) \in E'$ is the sum of weights of links in set E' which interfere with link $(i, j; k)$ according to the binary interference model and have the same channel number k as link $(i, j; k)$.

With the above definition, our approach based on the PSO algorithm can be applied without any modification for the weighted minimum-interference channel assignment problem since the interference number of link e has explicitly demonstrated the sum of traffic load of links that are interference links of e.

It shall be mentioned that the traffic between the mesh node and the mobile end-users is out of range of our algorithm. Our works have aimed at the aggregated traffic among the mesh nodes. The aggregated traffic in the corresponding area of one mesh node may stand stable for a period of time in the view of statistics, although the traffic between the source and destination nodes varies at different time. However, in case that the traffic has changed significantly in the network, a new channel assignment result is necessary to satisfy the user requirement which can be done by running our algorithm in regular intervals.

7. Conclusion

The throughput improvement of the wireless mesh network relies heavily on the utilizing the orthogonal channels. In this paper we have addressed the problem of channel assignment and aimed at minimizing the overall network interference while preserving the original topology. We have formulated an algorithm named as DPSO-CA which is based on the discrete particle swarm optimization and can be used to find the approximate optimized solution. The case with uneven traffic in the network is also considered and is formulated as a weighted channel assignment problem. It is shown that our algorithm is robust to this case with minimum modification. We also have discussed the radio utilization problem which appears in many current algorithms but is generally ignored. The impact of radio utilization has been researched too in this paper. Extensive simulation results have demonstrated that our algorithms have good performance in both fractional network interference and throughput compared with related works.

Acknowledgements

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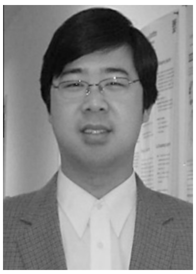

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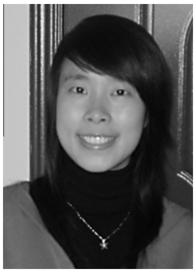

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