A mathematical formulation for joint channel assignment and multicast routing in multi-channel multi-radio wireless mesh networks

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ABSTRACT

Multicast routing is generally an efficient mechanism for delivering identical content to a group of receivers. Multicast is also deemed a key enabling service for a wealth of audio and video applications as well as data dissemination protocols over the last-mile backhaul Internet connectivity provided by multi-channel multi-radio wireless mesh networks (MCMR WMNs). Major prior art multicast protocols in these networks center around heuristic or meta-heuristic initiatives in which channel assignment and multicast routing are considered as two separate sub-problems to be solved in sequence. It might even be the cast that the solution for either of these two sub-problems is assumed to be preparatively calculated and given as input to the other. Within this perspective, however, the interplay between the two sub-problems would essentially be ruled out from the computations, resulting in sub-optimal solutions for network configuration. The work in this article is targeted at promoting the adoption of cross-layer design for joint channel assignment and multicast tree construction problem in MCMR WMNs. In the proposed scheme, contrary to the existing methods, these two sub-problems will be solved conjointly and an optimal solution is provided. In particular, a comprehensive cross-optimization framework based on the binary integer programming (BIP) formulation of the problem is presented which also addresses the *hidden channel problem* in MCMR WMNs. We have, as well, conducted an extensive series of simulation experiments to verify the efficacy of the proposed method. Also, experimental results demonstrate that the proposed method outperforms the genetic algorithm and the simulated annealing based methods proposed by Cheng and Yang (2011) in terms of interference.

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1. Introduction

Wireless mesh network (WMN) is an emerging technology primarily aimed at provisioning for wireless Internet access and scalable QoS-aware delivery of heterogeneous traffic over an integrated milieu of both ad-hoc and infrastructure operation modes (Akyildiz and Wang, 2005; Martínez and Bafalluy, 2010). A typical deployment of a WMN is comprised of three layers: the highest layer consists of one or more *gateways*, also referred to as *mesh portals*, which connects the WMN to wireline Internet and enables the traffic exchange in between the two networks. The middle layer, however, features the *mesh routers* which form the WMN's backbone and are in charge of managing the traffic flow across the mesh setting. The nodes located at the lowest layer are essentially the network users (*mesh clients* in WMN's parlance) with limited capability. This level may also consist of several

WLANs or cellular networks. Contrary to mobile ad-hoc networks (MANETs), the wireless mesh backbone is usually stationary, and as opposed to wireless sensor networks (WSNs), there is no limitation on the nodes' power consumption. An indispensible concern in WMNs, however, is to boost the physical layer capacity and to reduce interference, which is normally achieved by equipping each node with a limited number of radios, usually less than or equal to the number of available channels (Ma et al., 2008; Baul et al., 2004). Each node would then be able to transmit and receive data simultaneously through different channels (Gupta and Kumar, 2000; Das et al., 2006; Xu, 2006). Wireless mesh networks operating with multiple channels on multiple radio interfaces are henceforth referred to in this article as MCMR WMNs.

Of the niche areas of application in the context of MCMR WMNs are multicast-based systems such as video conferencing, online games, webcast and distance learning, to name a few. While wireless communication is intrinsically apt for performing multicast routing due to the broadcast nature of the air medium, the inter-channel interference in WMNs plays a key factor in determining the actual data rate achievable for a multicast service.

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The issue of interference reduction in MCMR WMNs is typically dealt with by developing a channel assignment strategy which effectively specifies the most appropriate channel-radio associations. However, channel assignment brings about its own complications; in effect, an additional constraint ought to be satisfied for network connectivity in MCMR WMNs as compared to the conventional wireless networks; more specifically, two nodes are considered neighbors only if: (1) they are located within the transmission range of each other and; (2) there exists a common channel assigned to the radios of both nodes. This second constraint essentially complicates the multicast routing problem in that the multicast tree construction should necessarily be performed in accord with channel-radio associations such that the overall interference in the network is kept at minimum. The channel assignment problem has previously been investigated in the context of unicast routing by many researchers (e.g. Skalli et al., 2007; Subramanian et al., 2007; Mohsenian and Wong, 2006; Ramachandran et al., 2006; Marina and Das, 2005; Das et al., 2005; Alicherry et al., 2005; Tang et al., 2005; Raniwala et al., 2004; Tasaki et al., 2004; Kodialam and Nandagopal, 2005); unicast-based interference reduction schemes can, in essence, be classified along the lines of the following two categories:

- Disjoint
  - channel assignment on a given routing topology (Mohsenian and Wong, 2006; Das et al., 2005; Raniwala et al., 2004)
  - routing over a given channel assignment scheme (Subramanian et al., 2007; Ramachandran et al., 2006; Marina and Das, 2005; Tang et al., 2005)
- Joint channel assignment and routing (Alicherry et al., 2005; Kodialam and Nandagopal, 2005)

Obviously, unicast-based implementations are not readily applicable or at least scalable enough to be employed in the one-to-many paradigm of a typical multicast communications setting. Moreover, given the bandwidth-constrained operation of wireless networks, the existing wireline multicast solutions cannot be ported to mesh systems without fundamentally changing their behavior to reduce overhead. Multicasting in MANETs and WSNs also address route recovery and energy concerns, respectively, which are characteristically different from the pivotal issues of throughput and interference raised in the middle layer of MCMR WMNs. Routing in these networks is further complicated given that the multiple radios on each node may dynamically switch on different channels. WMN-based multicasting has been discussed in Keegan et al. (2008), Ruiz and Gomez-Skarmeta (2005), Roy et al. (2008), Zhao et al. (2006), Yuan et al. (2006), Shittu et al. (2008), Ruiz et al. (2006), Akyildiz and Wang (2008)and Palomar and Chiang (2006), albeit for single channel single radio scenarios, as well as in Karimi et al. (2010) for multi-channel single radio settings, which characterize significantly different network configurations and thus lie outside the scope of this paper.

Fig. 1 depicts an example of the joint multicast tree construction and channel assignment problem in an MCMR WMN. The node 'MS' (i.e. multicast source) sends the same data to multicast targets which happen to be connected to different networks at the lowest layer of the mesh hierarchy. MT1 through MT4might, for instance, be laptops, cell phones, PDAs, or even a sensor node. The numbers printed next to the links denote the channel-radio associations. Despite its vast number of applications and practical importance, few works have specifically been targeted at multicast performance optimization in MCMR WMNs. The mainstream of research in this area has considered the channel assignment and multicast routing as two disjoint sub-problems to be solved in sequence (Zeng et al., 2007; 2010; Cheng and Yang, 2008a; 2008b; in press; Lim et al., 2009); as envisaged in Nguyen and
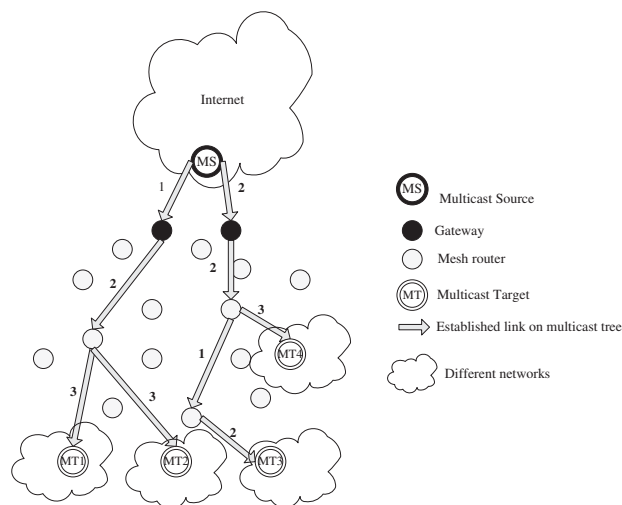

Fig. 1. An example of multicast tree construction in MCMR WMNs.

Nguyen (2008; 2009a; 2009b) and Yin et al. (2007), it might even be the cast that the solution for either of these two sub-problems is assumed to be preparatively calculated and given as input to the other. The downside associated with these schemes, however, is that the cross-interaction between the two sub-problems would not be accounted for and that their reliance on heuristic or meta-heuristic initiatives does not come up with the optimal solution.

In general, practical network-driven application scenarios call for proper mathematical formulations of the underlying logic to ensure the optimality of the resultant configurations and of the choices made for performance tuning parameters. To the best of our knowledge, no previous study has explored the mathematical formulation for the joint channel assignment and multicast tree construction problem in MCMR WMNs. Therefore, in this article, for the first time, we present a cross-layer optimization framework for the joint channel assignment and multicast tree construction problem. In comparison with the existing schemes, the two sub-problems would be solved conjointly and their impact on each other will be thoroughly examined. Our proposed framework is based on binary integer programming (BIP) which is particularly interesting given its specific capability in fully utilizing a larger pool of available resources (viz. channels and/or radios) in order to come up with the most efficient assignment scheme necessary for multicast routing interference minimization. Moreover, the solution resultant from a BIP formulation of the problem basically serves as a yardstick for performance evaluation of comparable centralized and/or distributed methods.

Given the relatively limited scale of typical WMN deployments and their arguably low density (Nguyen and Xu, 2007; Nguyen, 2008), a BIP-based formulation would prove a reasonable choice. BIP models also exhibit appropriate degrees of flexibility in that in many cases we might be able to extend the problem definition with new constraints simply via adding new variables and inequalities. Our proposed model also accounts for the *hidden channel problem* (Lim et al., 2009), which typically occurs when two-hop away nodes attempt to tune on the same channel. Finally, we demonstrate the efficacy of our approach through an extensive set of experimental evaluations.

The reminder of this paper is organized as follows: In Section 2, we survey the prior art multicast methods in MCMR WMNs and would highlight their advantages as well as the associated performance issues. Our mathematical formulation for the cross-optimization of the joint channel assignment and multicast routing problem will be presented in Section 3. In Section 4, we examine the

correctness of our approach with respect to connectivity and loop occurrence and will also discuss the outcome of several performance measurement studies. Section 5 concludes the article.

2. Related work

There are some works on multicast routing in single-channel single-radio WMN. For example in Keegan et al. (2008) a method for multicast tree construction has been proposed in which channel assignment is not considered. Authors have tried to optimize shortest path tree (SPT) with regard to edge cost using interference and transmission rate. In this reference multicast routing details were not mentioned. A hybrid method is presented for multicast routing in Shittu et al. (2008). In this reference a multicast proactive method is proposed for routing across the network backbone together with a multicast reactive method for communication between client and access points. But proposed method is not evaluated. In addition, the channel assignment problem has not been considered. A throughput maximization problem which jointly considers the multicast routing problem at the network layer and the power control problem at the physical layer has been reported in Yuan et al. (2006). This issue utilizes network utility maximization (NUM) (Palomar and Chiang, 2006). Unlike this reference in which throughput maximization problem is considered and multicast tree is not constructed, here we focus on joint channel assignment and multicast tree construction. Since this method is proposed for single channel single radio wireless mesh network, it differs from our work in which the assumption of multiple channels and multiple radios complicates the issue. There are also many other researches in the field of multicast routing in single-channel single-radio WMN that stay outside the scope of this paper (Ruiz and Gomez-Skarmeta, 2005; Roy et al., 2008; Zhao et al., 2006; Ruiz et al., 2006; Akyildiz and Wang, 2008).

In Karimi et al. (2010) the focus is on designing multicast solutions for the problem of throughput maximization in multi-channel single radio WMN. In this approach initially multi-channel single radio WMN multicast problem is formulated into a mathematical program, and then an iterative primal-dual optimization framework for it based on Lagrange relaxation and primal problem decomposition has been designed. Then an iterative heuristic channel assignment at the MAC/PHY layer for each sub-problem has been proposed. Our work differs from this reference in that the problem reported in this reference is throughput maximization in which multicast tree is not constructed, but here the problem is joint channel assignment and multicast tree construction with minimal interference. Also unlike to this reference we work on MCMR WMN in which the presence of multiple radios further complicates the problem.

In Gopinathan et al. (2009), multicast throughput optimization in MCMR WMN is modeled as an integer linear programming (ILP). In this centralized method, authors believe that the pure LP model loses its efficiency in a large-scale network. Therefore, its LP relaxation was used and two methods for the throughput optimization have been proposed. In the first approach, initially using breadth-first search (BFS) channels are greedily assigned to radios. The result of channel assignment phase is considered as input to LP model and then the network throughput model is solved. The second approach essentially relies on iteration. Here, much in the same way as the previous scheme, at first channel assignment phase using BFS algorithm is greedily done and is applied to the LP model as input. In the next step, the resultant channel assignment scheme will be corrected and solved by the LP model again. The weakness of this approach is that, using BFS and greedily channel assignment does not lead to optimal solution. Moreover, performing channel assignment initially and then solving the LP model does not guarantee the optimal solution. That means separation of the issue into two sub-problems and solving them sequentially is not a good idea. In other words, considering the impact of channel assignment in MAC layer and multicast routing in the network layer on each other is a must (Akyildiz and Wang, 2008), which has been neglected in Gopinathan et al. (2009). In sum, in this method multicast tree construction is not considered and hence differs from our work. In Chiu et al. (2009), a call admission control for multicast in multi-radio multi-channel WMN was proposed which is different from our work too.

However, our focus is mainly on joint channel assignment and multicast tree construction in MCMR WMNs. This issue has been discussed only in papers (Zeng et al., 2007; 2010; Nguyen and Nguyen 2008; 2009a; 2009b; Yin et al., 2007; Cheng and Yang 2008a; 2008b; 2011; Lim et al., 2009). The objective of these papers is minimizing the interference between multicast links in order to maximize the throughput. Generally, the existing schemes in the field of joint channel assignment and multicast tree construction problem in MCMR WMN can be divided into three categories:

- The methods which have assumed channel assignment is already performed and the main issue is how to construct a multicast tree (Nguyen and Nguyen, 2009).
- The methods which have assumed the multicast tree has already been constructed and thus channel assignment is the core problem (Nguyen and Nguyen, 2008; 2009; Yin et al., 2007).
- The methods in which both multicast tree construction and channel assignment are performed sequentially (Zeng et al., 2007; 2010; Cheng and Yang 2008a; 2008b; 2011; Nguyen and Nguyen, 2009; Lim et al., 2009).

In this section, we survey the researches in the field of joint channel assignment and multicast routing problem in MCMR WMNs:

Reported works in Zeng et al. (2007; 2010), Nguyen and Nguyen (2008; 2009a; 2009b), Yin et al. (2007), Cheng and Yang (2008a; 2008b; 2011) and Lim et al. (2009) are closer to our work. In Zeng et al. (2007) and in its extended version in Zeng et al. (2010), two methods for multicast tree construction and channel assignment in MCMR WMN have been proposed. In the first method of this reference, at first mesh nodes according to BFS starting from multicast source are visited. Therefore, nodes are placed at different levels (number of hops from source to multicast group members). In the next step, multicast tree is constructed according to the following algorithm: Initially, the sender node and all receiver nodes of multicast group are included in the multicast tree. In the next step, forwarding nodes in multicast tree should be specified. So, taking on a bottom-up approach, if each receiver node v has several parents and one of their parents is on multicast tree, this receiver is connected to that parent (f_v). Otherwise, one of the parent nodes is selected randomly and one link is established to that parent (f_v). The algorithm for node f_v would continue recursively. After constructing multicast tree, using the algorithm 'LCA' (level channel assignment), channels are assigned to nodes according to what level of BFS traversal tree they are located. In other words, channel i is assigned to nodes located in level i of the tree. Advantage of the above method is its simplicity. But its disadvantage regarding both multicast tree construction and channel assignment phases can be stated as the following:

- Regarding multicast tree construction, when a multicast receiver has several parents that none of them are included in multicast tree, selecting randomly one of them as a parent node is not a good idea. Also, from which receiver node multicast tree construction algorithm should be initiated is not a trivial issue. Because the resultant trees will be different

and the number of packet copies can be increased. Therefore, the interference would be increased which leads to throughput decreasing.

- Regarding channel assignment, some nodes that are placed in the same level may have interference. Also, if the number of channels is more than the number of levels, the other channels will not be used.

Another method named 'MCM' (multi-channel multicast) for overlapping channels has been proposed in this reference. In this method, initially, tree nodes are placed at different levels using BFS. At the next step, the edges which are between the nodes at the same level are omitted. Then, the minimum relay nodes (RN) which form the multicast tree should be determined. Authors have presented the following approximation algorithm:

1. Parents can be chosen as RN if one of their children has a fewer number of parents.
2. Between candidate RNs, a node with the largest number of children is selected.
3. Selected RN and its children are removed from the tree and steps 1 and 2 are repeated until all nodes placed in level $i+1$ are removed.

The major drawback associated with this multicast tree construction method is its overhead. After constructing the multicast tree, two channel assignment methods as follows have been proposed: In the former named 'ascending channel assignment', from top to down, channels have been assigned to levels from number zero. Once run out of channels, the algorithm re-assigns channel zero to the nodes of the next level and on the process repeats. The following highlights the disadvantages of this channel assignment scheme:

- If the number of sibling nodes is not equal in the whole tree, *under-utilization* may occur in some channels.
- *Hidden channel problem* may occur.
- If the tree is almost diagonal, similar problems as those mentioned for LCA (Zeng et al., 2010) may arise.

As for the second approach discussed in Zeng et al. (2010), referred to as 'Heuristic Channel Assignment', the channel separation concept is utilized. Channel separation indicates the disparity between two channel numbers. For example separation between channels 2 and 5 is 3. In this method when a channel is assigned to node u, it should minimize the sum of squares of interference factor (Ding et al., 2008) between node u and all nodes v in its neighborhood. Probably, the most significant advantage associated with this perspective lies in the factoring of throughput and delay into the evaluations. The impact of network size, channels, transmission range in simulation is considered too. Some of the drawbacks with this assignment can be stated as follows:

- This method considers its single-hop neighbors only, so *hidden channel problem* may occur.
- Since interference factor is a variable which depends on both transmission range and network condition, there is no fixed relationship between interference range and channel separation. So, if we are supposed to use this method, network condition and transmission range should be specified.
- In addition, interference factor may be different in one part of the network compared to another part which might lead to channel fluctuation.
- Also, if channel separation is greater than or equal to a threshold, interference factor is zero. Therefore, several channels may

satisfy the conditions. In this situation, random selection of channels is not rational.

In Nguyen and Nguyen (2008) and its extended version in Nguyen and Nguyen (2009), authors in order to cope with *hidden channel problem* of Zeng et al. (2007; 2010) and to improve interference have proposed a rational function for evaluation of assignment of channel c to node v. In the denominator of the function, the maximum channel separation is divided to minimum channel separation. The numerator of the function is product of the channel separation between the node v and its one and two hop neighbors. Therefore, in this method which is called M4, *hidden channel problem* is solved by adding channel information of nodes located within two hopes to objective function. This information can be achieved by sending broadcast messages by each node to all of its neighbors. Each node by receiving this message adds its channel information to the message and re-broadcasts. In the aforementioned function, those nodes are considered which channel is already assigned to them. It is worth mentioning this reference assumes that multicast tree is readily available. It also relies on heavy broadcast message exchanges. Another weakness of this method is that the joint channel assignment and multicast tree construction is separated into two sub-problems in which the impact of the two sub-problems on each other is not considered. This strategy, thus, does not lead to optimal solution.

An evaluation function for assignment of channel c to node v is also proffered in Yin et al. (2007). In this function, the assignment of channel c to node v is evaluated based on the probability of packet transmission by neighboring nodes of v on channel c. However, the authors have not specified how this probability is computed. In addition, in this reference, nodes according to BFS are met in order by the first level and channels are assigned to them greedily but, gathering this information from all the edges induces too much overload. In this reference, it is supposed that multicast tree is already constructed and then the channel assignment is performed. This method does not provide the optimal solution.

In Cheng and Yang (2008) and its extended version in Cheng and Yang (2011) another method based on genetic algorithm was proposed. In this work, the binary interference model is used; i.e. two edges whether interfere or not. In this method, it is tried to reduce the end-to-end delay in multicast tree. Here, each multicast tree is represented by a two dimensional array (chromosome) each row of which determines a path from multicast source S to the receiver R_i. So if we have K receivers, the chromosome has K rows. The number of columns in the chromosome is equal to the maximum path length from S to the multicast group members. Representation of the chromosomes is based on the nodes' IDs that are along the path from sender S to the multicast group members. In this method, chromosomes are created as follows: the algorithm begins from the multicast source node S. One of the Node S's one-hop neighborhood is randomly selected and its ID is inserted into the chromosome. This process continues to the end till reaches receiver R_i. Thus, a row of chromosomes is made. Then the above method for the next receiver (next row) is repeated. After constructing the multicast tree for each row of the chromosome which is a path from S to R_i, channel is assigned to the edges sequentially. The initial value of n is zero and it is incremented by one after passing each edge. The reason is three channels are available. The fitness function for chromosome is defined such that if there are many multicast trees (chromosomes) that have an identical number of interfering links in the conflict graph, the tree with the lowest delay will be chosen. Fitness function was defined as the inverse of interference. The disadvantages of this method are as follows:

- The joint problem is divided into two sub-problems and solved sequentially in which cross-layer interactions are not neglected.

- This method does not provide the optimal solution
- In addition, the assignment of the channels to each row of the chromosome is subject to similar shortcomings as those of the LCA algorithms; i.e. the *hidden channel problem* is not accounted for.
- Interference among the nodes of a same level in the multicast tree may occur.
- If the number of channels is more than the number of multicast tree levels, some channels will not be used at all.
- It has too overhead.

Another method was also proposed in Cheng and Yang (2011) that utilizes simulated annealing (SA) algorithm. Solution representation, fitness function and channel assignment of this method is the same as the genetic based method described above. SA performs searching from one solution to one of its neighbors in the solution space. Hence, authors proposed two methods to construct the neighborhood. In the first method called fine-grain adjustment, one receiver R_i is randomly selected, and then a node v_i on the path from source to the receiver R_i is randomly selected. Then using the algorithm described in genetic based method, the sub-path between v_i to the selected receiver R_i is replaced by a new one. In the second method, namely coarse-grain adjustment, the first method is performed for two randomly selected receivers together. In the first half of temperature decreasing procedure fine-grain and in the rest of it coarse-grain adjustment is applied. In this method, initially LCA (Zeng et al., 2010) and shortest path based trees are generated and then channel assignment is performed. Then their interference is computed and the tree with the lower interference is selected as initial solution and its neighbors should be constructed according to above two methods.

The methods proposed in Zeng et al. (2007; 2010), Nguyen and Nguyen (2008; 2009), Yin et al. (2007) and Cheng and Yang (2008a; 2008b; in press) either construct a multicast tree or have assumed the tree is already constructed and then channels are assigned. In Nguyen and Nguyen (2009), however, the channel assignment is supposed to be done a priori and instead, the multicast tree should be constructed. In this centralized multicast tree algorithm, named 'Minimum Number of Transmission' (MCMNT), it is attempted to minimize the number of copies of a packet on different channels in each node. In this reference, a method for evaluating the cost of links was proposed and the cost of a path is equal to the sum of the cost of the edges on the path. Hence, the objective is to construct a tree with minimum cost using either the Dijkstra or the Bellman_Ford algorithm. The disadvantages of this method are as follows:

- It is assumed that one of the sub-problems is already prepared. In this case, the impact of the two sub-problems on each other is not considered.
- This strategy does not lead to an optimal solution.

- It is not specified that which channel is considered for computing the link cost.

The methods reported in Zeng et al. (2007; 2010), Nguyen and Nguyen (2008; 2009a; 2009b), Yin et al. (2007) and Cheng and Yang (2008a; 2008b; 2011) have not proposed any protocol for nodes joining/leaving to group/from the group. Thus, in Lim et al. (2009), a distributed bottom-up approach to construct multicast tree as well as assignment of the channels has been proposed. In this method, initially using the following approximate algorithm, the minimum RN's set is generated and the multicast tree is constructed:

1. At first, the node selects its two-hop neighbors with the fewer parents.
2. Some of the parents of two-hop neighbors are candidate such that the selected ones have fewer children.
3. Candidates with the best link quality will be selected.
4. The selected nodes and all of its children are removed from the single-hop and two-hop node's list.
5. This algorithm continues until both single-hop and two-hop neighbors' list would be empty.

After determining the set of RNs, a node, willing to join the group, sends a unicast joint_REQ message to its parent. Then the parent node selects a node from its parent candidate list and gives information to his parent too. Every node that receives joint_REQ should send joint_REP. Embedded within these messages is the information on channel settings. In case the node sending the joint_REQ message happens to be the first child node of its parent, the 'channel adjustment information' is equal to the fixed channel of the sender node. In this case, if the fixed channel of the sender and receiver are the same, the parent node selects another channel to prevent interference. If the node that sends joint_REQ is not the first child of its parent, then channel adjustment information equals to the channels used by the majority of the children of the current node's. Over the course of the subsequent step, joint_RPL is sent to the requesting node. Upon receiving the joint_RPL message, the node switches its fixed channel according to channel adjustment information and keeps this channel fixed during multicast session. The drawbacks associated with this method are as follows:

- The underlying heuristic model may not provide the optimal solution.
- The *hidden channel problem* may occur.
- Heavy broadcast message exchanges are required to place nodes across levels.

Table 1 summarizes the existing methods with respect to their underlying idea for both multicast tree construction and channel

Table 1
Summary of the existing joint multicast tree construction and channel assignment methods.

Reference	Multicast tree construction	Channel assignment
Zeng et al. 2007, 2010	A centralized heuristic bottom-up algorithm which utilizes BFS	An ascending method named LCA An ascending method
	A centralized approximate top-down algorithm named MCM	A heuristic method based on channel separation which only considers single-hop interference
Nguyen and Nguyen (2008, 2009)	Multicast tree is assumed to be constructed a priori.	An improved version of Zeng et al. (2010), named M4, which also considers two-hop interference.
Yin et al. (2007)	Multicast tree is assumed to be constructed a priori.	A greedy channel assignment that utilizes BFS
Cheng and Yang 2008a, 2008b, 2011;	A centralized algorithm based on genetic algorithm and simulated annealing	An ascending method
Nguyen and Nguyen (2009)	A heuristic method, named MCMNT, for computing edge cost, coupled with minimum cost tree construction using either the Dijkstra or the Bellman-Ford algorithms	Channel assignment is assumed to be performed a priori.
Lim et al. (2009)	Improved version of MCM which factors in the link quality	A heuristic algorithm

assignment. In sum, the major drawback with the existing methods is that they have considered channel assignment and multicast tree construction in the form of two independent issues and thus have taken on an essentially sequential approach to the problem. In particular, the cross-interaction between multicast at the network and channel assignment at the MAC/PHY layer is not accounted for in Zeng et al. (2007), Cheng and Yang (2008a; 2008b; 2011) and Lim et al. (2009), and even in some methods, it is assumed that the solution for either of these two sub-problems is pre-calculated (e.g., Nguyen and Nguyen 2008; 2009a; 2009b; Yin et al., 2007). This is while cross-layer design forms an integral part of a successful WMN-based implementation, as has been extensively and methodically argued in Akyildiz and Wang (2008).
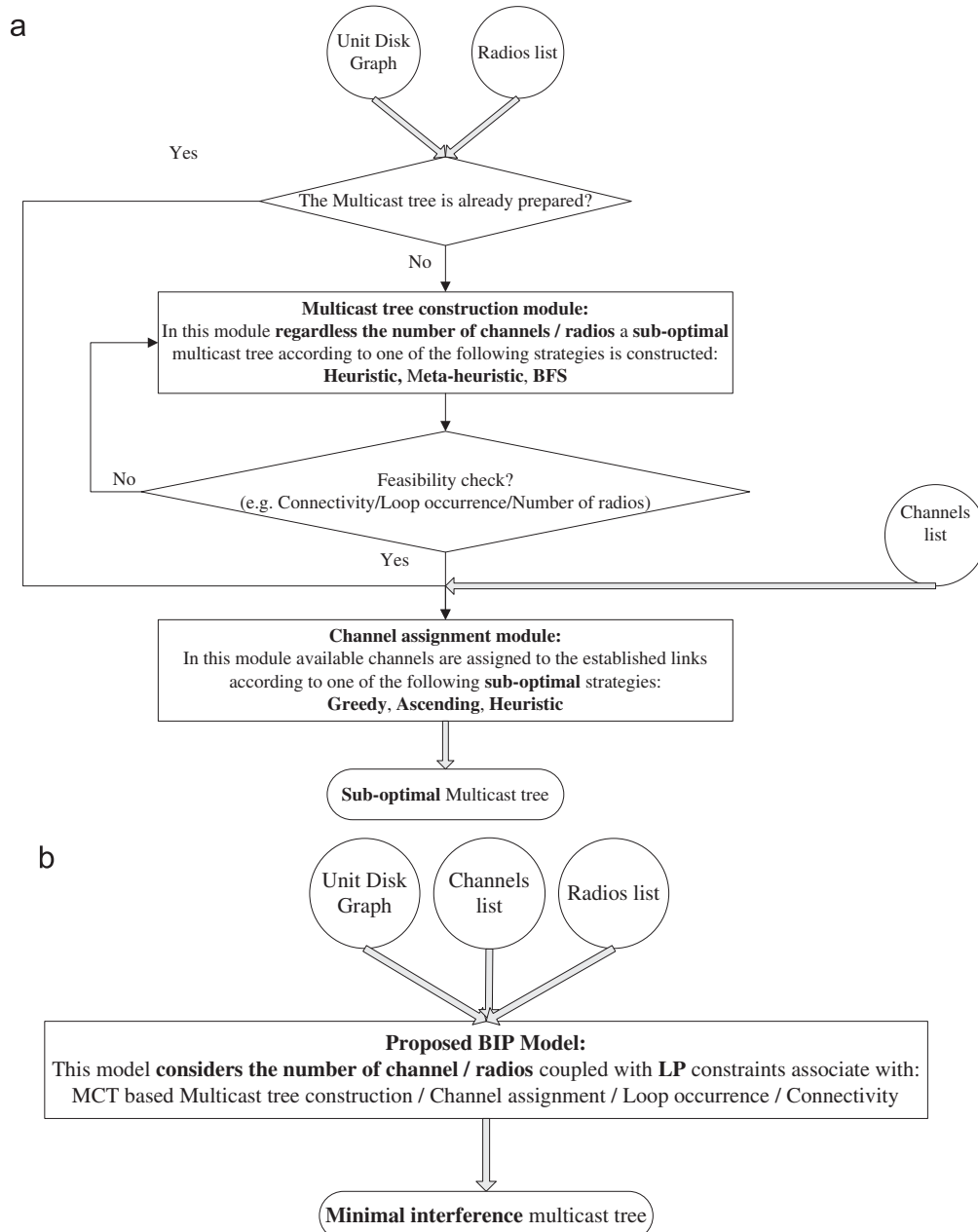
Moreover, all the reviewed schemes, except of course for Lim et al. (2009), are built around a centralized perspective, and their heuristic mentality is essentially incapable of providing the optimal solution.

Based upon this understanding, the prime intention in this article is to cross-optimize the joint channel assignment and multicast tree construction in MCMR WMNs. Fig. 2 depicts the flowchart of the proposed method as compared with that of the existing methods except to Nguyen and Nguyen (2009) in which the channel assignment is assumed to be already prepared and then multicast tree should be constructed. This figure highlights the differences of our framework to the existing method in bold characters.

In what follows, we present the details of the mathematical formulation for these two sub-problems.

3. Mathematical framework

The proposed framework in this paper is based on a binary integer programming (BIP) model which, compared to the

Fig. 2. Flowchart of the proposed methods compared to the existing methods. (a) Flowchart of the existing algorithms in which two sub-problems multicast tree construction and channel assignment are solved sequentially leading to a sub-optimal solution. (b) Flowchart of the proposed mathematical framework in which two sub-problems multicast tree construction and channel assignment are solved conjointly.

previous heuristic or meta-heuristic-based models, guarantees an optimal solution. Clearly, BIP is a special case of linear programming (LP) that is a mathematical method for determining a way to achieve the best solution for some linear equality/inequality constraints given in the mathematical model. Geometrically, the linear constraints define the feasible region, which is a convex polyhedron. In this region, if a feasible solution exists and also if the linear objective function is bounded, then the optimum value is always achieved on the boundary of optimal level-set, by the maximum/minimum principle for convex/concave functions (Boyd and Vandenberghe, 2004). On the other hand, the mathematical foundation underlying the BIP model ensures global optimality of the solution contingent upon coming up with an all-inclusive/exclusive formulation of the problem of interest in terms of constraints, parameters and variables.

3.1. System model and assumptions

In this section, we present our mathematical formulation for the cross-optimization of multicast tree construction with minimal interference. Studies (Nguyen and Xu, 2007; Nguyen, 2008) have undertaken a thorough investigation of the most widely multicast construction strategies namely shortest path and minimum cost tree (SPT and MCT). In scenarios entailing high multicast transmission rates, SPT-based multicast substrates incur a heavier loss of packets in comparison with their MCT counterparts, which is primarily due to the larger number of forwarding nodes for SPTs in general. On the other hand, MCT algorithms produce longer paths than SPT algorithms. Under light or moderate traffic, SPTs and MCTs have similar effects on flows in the network. In sum, it is argued in Nguyen and Xu (2007) and Nguyen (2008) that given the relatively limited scale of a mesh setting, access to global knowledge on topological information would be a fair assumption within the middle layer of a WMN; moreover, assuming the low density of mesh nodes, the minimum cost tree (MCT)-based construction of the multicast substrate is typically preferred for its comparatively less bandwidth consumption. We have accordingly formulated our BIP model to find the (MCT)-based multicast tree.

As for interference computation, like Zeng et al. (2007; 2010), Nguyen and Nguyen (2008; 2009a; 2009b), Yin et al.

(2007), Cheng and Yang (2008a; 2008b; 2011) and Lim et al. (2009) we have adopted the Protocol model described in Crichigno et al. (2008) and Hossain and Leung (2008). In this model, a given transmission from a node Src to a node Des is said to be successful only if: (1) the nodes' distance is less than the transmission range, and (2) no third node, $Temp$, located within the interference range of the receiving node Des, is transmitting. The adopted model can further be refined to comply with IEEE 802.11-style MAC protocols; i.e. the sending node Src is also required to be free of interference as it needs to receive the link layer acknowledgement from the receiving node Des. Specifically, any node $Temp$, which is within the interference range of Src or Des, should not be transmitting.

Other assumptions include: all mesh routers are distributed randomly on a plane. Each router is equipped with multiple radio interfaces, and the number of radios is not more than that of the available non-overlapping channels. All radio interfaces on wireless routers make use of omni-directional antennas, and have identical transmission/interference ranges.

3.2. Notations and problem formulation

In this subsection, the predefined sets, parameters, variables and constraints needed for our BIP formulation will be presented. The required set definitions and problem parameters are listed in Tables 2 and 3, respectively. As can be seen in Table 3, we model a WMN as a graph $G=(V, E)$, with nodes V and links E.

Since interference in the context of Protocol model is measured in terms of the number of interfering links, which is obviously an intrinsically integer quantity, the $Interference(Src,SR,Des,DR,C_i)$ variable used in our formulations is inevitably of integer type. Accordingly, $Link(Src,SR,Des,DR,C_i)$ in Eq. (1) is a binary variable which determines whether or not there is a link between radio SR of Src and radio DR of Des using channel C_i

$$Interference(Src,SR,Des,DR,C_i) = Link(Src,SR,Des,DR,C_i)$$
$$\times SIL(Src,SR,Des,DR,C_i) \qquad (1)$$

SIL (Sum of Interfering Links) in the above formula denotes the sum of the neighboring links which use the channel C_i. Clearly, if a link is established, then its interference is equal to variable SIL; otherwise, it is zero. Also, constraints (12)–(14), listed in Table 5, correspond to the multiplication of the two variables $Link$ and SIL in BIP terms.

Other variables and constraints used within the BIP model are listed in Tables 4 and 5, respectively, together with their associated descriptions.

Finally, the objective is to minimize the total number of links together with the overall interference; as specified below:

$$Minimize(Total\ links + Total\ interference)$$

Table 2
Required set definitions.

$Nodes = \{N_1,N_2,N_3,...,N_n\}$	mesh routers
$Channel\ list = \{C_1,C_2,C_3,...,C_c\}$	channels
$Multicast\ source = \{N_i\}, N_i \in Nodes$	multicast sources
$Multicast\ group = \{T_1,T_2,T_3,...,T_t\}, T_i \in Nodes$	multicast group
$Radio = \{R_1,R_2,R_3,...,R_r\}$	mesh routers' radios
$R(N_i), N_i \in Nodes$	node N_i 's Radios

Table 3
Parameter definitions.

$G=(V,E)$ /*A directed graph representing a multi-channel multi-radio wireless mesh network*/
R_T /*Transmission range*/
$R_I = q \times R_T, q \geq 1$ /*Interference range*/
$d_{Src,Des}, Src,Des \in Nodes$ /*Euclidean distance between mesh nodes Src and Des*/
$UDG(Src,Des), Src,Des \in Nodes$ /*A binary neighborhood matrix, named as unit disk graph, which is computed using R_T and
  $d_{Src,Des}$ and specifies whether there is a link between Src and Des or not*/
$|R(N_i)|, N_i \in Nodes$ /*Number of radios for node Src*/
$IsNeigh(Src,Des,Temp1,Temp2)$, $Src,Des,Temp1,Temp2 \in Nodes$
  /*A binary parameter which determines whether $Temp1$ or $Temp2$ is in interference range of Src or Des or not*/

Table 4
Variable definitions.

$F_{C_i,SR,Src}$, $Src \in Nodes$, $SR \in Radios$, $C_i \in ChannelList$
   /∗A binary variable which determines whether or not the channel C_i
   is assigned to radio SR of node Src∗/

$Link(Src,SR,Des,DR,C_i)$, $Src,Des \in Nodes$, $SR,DR \in Radios$, $C_i \in ChannelList$
   /∗A binary variable which determines whether or not there is a link between radio SR
   of Src and radio DR of Des using channel C_i∗/

$InputLink(Src) = \sum_{C_i} \sum_{SR} \sum_{TR} \sum_{Temp} Link(Temp,TR,Src,SR,C_i)$
   $Src,Temp \in Nodes$ $TR,SR \in Radios$, $C_i \in ChannelList$
   /∗A non-negative variable which determines the number of incoming links to mesh router Src∗/

$OutputLink(Src) = \sum_{C_i} \sum_{SR} \sum_{TR} \sum_{Temp} Link(Src,SR,Temp,TR,C_i)$
   $Src,Temp \in Nodes$ $TR,SR \in Radios$, $C_i \in ChannelList$
   /∗Anon-negative variable which determines the number of outgoing links from mesh router Src∗/

$Interference(Src,SR,Des,DR,C_i)$, $Src,Des \in Nodes$, $SR,DR \in Radios$, $C_i \in ChannelList$
   /∗Anon-negative variable which determines the number of interfering links with link (Src,SR,Des,DR,Ch)∗/

$SIL(Src,SR,Des,DR,C_i) = \sum_{Temp2} \sum_{TR2} \sum_{Temp1} \sum_{TR1} IsNeigh(Src,Des,Temp1,Temp2) \times Link$
     $(Temp1,TR1,Temp2,TR2,C_i) - Link(Src,SR,Des,DR,C_i)$

     $Src,Des,Temp1,Temp2 \in Nodes$, $SR,DR,TR1,TR2 \in Radios$, $C_i \in ChannelList$

     /∗SIL stands for Sum of Interfering Links and is a non−negative variable which

       computes the number of links within the interference range of Src or Des on channel C_i.This variable is mainly introduced to account for "hidden channel" problem∗/

$TotalInterference = \sum_{Des} \sum_{DR} \sum_{Src} \sum_{SR} \sum_{C_i} Interference(Src,SR,Des,DR,C_i)$
   $Src,Des \in Nodes$, $SR,DR \in Radios$, $C_i \in ChannelList$
   /∗Anon-negative variable which determines total interference across the multicast tree∗/

$Total\ Links = \sum_{Des} \sum_{DR} \sum_{Src} \sum_{SR} \sum_{C_i} Link(Src,SR,Des,DR,C_i)$
   $Src,Des \in Nodes$, $SR,DR \in Radios$, $C_i \in Channel\ List$
   /∗Anon-negative variable which determines the number of links forming the multicast tree∗/

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4. Performance analysis

In this section, we investigate the correctness of our approach in terms of connectivity and loop formation, and will report on the outcome of the performance measurements derived from several simulation experiments. The section ends with a brief discussion of results.

4.1. Connectivity

Here, we will examine the multicast tree connectivity in the proposed method.

Definition 1. Connectivity is satisfied only if there exists a path between the multicast source to all multicast group members.

Theorem 1. *The BIP formulation, given in* Section 3, *guarantees connectivity across the multicast tree.*

Proof. Without loss of generality, we demonstrate the notion of connectivity using the *unit disk graph* depicted in Fig. 3(a). In this graph, each link between two nodes indicates that they are located within the transmission range of each other. Two inter-linked nodes would be able to communicate only if identical channel numbers get assigned to one of their radios. MS denotes the multicast source and MT stands for the multicast target.

Constraint (6), listed in Table 5, ensures that MT has exactly one incoming link, as illustrated in Fig. 3(b). Constraints (9) and (10) stipulate that in case a mesh node has an outgoing link then it ought to have an incoming link as well. Inequality (1) requires that only one of the links (1,2) or (3,2) be established as demonstrated in Fig. 3(c). On the other hand, constraint (5) warrants that MS has at least one outgoing link. Therefore, mesh node 1 has to be necessarily associated with an output, and the outgoing link from node 3 should be removed (Fig. 3(d)). Hence, there exists a path from MS to MT. □

4.2. Loop occurrence

We investigate the correctness of our proposed formulation in terms of the loop formation issue through the following theorem:

Theorem 2. *The multicast tree associated with the BIP formulation, given in* Section 3, *is guaranteed to be loop-free.*

Proof. Given the *unit disk graph* depicted in Fig. 3(a), assume that there exists a loop, say (1,2,3,1) within the multicast tree Fig. 4(a). Constraints (4) and (5), listed in Table 5, ensure that MS has at least one outgoing link Fig. 4(b). Inequality (1) requires that link (3,1) be removed from the configuration (Fig. 4(c)). Also, constraints (9) and (10) warrant that node 3 have no incoming link (Fig. 4(d)). Finally, Constraint (6) stipulates that MT have exactly one incoming link (Fig. 4(e)). □

4.3. Experimental results

The BIP formulation, presented in Section 3, has been implemented within the AIMMS optimization software version 3.9 (AIMMS). A common ground in most BIP solvers, and specifically "AIMMS" in this article, is the behind-the-scene utilization of a branch-and-bound algorithm so as to comprehensively explore the entire problem space in search of an optimal binary integer solution (AIMMS). This approach solves the problem at each node, regarding the node's constraints and decides whether to branch or to move to another node depending on the result. Clearly, in each step it updates the best binary integer feasible solution found so far, and verifies that no better solution is provided yet.

We have carried out four experiments to verify the performance of our framework. The first experiment assumes a sparse and small-scale network, while the next three have been conducted on two large network settings. Furthermore, another experiment on a fairly large network was conducted to analyze the efficiency of the proposed method as compared with two of the latest methods described in Section 2, namely the genetic

Table 5
Joint multicast tree construction and channel assignment constraints.

$Input\ Link(Src) \leq 1, \quad Src \in Nodes \backslash (Multicast\ Source,\ Multicast\ Group)$

/*The number of all incoming links to a node except for the multicast Source and multicast Target should be at most 1*/ (1)

$Input\ Link(Src) + Output\ Link(Src) \leq |R(Src)|, \quad Src \in Nodes \backslash (Multicast\ Source,\ Multicast\ Group)$

/*The number of all incoming links to and outgoing links from a node except for the
multicast Source and multicast Target should be at most equal to the cardinality of $R(src)$*/ (2)

$Input\ Link(Src) = 0, \quad Src \in Multicast\ Source$

/*The number of incoming links to a multicast source should be zero*/ (3)

$Output\ Link(Src) \leq |Multicast\ Source|, Src \in Multicast\ Source$

/*The number of outgoing links from the multicast source should be at most equal to
the number of multicast targets*/ (4)

$Output\ Link(Src) \geq 1, \quad Src \in Multicast\ Source$

/*The number of outgoing links from a multicast source should be at least 1*/ (5)

$Input\ Link(Src) = 1, \quad Src \in Multicast\ Targ \quad et$

/*The number of incoming links to a multicast target node should be exactly 1*/ (6)

$Output\ Link(Src) = 0, \quad Src \in Multicast\ Targ \quad et$

/*The number of outgoing links from a multicast target should be exactly zero*/ (7)

$\sum_{Des} \sum_{DR} \sum_{C_i} Link(Src,SR,Des,DR,C_i) + \sum_{Des} \sum_{DR} \sum_{C_i} Link(Des,DR,Src,SR,C_i) \leq 1$

$Src, Des \in Nodes,\ SR, DR \in Radios, C_i \in Channel\ List$

/*Every radio SR on the Src node should be used at most once for either of input or output purposes*/ (8)

$Output\ Link(Src) \geq Input\ Link(Src)$ (9)

$\frac{Output\ Link(Src)}{|R(Src)|} \leq Input\ Link(Src),\ Src \in Nodes$

/*Constraints (9) and (10), together, define an "if and only if" constraint; i.e.
if a node has an incoming edge, then it definitely has an outgoing edge as well, and vice versa*/ (10)

$\sum_{Des} \sum_{DR} \sum_{SR} Link(Src,SR,Des,DR,C_i) + \sum_{Des} \sum_{DR} \sum_{SR} Link(Des,DR,Src,SR,C_i) \leq 1$

$Src, Des \in Nodes, \quad SR, DR \in Radios, C_i \in Channel\ List$

/*A channel C_i should be assigned to radios of a node at most once*/ (11)

$Interference(Src,SR,Des,DR,C_i) \leq (|Nodes| \times (|Nodes|-1)/2) \times Link(Src,SR,Des,DR,C_i)$ (12)

$Interference(Src,SR,Des,DR,C_i \leq SIL(Src,SR,Des,DR,C_i)$ (13)

$Interference(Src,SR,Des,DR,C_i) \geq SIL(Src,SR,Des,DR,C_i)$

$-(|Nodes| \times (|Nodes|-1)/2) \times (1-Link(Src,SR,Des,DR,C_i))$

$Src, Des \in Nodes, SR, DR \in Radios, C_i \in ChannelList$

/*Constraints(12),(13), and (14), compute the $Interference\ (Src,SR,Des,DR,C_i)$*/ (14)

$Link(Src,SR,Des,DR,C_i) \times d_{Src,Des} \leq Link(Src,SR,Des,DR,C_i) \times R_T$ (15)

$Link(Src,SR,Des,DR,C_i) \times F_{C_i,SR,Src} = Link(Src,SR,Des,DR,C_i) \times F_{C_i,DR,Des}$

$Src, Des \in Nodes, \quad SR, DR \in Radios, C_i \in ChannelList$

/*Constraints (15) and (16) stipulate the link establishment conditions between Src and Des : (1) they are located
within transmission range of each other, and : (2) a common channel is assigned to both radio SR of Src and radio
DR of Des*/ (16)

---

algorithm and simulated annealing based methods (Cheng and Yang, 2011). This experiment entails several sets of simulations.

Experiment #1:

In this experiment, the configuration corresponding to the *unit disk graph* depicted in Fig. 5(a) is given as a sample MCMR WMN to the BIP model. As can be seen in the figure, a 10-node (*N#*) network is assumed with one MS (Multicast Source) and two MTs (Multicast Target). We assume a multicast group of size 2 (*GS#*). All mesh nodes are expected to be equipped with 3 radios (*R#*). The number of channels will be varied from 3 to 4. The resultant network topologies associated with each configuration are shown in Fig. 5(b) and (c).

Table 6 lists the abbreviations used in Fig. 5. As depicted in Fig. 5(b), each radio is able to use three non-overlapping channels (*Ch#*). In this topology, radio 3 of MS and radio 3 of node 4are connected on channel *C3*. Other connections can be interpreted analogously. The total links (*TL#*) across the resultant

multicast tree and the total interference (*TI#*) turn out to be 4 and 2, respectively.

Fig. 5(c) depicts the resultant network topology in which each node is allowed to use a maximum of 4 non-overlapping channels. As it can be seen in the figure, increasing the number of channels to 4 results in zero *TI#*. In other terms, a total of four non-overlapping channels are required in order to achieve zero interference in a given network configuration

Experiment #2:

This experiment was conducted to study the effect of channel number variations on interference. We cover all cases of variations. That means we vary the number of radios and available channels systematically and compute interference. Recall from Section 1, the number of channels in MCMR WMN should be more than or equal to the number of radios. In particular, in this experiment, several simulation sets were conducted. In each set, the number of radios is fixed. In each simulation of a set, the
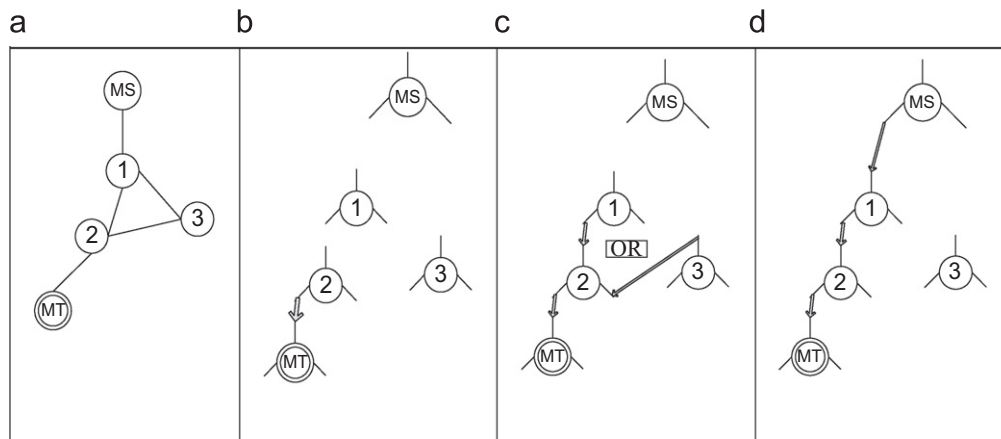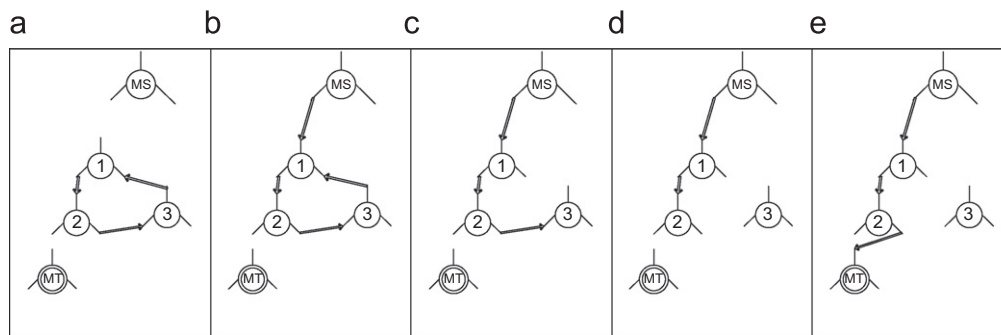
Fig. 3. Multicast tree connectivity.

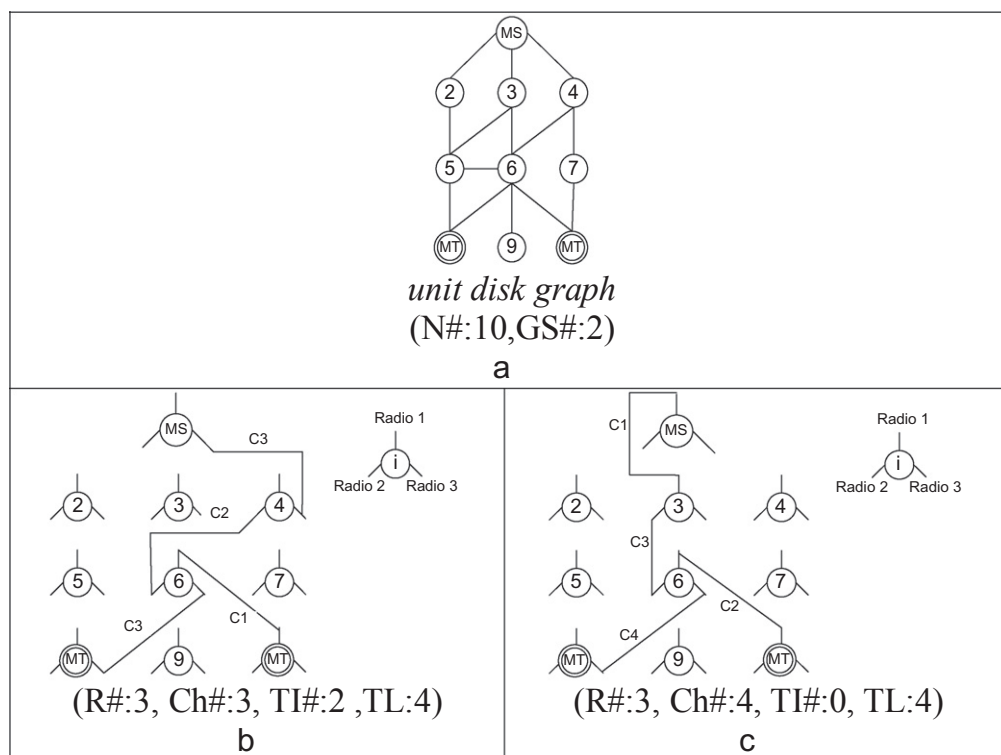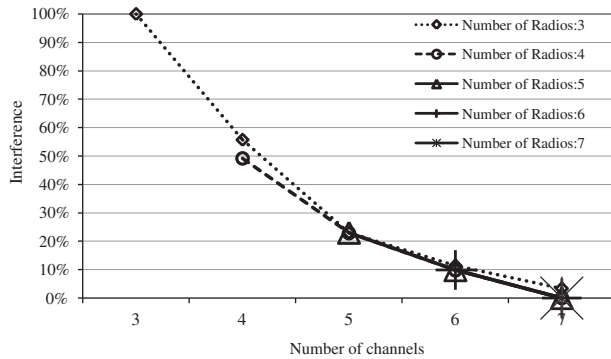**Fig. 4.** Multicast tree loop prevention.

Fig. 5. Joint multicast tree construction and channel assignment for different configurations.

Table 6
Description of the notations used in Fig. 5.

Input	*N#: Number of Mesh Routers*
	R#: Number of Radios Per Nodes
	Ch#: Number of Available Channels
Output	*TI#:Total Interference*
	TL: Total Links on Resultant Multicast Tree

Fig. 6. Impact of channel number variations on interference for a network with 20 nodes and 6 multicast receivers.
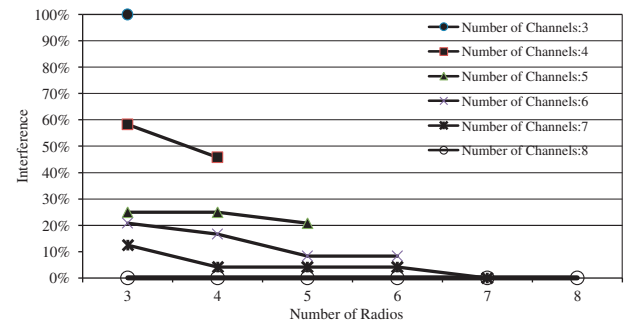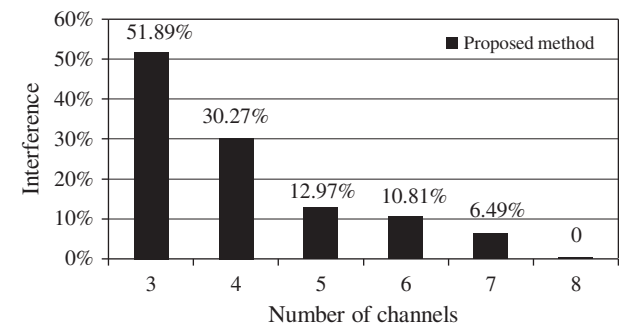
number of channels is increased by one and the simulation is run. This process goes on until interference gets to zero. Then the number of radios is increased by one and a new simulation set is started. Since defining different nodes as a member of multicast group in each experiment may leads to unfair evaluation, the size and set of multicast receivers in all of simulations of this and the next experiment is considered fixed and the same.

Fig. 6 shows the resultant interference for a random generated *unit disk graph* in which the number of nodes and the size of multicast receivers set are 20 and 6, respectively. This figure shows in the given network with 3 radios per each node, increasing the number of channel from 3 to 4 can reduce interference up to 45%. Other data points can be interpreted analogously. As another point of view, this figure shows that the number of channels is not the only factor for interference reduction. Clearly, the number of radios should be as enough as to use the available channels efficiently. For example, from this figure if we have four available channels, using four radios leads to 6% improvement in interference reduction rather than using three radios.

Experiment #3:

This experiment was conducted to examine the impact of the radio number variations on interference. In this experiment, unlike experiment #2, we fix the number of channels in each simulation set. The number of radios in each simulation of the set is increased by one. The results of this experiment for the given *unit disk graph* in experiment #2 come in fig. 7.

As it is mentioned above in a network with three available channels every node can have two or three radios. In the given *unit disk graph* using two radios leads the network to be disconnected. Therefore, we ran one simulation for 3-radio nodes and hence, just one date point is shown for this simulation set. This figure shows that in the given network with 4 available channels, increasing the number of radios from 3 to 4 can reduce the interference up to 6%. This figure also depicts increasing the number of channels from 4 to 5 both with 3 radios leads the interference is reduced around 33%. But in the given network with 5 available channels increasing the number of radios from 3 to 5 does not improve the interference. This implies the impact of the number of channels on interference reduction is more than that of the number of radios.
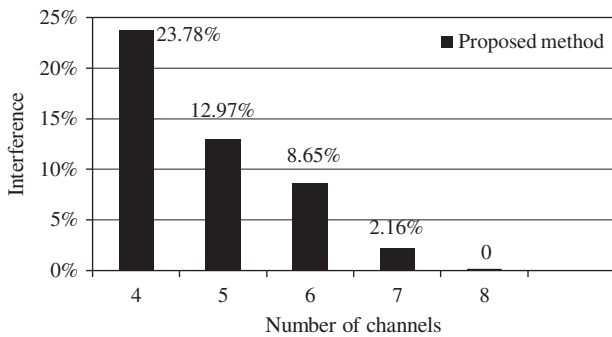

Fig. 7. Impact of radio number variations on interference for a network with 20 nodes and 6 multicast receivers.

Fig. 8. Impact of radio number variations on interference for a network with 30 nodes and 13 multicast receivers.

Fig.9. Interference versus channel number variations in a network 3 radios per each node.
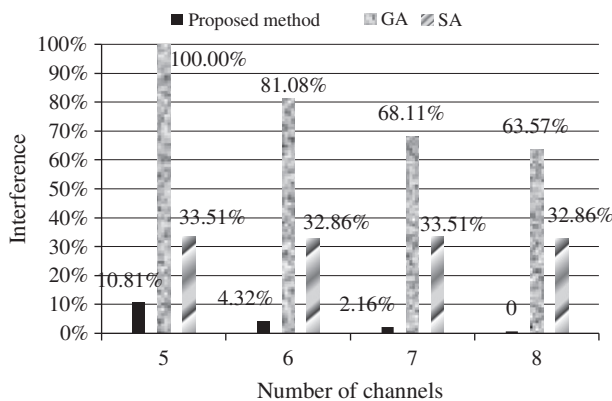
Experiment #4:

In this experiment, experiment 3 is repeated for a larger *unit disk graph* with 30 nodes and 13 multicast receivers. Fig. 8 depicts the results.
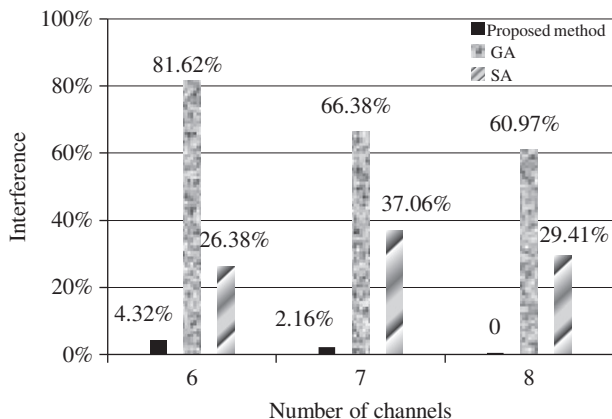
Experiment#5:

This experiment was mainly conducted to analyze the efficiency of the proposed technique compared to genetic algorithm (GA) and simulated annealing (SA) based methods (Cheng and Yang, in press). This experiment was accomplished on another randomly generated large *unit disk graph* in which the number of nodes and the size of multicast receivers set is 30 and 13, respectively. In simulations, parameters setting for the GA and SA-based methods are according to the suggested valued in this reference. The results are shown in Figs. 9–14. Fig. 9 shows the impact of channel number variations on interference when each node is equipped with just three radios. Recall from Section 1, in MCMR WMN, the number of radios is less than or equal to the number of channels. Hence, the number of channels varies from the number of radios to a point in which the interference reaches

Fig. 10. Interference versus channel number variations in a network with 4 radios per each node.
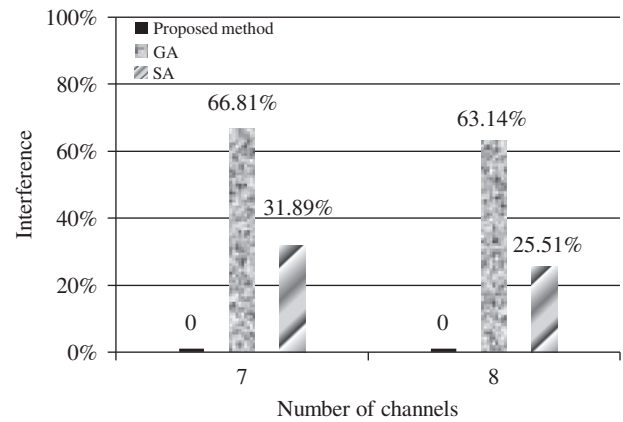

Fig. 11. Interference versus channel number variations in a network with 5 radios per each node.

Fig. 12. Interference versus channel number variations in a network with 6 radios per each node.

Fig. 13. Interference versus channel number variations in a network with 7 radios per each node.
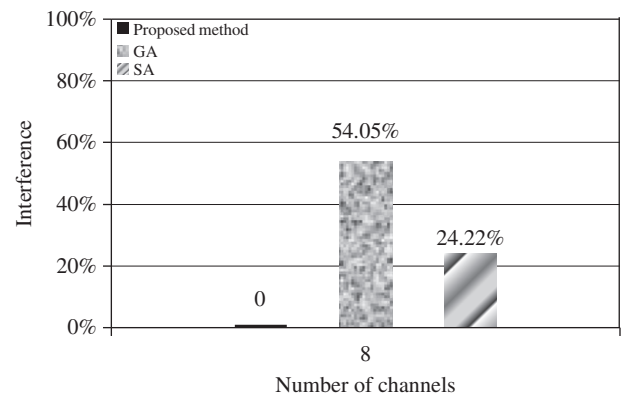

Fig. 14. Interference versus channel number variations in a network with 8 radios per each node.

However, when we increased the number of radios to 5, GA- and SA-based methods were able to accomplish the multicast problem with a feasible solution. Fig. 11 shows the resultant interference in all methods for different number of channels. In this figure, every data bar associated with GA- and SA-based algorithms, is the average of interference obtained by 5 times simulation. As it can be observed, the proposed framework gives the minimal interference.

Fig. 12 depicts the achieved interference in all methods when each node is allowed to use 6 radios. As it is seen the resultant interference in SA-based method has not any specific trend. The reason is that, the SA-based method is a randomized algorithm and the results were averaged by 5 separated simulations. Finally, we repeated the experiment for a network with 7 and 8 radios per each node. Results are shown in Figs. 13 and 14, respectively. From the results shown in Figs. 12 through 14, it can be observed that the proposed method can solve the multicast problem efficiently.

4.4. Discussion

The empirical results derived from the simulation of the proposed cross-layer design demonstrate that increasing the number of radios/channels generally leads to interference reduction. This can be primarily attributed to the capability of the BIP model in fully utilizing a larger pool of resources for coming up with the most efficient channel-radio associations.

Table 7 more specifically examines the details of resource management in our framework. Here, the results in experiments2

to zero. Both GA and SA methods could not solve the multicast problem with just three radios. That is, the generated solutions are infeasible. This figure demonstrate that in a network with 3 radios per each node, if we increase the number of channels from 3 to 4, then interference is reduced up to 20% . For the given *unit disk graph* if we increase the number of channels to 8, then the resultant interference gets to zero.

We repeat this experiment for a network in which every node is allowed to use four radios. Results are in Fig. 10. In this experiment, again the GA and SA methods could not solve the problem.

Table 7
Number of links on the multicast tree coupled with resultant interference for different configuration.

Ch#	R#	TI#	TL	Row
2	2	Disconnected		
3	2	Disconnected		
	3	100%	24	A
4	2	Disconnected		
	3	55.74%	23	
	4	49.18%	20	
5	2	Disconnected		B
	3	22.95%	23	
	4	22.95%	19	C
	5	22.95%	19	
6	2	Disconnected		
	3	11.48%	23	
	4	9.84%	19	
	5	9.84%	19	
	6	9.84%	19	
	2	Disconnected		D
7	3	3.28%	23	E
	4	0	19	
	5	0	19	
	6	0	19	
	7	0	19	

and 3 which are conducted in a same *unit disk graph* are summarized. As it is seen in this table, if 3 non-overlapping channels are available and each node is equipped with 3 radios, the multicast tree with 24 links will be made in which interference is 100% (Row A). It is observed from this table that increasing the number of radios will be useful to a point. For example consider the network with 5 available channels. In this network if the number of radios varies from 2 to 3, the network will be connected and the multicast tree with 23 links and interference 22.95% is constructed (Row B). But as it can be observed increasing the number of *radios* no longer has any impact on resulting multicast tree and interference reduction (Row C), albeit the specifics of this trend varies with respect to network topology. Also, as seen in the table, increasing the channels is not the only factor effective in reducing the interference. For example if the number of channels is 7 and every node is equipped with just 2 radios, the resulting network is not connected (Row D). In this network increasing the number of radios to 3, not only leads the network to be connected but also the interference of the network will be dramatically decreased (Row E). The reason is that the number of radios must be as enough as to be able to use the available channels and to switch among them.

However, the outcome of the experiments 2 to 5 reveals that increasing the number of channels has significantly more impact on interference reduction compared to the number of radios. In order to further investigate the impact of channel number variation on *Interference*, we fit a logarithmic curve for the data series associated with experiment 2 using analytical software SPSS version 16 (SPSS), resulting in Eq. (2). *Adjusted R Square* is a statistic that will give some information about the goodness of fitting a model. In other words, it determines how well the regression curve approximates the real data points. *Adjusted R Square* of 1.0 indicates that the regression curve perfectly fits the data. *Adjusted R Square* in proposed model is equal to 0.94 which indicates our model is well fitted. Furthermore, regression coefficients are all significant

$$-64.259 \times \ln(Channel\ number) + 122.585 \cong Total\ interference \qquad (2)$$

Eq. (3), on the other hand, is resultant from a logarithmic curve fitting intended to model the impact of channel number variations on *Interference* for experiment 5. Recall that this experiment is the same as experiment #2 but has been carried out on a larger and *unit disk graph*. Here, *Adjusted R Square* is 0.877, and regression coefficients are also all significant

$$-40.598 \times \ln(Channel\ number) + 81.7 \cong Total\ interference \qquad (3)$$

5. Conclusion and future works

This paper addresses a fundamental design issue for joint multicast routing and channel assignment in MCMR WMN. In this paper, initially the existing methods of multicast routing in MCMR WMN along with their advantages and disadvantages are surveyed. Then unlike the existing methods, a novel method based on BIP to solve the joint channel assignment and multicast routing problem in MCMR WMN was proposed. In the proposed method two sub-problems are solved conjointly. Using this strategy impact of two MAC and routing layers on each other is considered. The proposed method guarantees the connectivity in the network and constructs the MCT based multicast tree with minimal interference. Also in the proposed method loop does not occur. *Hidden channel problem* in mathematical formulation is considered as well. Through simulations, correctness of the proposed framework as well as its efficiency compared to proposed methods in Cheng and Yang (2011) was demonstrated.

In sum, providing the mathematical frameworks such as BIP models in the networks is a must to achieve the optimal solution. In this paper, the BIP-based proposed framework leads to obtain the minimal interference. Besides, the resultant solution from our method can be as a metric to evaluate the efficiency of the other distributed and centralized methods. On the other hand, as a consequence of utilizing the proposed method, it is worth mentioning that our framework is centralized and it entails the weaknesses of centralized systems. For example, its time complexity can be increased with the size of the problem. To cope with this problem our future research is concentrated to propose a distributed method to achieve the optimal or sub-optimal solution. We would like to extend our work to multiple data sessions in MCMR WMN. Note that in this case may be there exist more than one output link from any mesh router to another one using different radios assigned to different channels one for every multicast session. This complicates the construction of multicast tree. We would also like to investigate the problem of optimal throughput in MCMR WMN.

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