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Dynamic Multicast Membership Algorithms for Multi-Channel Multi-Radio Wireless Mesh Network

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***Abstract*— Wireless Mesh Networks (WMNs) have emerged as one of the new hot topics in wireless communications. The use of multi-channel multi-radio (MCMR) systems can considerably enhance the throughput capacity of a WMN which requires suitable routing approaches and efficient channel assignment (CA) to the different links in order to minimize the interference and maximize the throughput. Multicast is an efficient mechanism that simultaneously delivers identical data to a group of receivers. Several approaches and mechanisms have been proposed to build multicast trees and to do an efficient CA. Existing multicast routing and CA algorithms suppose that the multicast membership is static, whereas, it is dynamic in practice. In this paper, we aim to make the group membership of a multicast tree dynamic i.e. we allow nodes to join and to leave the multicast tree freely without compromising the effectiveness of the CA. Particularly, we propose two algorithms to make a multicast tree dynamic: Node Joining the Multicast session algorithm (NJM) and Node Disjoining the Multicast session algorithm (NDM). We illustrate the use of these algorithms by examples and we show how they maintain the number of relay nodes minimal in order to maximize the throughput which is the paramount priority in WMNs.**

***Index Terms*— Channel Assignment, Dynamic Multicast Membership, Multicast, Multi-Channel Multi-Radio Systems and Wireless Mesh Networks**

I. INTRODUCTION

THE increasing number of Internet users in the last decades led to the use of devices and applications with a huge amount of network resources in order to satisfy end users requirements. However, the performance of the traditional networks types which may be wired or wireless is not satisfactory enough: the cost is very high (wired network) or the throughput is not sufficient (wireless network). This leads to the emergence of a new powerful and promising networks type, called *Wireless Mesh Network* (WMN).

WMN is a technology that can support numerous applications such as; Internet access in urban, suburban and rural areas, public safety, building automation, and transportation systems [8], [9], [10], [11], [12], [13]. It is self configured and self healing and has many advantages over traditional wireless networks such us low costs, easy to maintain, large scale deployment, robustness and greater coverage area [1], [26].

WMNs consist of mesh clients and mesh routers. Mesh clients are often dynamic and have access to the network through mesh routers as well as directly meshing with each other. Mesh routers are often static and form the wireless mesh backbone. In this backbone some routers are access points (or gateways) acting both as Internet routers and wireless mesh routers [8]. The mesh backbone in a WMN provides multi-hop connectivity from one host to another, or to the Internet via the access points.

The throughput capacity of a single channel in WMN becomes unacceptably low when the network size increases [7], [17]. The use of systems with *Multiple Channels and Multiple Radios* (MCMR) per node improves considerably the aggregate network throughput since each node is in full-duplex mode i.e., each node is able to transmit and receive simultaneously. MCMR networks need efficient *Channel Assignment* (CA) [19], [22] which involves assigning channels to the different interfaces of each node. This CA must ensure in the same time the network connectivity and minimize the interference in order to maximize the throughput [4], [21].

Multicast communication is the simultaneous transmission of the packets from a source to a set of destinations in an efficient manner, such that each packet is transmitted over each link of the network only once. Multicast supports many important applications such as: multimedia conferencing, distributed interactive games, software distribution and distance education [5], [18]. Since mesh nodes are usually stationary and rechargeable, and unlike sensors and ad hoc networks, route recovery and energy constraints are not the main preoccupation of mesh network and for such network the main preoccupation is the optimization of the throughput.

Routing and Channel assignment have been extensively studied in the context of unicast communications [2], [6], [14], [20], [21], [22] and they have been recently studied in the context of multicast communications [15], [16], [19], [23], [25]. In [25] Zeng et al. proposed a multicast tree construction and CA algorithm in MCMR WMNs called *Multi-Channel Multicast* algorithm (MCM). In this algorithm, they consider that the multicast tree static while in reality, nodes may join and leave the multicast tree at any moment. In this paper we aim to make the multicast membership as well as the network topology able to be dynamic by proposing two algorithms that allow members to join or to leave the multicast tree freely and channels will be re-assigned based on the topology changes of the multicast tree.

The remainder of this paper is organized as follows. Section 2 describes the system model and basic definitions and assumptions. Section 3 provides an overview of MCM algorithm and analyzes its drawbacks and some potential improvements. Section 4 presents our proposed algorithms accompanied with examples showing join and leave operations of nodes to/from the multicast tree without compromising the effectiveness of the CA. Related works are discussed in Section 5, and the last section concludes this paper and sets directions for future works.

II. System model

We consider a backbone of the WMN among a MCMR system with stationary wireless routers. In MCMR systems, there are n available channels and each router is equipped with k interfaces (radios) where $1 < k < n$. The n channels may either overlap when a channel shares its spectrum with the adjacent channels, or may be orthogonal i.e. completely separated. We consider IEEE 802.11 b/g standard which provides 11 channels numbered from 1 to 11. The channel separation between two channels *C1* and *C2* is defined as $|C1-C2|$, the separation between orthogonal channels is at least five (*C1* and *C2* are separated by at least four other channels, e.g., channels 1 and 6), and so IEEE 802.11 b/g provides 3 orthogonal channels: 1, 6 and 11. We consider, Like MCM, both overlapping and orthogonal channels. We also consider that each router is equipped with 2 interfaces (k=2 and n= 11).

To simplify the model and like in MCM, we consider the network (backbone of the WMN) as a graph $G= (V, E)$, where V represents the set of the backbone routers i.e. gateways and mesh routers, and E represents the physical links among neighboring nodes. We assume that each node has the same fixed communication range: if node u can transmit directly to node v (and vice versa), there exists a link (u, v) in E.

MCM uses a metric named interference factor to measure the level of interference between neighboring nodes; the interference factor is defined as the ratio of the interference range over the transmission range. In [25], Zeng et al. performed an experiment to measure the interference factor. They use four laptops equipped with Netgear WAG511 PC cards to establish two wireless links (one between each pair of laptops). The authors gradually moved the two wireless links far away from each other until there is no interference between them. This gave the interference range of the two links in order to calculate the interference factor as defined above (ratio of the interference range over the transmission range). Through this experiment, they found that the interference range decreases with the increase of the channel separation, the largest channel separation corresponds to the lessest interference and the lowest interference factor. When the channel separation is five or more, the interference factor approaches zero. Therefore, the use of all the available channels, orthogonal and partially overlapping, can furthur attenuates the total interference in the network, and thus, improves the network throughput.

The parent-child and sibling relationships between nodes in a multicast tree are the same as those defined for the traditional rooted tree data structure [24], where the multicast source is defined as the root of the tree. As mentioned above, we consider that each router is equipped with two interfaces (radios): one for receiving multicast data from its parent (*Receive interface*), and the other for sending multicast data to its children (*Send interface*).

We also assume that the multicast tree has been already constructed according to MCM algorithm, and that the CA has been done using the interference factor metric to minimize the interference between adjacent links. Our objective is to develop two algorithms which allow members to join and to leave an existing multicast tree.

III. Multi-Channel Multicast algorithm (MCM)

The MCM algorithm builds a multicast tree using shortest path trees approach. Several approaches to build a multicast tree exist such as shortest path trees, minimum Steiner trees and minimum number of transmissions trees [18]. To assign channels to the different routers interfaces, MCM considers both orthogonal and overlapping channels and uses the interference factor to minimize interference among adjacent links. In this section, we describe MCM algorithm, we analyze its drawbacks and we give the potential improvements which is to make the multicast membership dynamic.

A. MCM multicast tree construction

In the aim to build the multicast tree, MCM starts with exploring the whole network using the *breadth first search* (BFS) [3] which partitions all the nodes into different levels according to the hop count distances between the multicast source and the remainder of nodes. The parent-child and sibling relationship is found here by considering that node A is a parent of B and node B is a child of A, if A is in level i, B is in level $i+1$ and they (nodes A and B) are within each other communication range.

After having divided nodes into different levels, the edges between any pair of nodes of the same level will be deleted to get the elementary communication structure (tree mesh). They use BFS to build the tree mesh mainly to reduce the total hop count distances from the source to the receivers; thus allowing to mitigate the intra-flow contention and minimize the transmission delay which are very important in WMNs.

Starting from the tree mesh, the next step of the multicast tree construction is to identify the minimal number of relay nodes that forms the multicast tree. The process starts from the bottom to the top and aim at each step to minimize the number of relay nodes at the upper level, which can cover all the receivers (a receiver is a node which desire to receive the multicast data) and relay nodes at the lower level. The only parent is identified as relay node for each node which has more than one parent in a manner that the number of relay node is minimal. Identifying the minimal number of relay node will result in less traffic flows in the network, which means less local interference and more throughput capacity.

The source node (level 0) only uses one interface, which is responsible for sending multicast data to the tree nodes in level 1. Relay nodes at level i ($i \geq 1$) use two interfaces: one is used to receive multicast data from its parent (at level i-1) named Receive-Interface (RI), and the other one is used to forward packets to their children (at level i+1) named Send-Interface (SI), the SI of a receiver node is used to forward multicast data to the mesh clients within its communication range who desire to receive the multicast data.

The example used in Fig.1, illustrates MCM multicast tree construction. Fig.1 (a) represents the network topology, node S is the multicast source and nodes F, G, I and J are the multicast receivers. By applying the BFS, the network will be divided into 4 levels: level 0(node S), level 1 (nodes A and B), level 2 (nodes C, D and E) and level 3 (nodes F, G, H, I and J). As shown in Fig.1 (b), the tree mesh is obtained by deleting links between nodes which are at the same level (between A and B, C and D…, I and J). Then comes the step of determining the minimal number of relay nodes, nodes C and E are selected in level 2 because they cover all the multicast receivers in level 3, node C is the parent of nodes F and G, node E is the parent of nodes I and J. In level 1 the relay nodes are the two nodes A and B, A covers node C (its parent) and B covers node E, the multicast tree obtained is shown in Fig.1 (c).

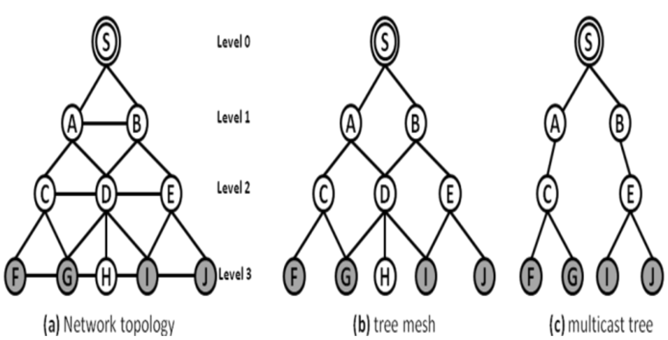

Fig. 1. MCM multicast structure example

B. Channel assignment

To assign channels to the interfaces (SI and RI) of each node, MCM considers both orthogonal and overlapping channels. As mentioned above, it uses the interference factor to minimize interference among one-hop neighboring nodes. Let $N(v)$ denotes the set of one-hop neighbors of node v that have already been assigned a channel; cv is the channel that is assigned to node v; $\delta(cv, cw)$ is the interference factor between two channels cv and cw. For each forwarding node v in the multicast tree (excepting the source), MCM selects a channel cv for v that minimizes the following function:

$$\sum_{\forall w \in N(v)} \delta^2(cv, cw) \quad (1)$$

The MCM CA algorithm starts with the source node by assigning channel 1 to its SI. Then, all the nodes in level 1, i.e. children of the source node, turn their RI interface into the channel assigned to the source's SI (channel 1). The algorithm processes the source's children (nodes in level 1), by exploring the multicast tree using the BFS. For each child, the algorithm assigns a channel to the SI of the node in manner that the assignment minimizes the interference factor between this node and all of its one-hop neighbors which have already been assigned a channel. In the case where more than one channel satisfies the optimization function, a channel will be randomly chosen from the multiple solutions. The CA procedure repeats until it covers all forwarding nodes of the multicast tree in the BFS traversal order.

Applying MCM CA on the multicast tree of Fig.1 (c) produces, the CA shown in Fig.2 (a).

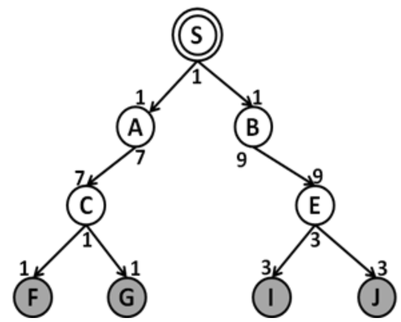

Fig. 2. MCM channel assignment example

C. Drawbacks of MCM algorithm

MCM built a static multicast tree in which the set of the multi receivers is always the same, it does not change. While in reality, a multicast tree is dynamic and its topology changes frequently, because at any time, a node can join or leave the multicast tree freely. MCM does not offer any solution that enables dynamism in the multicast tree.

In order to make a multicast tree dynamic and reflecting reality, we design efficient algorithms that allow the addition and the subtraction of nodes to/from the multicast tree while keeping the number of relay nodes minimal. The channels are also re-assigned efficiently in response to changes of topology of multicast tree.

To further improve MCM algorithm, we present in the next section how to proceed when a node desires to join or to leave the multicast tree that allows it to be dynamic.

IV. Dynamic Group Membership Algorithms

We have seen in the last section that MCM does not treat the case where a node wants leave or join the multicast tree. We will propose in this section the solution to make the multicast tree dynamic.

As mentioned above, we consider the network as a graph G=(V, E).We denote by T the multicast tree; by $V(T)$ we denote the set of nodes belonging to the multicast tree and we denote by *E(T)* the set of links belonging to the multicast tree (*V(T)* $\subseteq$ *T* and *E(T)* $\subset$ *E*). A candidate parent of a node *v* is a node *u* that exists at the higher level of *v, u* is within the transmission range of *v* (vice versa) and *u* is not a relay node in the multicast tree. For example, in the multicast tree of Fig. 1, node *D* is a candidate parent (the only one here) of nodes *G* and *I*, it is also the candidate parent of node *H* which is not a multicast node.

In the next subsection, we will present the *Node Disjoining the Multicast* session algorithm (NDM) which details how to proceed when a node wants to leave the multicast tree.

A. NDM algorithm

The Node Disjoining Multicast session algorithm (NDM) allows a node to leave multicast tree. It has as an input the node (v) wishing to leave the multicast tree (T) and the multicast tree (T). The algorithm has as an output a new structure of the multicast tree (T). This algorithm is described in Algorithm 1.

LeaveMultiTree (T, v)

```
1   u=v's parent ;
2   V(T)=V(T) - {v} ;
3   E(T)=E(T) - { (u, v) } ;
4   continue = true ;
5     while (continue) do
      begin
6       if u has not a child in the multicast tree then
        begin
7         V(T)=V(T) - {u} ;
8         E(T)=E(T) - { (u's parent, u) } ;
        end
9       else
        begin
10        for each n child of u do
          begin
11          if n has not a candidate parent (CP(n)) in the multicast tree then
12            continue= false ;
          end
13        if (continue) then
          begin
14          for each n child of u do
            begin
15            find n's candidate parent CP(n) in the multicast tree with the
                maximum number of children;
16            E(T)= E(T) - { (u, n) } ;
17            E(T)= E(T) U{ (CP(n), n) } ;
18            assign to RI of n the channel assigned to SI of CP(n) ;
19            re-compute the channel assigned to SI of n and assign this
                channel to RI of n's children;
            end
20          V(T)=V(T) - {u} ;
21          E(T)=E(T) - {(u's parent,u) } ;
          end
        end
22      u= u's parent ;
      end
```

Algorithm.1: NDM algorithm

The algorithm starts by removing the node *v*, which desires to leave the multicast tree, from the set of the multicast tree nodes (*V(T)*), and deletes the link between *v* and its parent *u* from the set of the multicast tree links (*E(T)*) (lines 1-3), the node *v* is no longer a child of the relay node *u*. Once *v* leaves the multicast tree, we check whether *u* still has children in the multicast tree (line 6), two cases are possible: i) If *u* doesn't have a child, *u* stops receiving multicast data from its parent and leaves multicast tree, then the node *u* and the link between *u* and its parent are removed from the multicast tree (lines 7-8). ii) If *u* still has child in the multicast tree (line 9), we check whether each *u*'s child has a candidate parent in the multicast tree (lines 10-12). For that, we use here a boolean variable –*continue*– initialized to true (line 4), if there is a *u*'s child which does not have a candidate parent in the multicast tree, the boolean variable *continue* will be changed to false.

If each *u*'s child has a candidate parent in the multicast tree (condition in line 13, boolean variable *continue* is still true). In this case, links between node *u* and its children are removed from the multicast tree, each child will be connected to its candidate parent according to MCM algorithm principle [24] (node having the maximum number of children) and those links will be added to the multicast tree (lines 14-17). Thus, each child assigns to its RI the channel assigned to SI of its selected candidate parent, then if it is a relay node, it re-computes the channel assigned to its SI according to its new one hop neighbor (the selected candidate parent) (lines 18-19). After that, we remove node *u* and the link between it and its parent from the multicast tree (lines 20-21).

In order to minimize the flow in the multicast tree, and to maintain the number of relay nodes minimal as in MCM algorithm, the node which has the maximum number of children is chosen among all the candidate parents.

Then the process continues with the parent of *u* (line 22) and so on until an ancestor of *u* has at least one child which has no candidate parent in the multicast tree i.e. until the boolean variable *continue* is false.

An example is shown in Fig.3. Fig. 3(a) shows a multicast tree with the channel assignment, where, *S* is the source of the multicast session, nodes *J, K, L, M, N, O* and *P* are the multicast receivers. Dotted lines are not part of the multicast tree and they are used to show direct connectivity between nodes. Supposing now that node *O* desires to leave the multicast tree. *O* stops receiving data from its parent and it leaves the multicast tree, node *H* (parent of *O*) still has another child (node *N*) in the multicast tree, we connect node *N* to its candidate parent node *G*. Node *H* in turn will leave the multicast tree. Node *D, H*'s parent, has also node *I* as a child. This latter will be connected to its candidate parent *E* and it will re-compute the channel assigned to its SI. the channel obtained is assigned to RI of node *P* (child of node *I*), and so, *D* leaves the multicast tree. Node *A, D*'s parent, has also node *C* as a child, but this latter does not have any candidate parent. Therefore the process stops here and the multicast tree obtained with necessary channel re-computation (SI of node *I*) are shown in Fig. 3(b).

After having presented the NDM algorithm, now we present in the next subsection the *Node Joining the Multicast* session algorithm (NJM) which details how to proceed when a node desires to join the multicast tree.

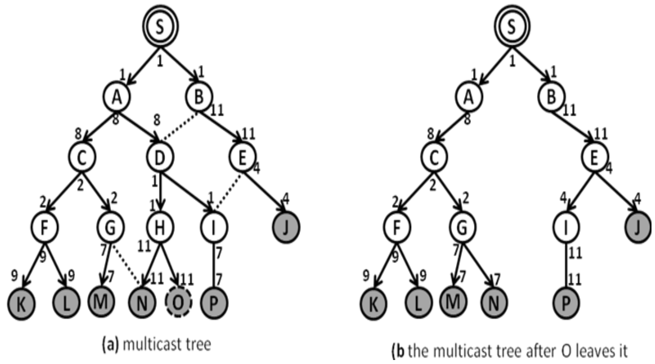

Fig. 3. An example for NDM algorithm

B. *NJM algorithm*

The Node Joining Multicast session algorithm (NJM) has as an input the node (*v*) wishing to join the multicast session and the multicast tree (*T*). The result is the addition of this node to the multicast tree while respecting the effectiveness of the CA through the path established between node (*v*) and the nearest relay node. This algorithm is described in Algorithm 2.

***JoinMultiTree* (*T*, *v*)**

```
1   N = {v} ;
2   R=∅ ;
3   while (R==∅)
    begin
4     CP(N)= all the candidate parents of all the nodes of N;
5     for each x ∈ CP(N) do
6       if (x ∈ V(T)) then
7         R=R ∪{x} ;
8     N=CP(N) ;
    end
9   find the node p ∈ R that has the maximum number of children ;
10  choose a path C between p and v ;
11  V(T)=V(T) ∪{V(C)-p} ;
12  E(T)=E(T) ∪E(C) ;
13  n=p's child in path C ;
14  while(n ≠ v) do
    begin
15    Assign to RI of node n the channel assigned to SI of its parent ;
16    Compute the channel assigned to SI of node n according the principle of
      MCM CA;
17    n=n's child;
    end
18  Assign to RI of node v the channel assigned to SI of its parent;
```

Algorithm.2: NJM algorithm

R contains the set of the nearest multicast tree relay nodes among *v's* ancestors. At first, *R* is empty (line 2), and *NJM* starts the search of the nearest relay node in the multicast tree until *R* is not empty (line 3) i.e. find a *v's* ancestor that belongs to the multicast tree. Each candidate parent of *v* belonging to the multicast tree will be added to *R* (lines 5-7) and the search process will be stopped when *R* becomes not empty. If *v* has not a candidate parent that belongs to the multicast tree, *NJM* checks the candidate parents of all *v's* candidate parents (line 8) until a *v's* ancestor that belongs to the multicast tree was found. After that, *NJM* selects, among the nodes belonging to *R*, the node which has the maximum number of children in the multicast tree (line 9) and then, it chooses a path between this node and the node *v*. Finally, this path is added to the multicast tree while assigning channels to different links of this path following a top down assignment according to MCM CA principle (lines 10-18). Note that the node selected from the multicast tree to be a *v*'s ancestor, does not re-compute the channel assigned to its SI, but its new child, from the added path, assigns this channel to its RI.

As an example, let's take the multicast tree shown in Fig. 4(a). The multicast source is node *S*. nodes *G*, *I* and *J* are the multi receivers. Nodes *D* and *H* are not part of the multicast tree. Supposing now that node *H* desires to join the multicast session. We check whether a *H*'s candidate parents belongs to the multicast tree, node *H* has only one candidate parent, node *D*, which does not belong to the multicast tree, so we check the candidate parents of node *D*, this latter has two candidate parents: nodes *A* and *B*, which belong to the multicast tree, node *A* has one child while node *B* has two child in the multicast tree, this latter is chosen to be a *H*'s ancestor in the multicast tree because he has the maximum number of children among *H*'s nearest relay node. We choose a path between *B* and *H* and do the channel assignment in this path. Fig. 4(b) shows the multicast tree (with the CA in the new path between *H* and *B*) after adding node *H* to the multicast tree.

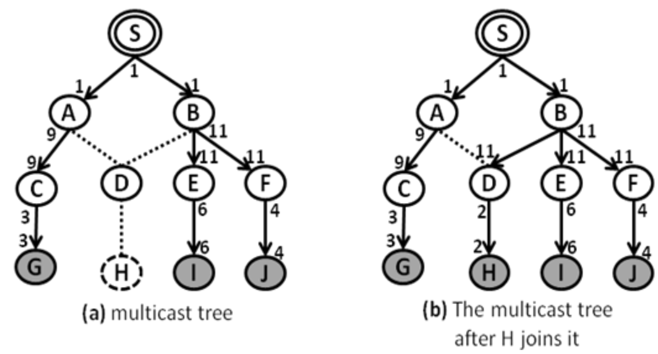

Fig. 4. An example for NJM algorithm

In the two algorithms, we choose the candidate parent with the maximum number of children in order that the multicast tree after the change (the node joining or disjoining) is as close as possible to the tree constructed by considering the membership changes in the beginning of construction e.g. in Fig. 3(b) the multicast tree obtained after node *O* leaves the multicast tree is the same tree obtained if we construct the tree in the beginning by considering that node *O* is a multi receiver. The same thing with Fig. 4(b) by taking in consideration in the beginning that node *H* is a multi receiver.

The next section summarizes some related work.

V. RELATED WORK

Routing and Channel assignment have been extensively studied in the context of unicast communications [2], [6], [14], [20], [21], [22]. For instance, S. Avallone and I. F. Akyildiz

[2] propose a centralized CA and routing algorithm for MCMR WMNs, called *Maxflow-based Channel Assignment and Routing* (MCAR). A flow rate computation method is proposed and the CA is done such as a given set of flow rates are schedulable. This algorithm performs in two steps: the first step groups the network links based on the flows they carry. In the second step, for each group of links a channel is selected and assigned to all the links of the group. These two steps not only ensure the network connectivity but also guarantying that the number of channels assigned to a node does not exceed the number of its interfaces. Instead of performing routing first and CA second, V. Gardellin et al. in [6] perform them jointly. They propose a generalized scheme called *Generalized Partitioned Mesh network traffic and interference aware channeL Assignment* (G-PaMeLA). In order to simplify the joint CA and routing problem, they follow a sequential divide-and-conquer approach. They divide the global joint CA and routing problem into sub-problems which are simpler to solve than the global joint CA and routing problem.

Unicast-based CA and routing solution are not readily or consistently suitable to be applied in the context of multicast communications. CA and routing have been recently studied and discussed in the context of multicast communications [15], [16], [19], [23], [25]. In [23], Roy et al. studied routing problem in the case of single-radio single-channel WMNs. They show that metrics of unicast routing can be adapted and exploited in multicast. In [19], H. Nguyen and U. Nguyen assume that the multicast tree is constructed a priori according to MCM multicast tree construction. Authors propose a CA algorithm, named *Minimum interference Multi-channel Multi-radio Multicast* (M4), which is an improved version of MCM by considering the interference caused by two-hop neighbors. In [16] Li et al. investigate routing metrics in MCMR WMNs. Two load-aware multicast routing metrics, named *Flow Load Multicast Metric* (FLMM) and *Reliable Flow Load Multicast Metric* (FLMMR), are proposed and they are incorporated in MAODV protocol to design an enhanced MAODV multicast routing protocol. Jahanshahi et al. [15] propose a mathematical formulation for the cross-optimization of multicast tree construction. Authors survey the existing techniques and methods of multicast routing in MCMR WMNs, and a method to solve jointly the two sub-problems of CA and multicast routing is proposed. The MCM algorithm [25] considers that the multicast tree is static. Previous multicast routing and CA approaches consider that the multicast tree is static and they do not propose any solution which allows nodes to join and to leave the multicast tree. Our work in this paper dresses the problem of dynamism in a multicast tree. Our proposed algorithms allow nodes to join and to leave the multicast tree while re-assign channels according to the multicast tree topology changes.

VI. CONCLUSION

This paper addresses a fundamental design issue to make multicast routing dynamic in MCMR WMN. For that we proposed two algorithms: the first one allows a node to leave the multicast tree and the second one allows a node to join the multicast tree. In both algorithms, an effective multicast structure is constructed to minimize the number of relay nodes and the communication delay. They guarantee the connectivity in the network and construct dynamic multicast tree without compromising the effectiveness of CA. Our future work will address the problem of incorporating traffic load information into the multicast routing and the CA.

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