A Genetic-Inspired Joint Multicast Routing and Channel Assignment Algorithm in Wireless Mesh Networks

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Abstract

This paper proposes a genetic algorithm (GA) based optimization approach to search a minimum-interference multicast tree which satisfies the end-to-end delay constraint and optimizes the usage of the scarce radio network resource in wireless mesh networks. The path-oriented encoding method is used and each chromosome is represented by a tree data structure (i.e., a set of paths). Since we expect the multicast trees on which the minimum-interference channel assignment can be produced, a fitness function that returns the total channel conflict is devised. Crossover and mutation are well designed to adapt to the tree structure. A simple yet effective channel assignment algorithm is proposed to reduce the channel conflict. Simulation results show that the proposed GA based multicast algorithm achieves better performance in terms of both the total channel conflict and the tree cost than that of a well known algorithm.

1 Introduction

Wireless mesh networks (WMNs) [2] have emerged as a new paradigm of static multi-hop wireless networks. Multicast [8] is an important network service, which is the delivery of information from a source to multiple destinations simultaneously. Quality of Service (QoS) requirements [8] proposed by different multicast applications are often versatile. Among them, end-to-end delay [3] is a pretty important QoS metric since real-time delivery of multimedia data is often required. The multicast tree cost, used to evaluate the utilization of network resource, is also an important QoS metric especially in wireless networks where limited radios and channels are available. So far, little work has addressed QoS multicast in WMNs. However, it is believed that efficient multicast, which cannot be readily achieved through combined unicast or simplified broadcast, is essential to WMNs and deserves a thorough investigation [9].

In WMNs, the wireless interference occurs when two links whose distance is less than 2 hops away are assigned to the same channel to support the concurrent communications, which is termed as channel conflict [4]. Therefore, for multicast routing, each link on the multicast tree requires to be assigned to one channel and the assignment should lead to minimum interference. In fact, the minimum-interference channel assignment problem itself is basically the Max K-cut problem [6], which is known to be NP-hard. Therefore, our problem, i.e., the routing tree construction plus minimum-interference channel assignment, is also NP-hard. In this paper, we propose an efficient QoS multicast routing algorithm in WMNs, which utilizes a well-designed genetic algorithm (GA) to search a low cost routing tree on which the channel assignment can produce the minimum interference. Intuitively by exploring the strong search capability of GA, more candidate routing trees can be examined to help find the one with the minimum channel conflict.

The rest of this paper is organized as follows. We discuss related work in Section 2. We describe the network model and the formulation of our problem in Section 3. We present the proposed GA multicast routing algorithm and channel assignment algorithm in Section 4. We present our simulation results in Section 5 and conclude this paper in Section 6, respectively.

2 Related Work

In WMNs, little work has been done on multicast routing due to its intractability. In [9], two multicast algorithms were proposed, which first build a multicast tree between the source and receivers, and use dedicated strategies to assign channels to the tree aiming to reduce interference. However, since both algorithms separate the construction of the multicast tree and the channel assignment, they will bear a potential drawback, that is, channel assignment cannot work well with the determined multicast tree. Furthermore, they do not consider the delay constraint which is a common issue for multicast problems.

We are not aware of any other work that jointly considers multicast routing, which further consists of channel assignment as well as QoS in multiradio multichannel wireless mesh networks, although there are quite a few works that are related to some relevant aspects. Genetic algorithm has been extensively used in solving the QoS multicast problems in various networks such as the wired multimedia networks [8]. However, to our best knowlege, GA has not been addressed to solve the multicast problems in WMNs.

3 Problem Formulation

We consider a wireless mesh network with stationary mesh routers where each router is equipped with a certain number of radio network interface cards (NICs). We model a wireless mesh network by a undirected and connected topology graph $G(V, E)$, where V represents the set of mesh routers and E represents the set of communication links connecting two neighboring mesh routers falling into the radio transmission range. A communication link (i, j) can not be used for packet transmission until both node i and node j have a radio interface each with a common channel. In addition, message transmission on a wireless communication link will experience a remarkable delay.

For clarity of presentation, we assume the *binary interference model*, i.e., two communication links either interfere or do not interfere. Given the binary interference model, the set of pairs of communication links that interfere with each other over the same channel can be represented by a conflict graph [4]. A communication link in the topology graph corresponds to a vertex in the conflict graph. With the binary interference model, the conflict graph $G_c(V_c, E_c)$ can be easily derived from the topology graph $G(V, E)$. We assume the communication links (a, b) and (c, d) in the topology graph $G(V, E)$ are represented by the node i_c and node j_c in the conflict graph $G_c(V_c, E_c)$, respectively. Then if the minimum distance between (a, b) and (c, d) is less than 2 hops, we have $(i_c, j_c) \in E_c$.

Here, we summarize some notations that we use throughout this paper.

- $G(V, E)$, the WMN topology graph.
- $G_c(V_c, E_c)$, the conflict graph derived from the WMN topology graph.
- $K = \{0,1,2,...,k\}$, the set of available orthogonal channels.
- s, the source node of the multicast communication.
- $R = \{r_0, r_1, ... r_m\}$, the set of receivers of the multicast communication.
- $T(V_T, E_T)$, a multicast tree with nodes V_T and links E_T.
- V_T^{Leaf}, the set of leaf nodes on the tree T.
- $P_T(s, r_i)$, a path from s to r_i on the tree T.
- d_l, the delay on the communication link l.
- $I_T(f)$, the total channel conflict on the tree T.
- C_T, the cost of the tree T.

The problem of joint QoS multicast routing and channel assignment in a multiradio multichannel wireless mesh network can be informally described as follows. Given a network of mesh routers with multiple radio interfaces, a delay upper bound, a source node and a set of receivers, we wish to find a delay-bounded multicast tree and assign a unique channel to each communication link on the tree. We define the *total channel conflict* as the number of pairs of communication links on the tree that are interfering (i.e., are assigned the same channel and are connected by an edge in the conflict graph). The objective of our problem is to minimize the above defined total channel conflict, as it results in improving the system throughput [9].

We also want to optimize the usage of the scarce network resources in the multicast tree. So we define the *tree cost* as the number of the radio interfaces involved in the multicast communications. We aim to find a multicast tree with low cost. There are two factors related to the tree cost. One is the number of communication links on the tree. Each communication link has one sender and one receiver, thereby occupying two radio interfaces. So we should reduce the number of links on the multicast tree, which also helps reduce the multicast end-to-end delay. The other factor is the number of broadcast nodes generated from the channel assignment. We make all the branch nodes become broadcast nodes by exploiting wireless multicast advantage (WMA) [7] and the detail is described in Section 4.2. If there are several multicast trees which have the same channel conflict value, we will choose the one with the minimum tree cost.

More formally, consider a wireless mesh network $G(V, E)$ and a multicast communication request from the source node s to a set of receivers R with the delay upper bound Δ. The *joint QoS multicast routing and channel assignment problem* is to find a multicast tree $T(V_T, E_T)$ satisfying the delay constraint as shown in (1) and compute a function $f : E_T \rightarrow K$ defined in (2) to minimize the *total channel conflict* $I_T(f)$ defined in (3).

$$\max_{r_i \in R} \left\{ \sum_{l \in P_T(s,r_i)} d_l \right\} \leq \Delta \, . \quad (1)$$

$$f(i_c \in E_T) = \{j | j \in K\} \quad (2)$$

$$I_T(f) = |\{(i_c, j_c) \in E_c | f(i_c) = f(j_c), \\ i_c \in E_T, j_c \in E_T\}| \quad (3)$$

Since the source only transmits packets and all the leaf nodes only receive packets, each of them occupies one radio interface only. All the other nodes are branch nodes which need to do both the transmission and reception. So each branch node occupies two radio interfaces. As a result, the tree cost C_T is calculated as follows:

$$C_T = |\{s\}| + |V_T^{Leaf}| + \\ 2 * (|V_T| - |\{s\}| - |V_T^{Leaf}|) \quad (4)$$

4 Algorithm Design

This section describes the proposed GA-based joint QoS multicast routing and channel assignment algorithm. The GA operations consist of several key components: genetic representation, population initialization, fitness function, selection scheme, crossover and mutation. Chromosomes are expressed by tree data structure. The initial population is generated and explores the genetic diversity the most. Fitness function returns the total channel conflict of the multicast tree. Variation operators (i.e., crossover and mutation) efficiently promote the search capability. Note that every step guarantees that a tree does not violate the delay constraint. The population keeps evolving until it converges. The channel assignment algorithm aims to achieve minimum interference on a given multicast tree.

4.1 Design of Genetic Algorithm

4.1.1 Genetic Representation

A multicast tree is a union of the routing paths from the source to each receiver. Hence, it is a natural choice to adopt the path-oriented encoding method [1]. A routing path is encoded by a string of positive integers that represent the IDs of nodes through which the path passes. Each locus of the string represents an order of a node (indicated by the gene of the locus). The gene of the first locus is for the source and the one of the last locus is for the receiver. The length of a routing path should not exceed the maximum length $|V|$, where V is the set of nodes in the WMN.

For a multicast tree T spanning the source s and the set of receivers R, there are $|R|$ routing paths all originating from s. Therefore, we encode a tree by an integer array in which each row encodes a routing path along the tree. For example, for T spanning s and R, row i in the corresponding array A lists up node IDs on the routing path from s to r_i along T. Therefore, A is an array of $|R|$ rows. Chromosomes are encoded under the delay constraint. In case it is violated, the encoding process is usually repeated so as to satisfy the delay constraint.

4.1.2 Population Initialization

In GA, each chromosome corresponds to a potential solution. The initial population Q is composed of a certain number, denoted as q, of chromosomes. To explore the genetic diversity in our algorithm, for each chromosome, all its routing paths are randomly generated. We start to search a random path from s to $r_i \in R$ by randomly selecting a node v_1 from $N(s)$, the neighborhood of s. Then we randomly select a node v_2 from $N(v_1)$. This process is repeated until r_i is reached. Thus, we get a random path $P_T(s, r_i)=\{s, v_1, v_2, ..., r_i\}$. Since no loop is allowed on the multicast tree, the nodes that are already included in the current tree are excluded, thereby avoiding reentry of the same node. The initial population is generated as follows.

Step 1: Start(i=0).
Step 2: Generate chromosome Ch_i:
  a) Start(j=0, V_T=$\emptyset$,E_T=$\emptyset$);
  b) Search a random path $P_T(s, r_i)$ which can guarantee $T \cup P_T$ be an acyclic graph;

c) Add all the nodes and links in P_T into V_T and E_T, respectively;

d) $j = j$+1. If $j < |R|$, go to *b*).

Step 3: i=i+1. If $i < q$, go to *Step 2*; otherwise, stop.

Thus, the initial population Q ={Ch_0, Ch_1, ..., Ch_{q-1}} is obtained.

4.1.3 Fitness Function

Given a solution, we should accurately evaluate its quality (i.e., fitness value), which is determined by the fitness function. In our algorithm, we aim to find a low cost multicast tree on which the minimum interference channel assignment can also be achieved. Our primary criterion of solution quality is the total channel conflict and the subsidiary one is the tree cost. Therefore, among a set of candidate solutions (i.e., multicast trees) with the same minimum channel conflict value, we choose the one with the lowest tree cost. The fitness value of chromosome Ch_i (representing multicast tree T), denoted as $F(Ch_i)$, is given by:

$$F(Ch_i) = [I_T(f) + 1.0]^{-1} \ . \qquad (5)$$

The proposed fitness function only involves the total channel conflict. As mentioned above, The tree cost is used in the course of selecting the elitism for keeping the searched optimal solution.

4.1.4 Selection Scheme

Selection plays an important role in improving the average quality of the population by passing the high quality chromosomes to the next generation. The selection of chromosome is based on the fitness value. We adopt the scheme of pairwise tournament selection without replacement as it is simple and effective.

4.1.5 Crossover and Mutation

Genetic algorithm relies on two basic genetic operators - crossover and mutation. Crossover processes the current solutions so as to find better ones. Mutation helps GA keep away from local optima [1]. Performance of GA very much depends on them. Type and implementation of operators depends on encoding and also on a problem.

In our algorithm, since chromosomes are expressed by tree data structure, we adopt single point crossover to exchange partial chromosomes (sub-trees) at positionally independent crossing sites between two chromosomes [1]. With the crossover probability, each time we select two chromosomes Ch_i and Ch_j for crossover. To at least one receiver, Ch_i and Ch_j should possess at least one common node from which one, denoted as v, is randomly selected. In Ch_i, there is a path consisting of two parts: ($s \xrightarrow{Ch_i} v$) and ($v \xrightarrow{Ch_i} r_i$). In Ch_j, there is a path consisting of two parts: ($s \xrightarrow{Ch_j} v$) and ($v \xrightarrow{Ch_j} r_i$). The crossover operation exchanges the paths ($v \xrightarrow{Ch_i} r_i$) and ($v \xrightarrow{Ch_j} r_i$).

The population will undergo the mutation operation after the crossover operation is performed. With the mutation probability, each time we select one chromosome Ch_i on which one receiver r_i is randomly selected. On the path ($s \xrightarrow{Ch_i} r_i$) one gene is selected as the mutation point (i.e., mutation node) denoted as v. The mutation will replace the path ($v \xrightarrow{Ch_i} r_i$) by a new random path.

Both crossover and mutation may produce new chromosomes which are infeasible solutions. Therefore, we check if the multicast trees represented by the new chromosomes are acyclic. If not, repair functions [5] will be applied to eliminate the loops. Here the detail is omitted due to the space limit. All the new chromosomes produced by crossover or mutation satisfy the delay constraint since it has already been taken into consideration.

4.2 Channel Assignment Algorithm

In a wireless mesh network, a link cannot be used for data transmission until it has been assigned a wireless communication channel. To support the multicast communication over the routing tree, an appropriate channel should be assigned to each link on the tree so as to achieve the minimum interference (i.e., channel conflict). In addition, the number of available channels is limited in the current network protocols. For example, in IEEE 802.11-based wireless networks, there are 11 available channels. However, at most 3 of them are orthogonal (non-interfering). The number of radio interfaces is also limited as a type of scarce radio network resource. Hence the channel assignment should use as small number of channels and radio interfaces as possible.

Since the minimum-interference channel assignment problem is NP-hard, we propose a heuristic algorithm which aims to reduce both the channel conflict and resource utilization. Given the set of orthogonal channels K={0,1,...,k} ($k \geq 2$), the algorithm works on the multicast tree T as follows.

Step 1) Start(i=0).

Step 2) Assign channels to the routing path $P_T(s, r_i)=(s, v_1, v_2, ..., v_{j-1}, r_i)$. Here v_0 represents the source s and v_j represents the receiver r_i, respectively.

- *a*) Start(n=0);
- *b*) If link (v_n, v_{n+1}) has not been assigned a channel, assign channel n%3 to it;
- *c*) n=n+1. If $n < j$, go to *b*).

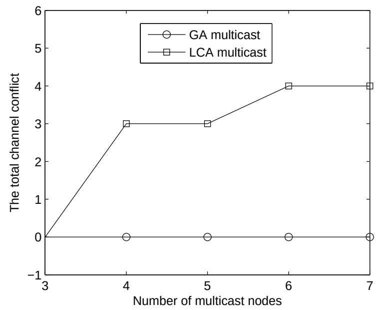
Step 3) i=i+1. If $i < |R|$, go to *Step 2*; otherwise, stop.

For each routing path, the algorithm uses 3 channels to do the assignment. Since the minimum distance between two links to avoid channel conflict is 2 hops, 3 is the least number of channels to achieve conflict free assignment on each routing path of the multicast tree. By our assignment strategy, all the links originating from the same branch node are assigned the same channel as utilizes the so-called WMA [7]. WMA refers to that a single transmission can be received by all the nodes that are within the transmission range of a transmitting node. Hence, using one radio interface only, the branch node transmits packets to all its children. This also saves the number of used radio interfaces.

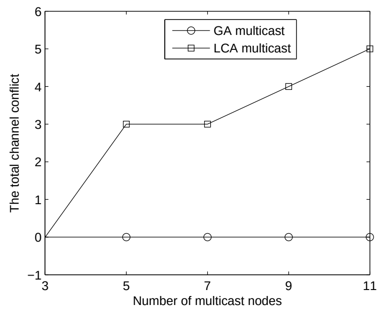
5 Performance Evaluation

In this section, the proposed GA-based joint multicast routing and channel assignment algorithm is compared with *Zeng'* Level Channel Assignment (LCA) multicast algorithm [9] through simulation experiments. The LCA multicast algorithm is composed of two components. First, it constructs a multicast tree based on breadth first search (BFS) aiming to minimize the hop count distances between the source and receivers. Second, it uses a dedicated strategy to assign channels to the tree aiming to reduce the interference. Hence, this algorithm separates the multicast tree construction and channel assignment. If the channel assignment strategy cannot work well on the generated multicast tree, the algorithm can do nothing while our algorithm can search other trees.

In our algorithm, there are three GA parameters: population size, crossover and mutation probabilities. In all the experiments, the population size is set to 10, the crossover probability is set to 0.8, and the mutation probability is set to 0.1. The delay upper bound Δ is set to 20. Each experiment is terminated when all the chromosomes in the population have converged to the same solution [5]. Without loss of generality, we assume each mesh router has two radio network interface cards: one for transmission and the other for reception. We assume there are 3 orthogonal channels as the case in 802.11 wireless network. We evaluate both algorithms on two different network topologies: one consists of 11 nodes and 20 links and the other consists of 23 nodes and 34 links. The metrics that we have evaluated include the total channel conflict and the tree cost.



(a)



(b)

Figure 1: Comparison of GA multicast and LCA multicast in terms of the total channel conflict in: (a) a WMN of 11 nodes; (b) a WMN of 23 nodes.

We have compared the GA multicast algorithm with the LCA multicast algorithm on various size of multicast groups. In the WMN of 11 nodes, the size ranges from 3 to 7 while in the WMN of 23 nodes it ranges from 3 to 11. Fig. 1 and Fig. 2 show the comparison results in terms of the total channel conflict and the tree cost, respectively. The results of GA multicast algorithm take the average values. From Fig. 1, we can see that in both networks, our GA multicast algorithm always finds the multi-

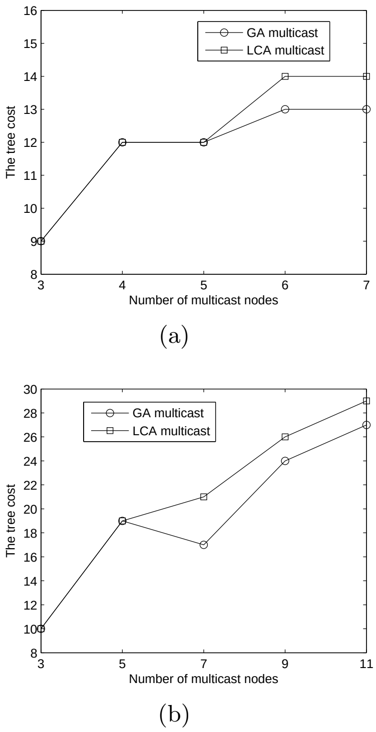


Figure 2: Comparison of GA multicast and LCA multicast in terms of the tree cost in: (a) a WMN of 11 nodes; (b) a WMN of 23 nodes.

cast trees on which the conflict-free channel assignment is achieved. However, the LCA multicast algorithm cannot find the multicast tree where channels can be assigned without conflict. Furthermore, with the increase in the multicast group size, more conflicts occur on the LCA multicast trees. Fig. 2 shows that the cost of our GA multicast trees is lower than the cost of the LCA multicast trees when the multicast group size exceeds 5. To sum up, our GA multicast algorithm logs conflict-free channel assignment and better cost values while satisfying the delay constraint.

6 Conclusions

A routing tree with orthogonal channels appropriately assigned is preferred to support the multicast service in WMNs. However, the optimal multicast routing and channel assignment problem is proved to be NP-hard. This paper presents a genetic-inspired joint multicast routing and channel assignment algorithm to discover a delay-bounded minimum-interference low cost multicast tree. We believe that the synergy achieved by combining the efficient search capability of GA and the effective channel assignment results in the improved quality of solution. We compare its performance with the prestigious LCA multicast algorithm. Experimental results demonstrated that our GA multicast algorithm always discover the conflict-free multicast trees which also have lower cost (i.e., less radio network interfaces occupied) than LCA multicast trees.

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