A Lower-Cost Minimal Relay Tree Algorithm for Wireless Mesh Networks

1 Ting T. LIU, 1,2 Wei YANG, 3 Yu Z. WANG

1 School of Electronic and Information Engineering, Beijing Jiaotong University, 100044, Beijing, China
2 National Mobile Communications Research Laboratory, Southeast University, Nanjing, China
3 Department of Aviatic Information System, North China Institute of Computing Technology, 100083, Beijing, China

1 E-mail: 09111040@bjtu.edu.cn

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Abstract: In order to improve the performance of multicast tree in wireless mesh networks and reduce the total cost of multicast tree, a Lower-Cost Minimal Relay Tree (LCMRT) algorithm for wireless mesh networks is proposed based on MCM (Multichannel Multicast) and DDSP (Destination-Driven Fast Lower-Cost Shortest Path tree). The algorithm selects the lower-cost path for data delivery on the condition of minimal relay nodes which reduces the end-to-end delay. At the same time, a more precise parameter of interference degree is introduced which decreases the interference between links and improves the system throughput. The algorithm analysis and simulation results show that LCMRT performs better than DDSP in computational efficiency. The total cost and delay of LCMRT are reduced by 13.33 % and 6.15 % respectively and the system throughput of LCMRT is improved by 4.29 % compared to MCM. Copyright © 2013 IFSA.

Keywords: Wireless Mesh Network, Multicast, Minimal Relay Tree, Lower-cost.

1. Introduction

Multicast is a delivery method that enable information to be transmitted by a source node simultaneously to a group of destination nodes. All receivers which have the same request share a common copy so that multicast technology decreases the number of copies and avoid the network congestion. Therefore, this communication mode was widely used in applications [1-3] such as VoD (Video on Demand), video conferencing, and file transferring. Multicast service in WMN (Wireless Mesh Networks) is an essential service oriented applications such as VoD and multicast tree construction is one of the core service implementations. Multicast tree with good performance can maximize the use of bandwidth, reduce interference and improve network service quality and QoE (Quality of Experience) on the condition of limited bandwidth and capacity [4-7], a Lower-Cost Minimal Relay Tree (LCMRT) algorithm is proposed in this paper. LCMRT guaranteed minimum number of relay nodes at the same time try to choose lower-cost path to forward data, which not only reduced interference caused by excessive relay nodes but also reduced the overall cost of the multicast tree.

The paper is organized as follows. In section II, we briefly describe existing multicast tree construction methods and problem we need to solve. The detail algorithm implementation and the mathematic analysis are discussed in section III and
section IV. Section V gives the simulation results and analysis. Conclusions are drawn in section VI.

2. The Construction of Multicast Tree

2.1. Multicast Tree Construction Methods

There are two basic construction methods of multicast tree in WMN, SPT (Shortest Path Trees) and MCT (Minimum Cost Trees) [8]. Literature [7] proposed a multi-channel multicast algorithm (MCM) by constructing a multicast tree with minimum number of relay nodes which reduced the flow of data in the network in order to reduce network bandwidth consumption and interference. Link cost was ignored by MCM in the constructing process so that the MCM multicast tree is not a MCT, to a certain extent, this decreased the network performance. To take multicast tree cost into account, a destination-driven shortest path tree Construction (DDSP) algorithm was proposed in [9]. DDSP took the idea of ascending path in Dijkstra algorithm. When there are multiple shortest paths existing between the source node and a certain destination node, the closest path to the current spanning tree was chosen instead of a random path. A fast low-cost shortest path tree algorithm (FLSPT) and a fast lower-cost shortest path tree algorithm (FLCSP) based on DDSP were proposed in [10] and [11] respectively by improving the search process. FLSPT has the same algorithm performance with DDSP but its efficiency is higher than that. Both of them (FLSPT and FLCSP) are not suitable for wireless mesh networks because they have more relay nodes and higher algorithm complexity than expected.

A Lower-Cost Minimal Relay Tree (LCMRT) algorithm is proposed in this paper. It chooses the lower-cost path for data delivery on the condition of minimal relay nodes which reduces the end-to-end delay and total multicast cost in the network. At the same time, a more precise parameter of interference degree is introduced which decreases the interference between links and improves the system throughput.

2.2. Problem Description

The objective of MCM algorithm is to search for a multicast tree which can cover all destination nodes subject to the minimum relay nodes. The main idea of it is searching for a set with the minimum number of nodes in upper layer which can cover all under layer nodes. Theoretically, the parent node that a certain node can select is not unique. According to this, there may exist many parent-sets that can fully cover the current layer. The sums of weights of the spanning tree constructed through different parent sets are also different. To choose the minimum one can reduce the cost of multicast tree. Therefore, MCM algorithm can be optimized.

Fig. 1(a) and Fig. 1(b) illustrates the original network topology and MCM multicast tree respectively. The solid dots represent the source node and destination nodes. The parent-set in the fourth layer than can fully cover the fifth layer (\{k,l,m\}) is \{h,i\}. Node h is selected as a parent of node m in a random way in MCM algorithm, as depicted in Fig. 1(b) with heavy line. Provided m selects i as its parent as depicted in Fig. 2, the number of relay nodes (N_r) are not increased at the same time the total length of path (path) and the total cost of the network are decreased.

![Fig. 1 (a). The original network topology.](image)

![Fig. 1 (b). The MCM multicast tree.](image)

![Fig. 2. The proposed LCMRT algorithm.](image)

The mathematic description is given as follows. Let undirected graph $G = (V,E)$ denote the network, the source node $S$ denotes the multicast...
source and set $D$ represents all of the destination nodes. If it exists an edge between node $u$ and node $v$, we denote the weight of the edge as $\text{cost}(u, v)$. The multicast tree construction process is equivalent to finding the subgraph of $G$, $T = (V, E)$. $T$ is a connected graph, $V$ is the set of all destination nodes and $E$ is the set of edges that meet the LCMRT demand. The nodes except the source node $S$ and destination nodes in $T$ are called relay nodes.

**Definition 1. The Minimum Relay Tree Problem** I.e. to find the multicast tree $T$ subject to the condition that $T$ has the minimum number of relay nodes and $T$ and completely cover $S$ and $D$.

**Definition 2. The Minimum Cost Tree Problem** I.e. to find multicast tree $T = (V, E)$ that can completely cover $S$ and $D$ such that the sum of weights in $T$ is minimum. It can be represented by $\min \{\text{cost}(u, v)\}_{(u, v) \in E}$.

**Definition 3. The Lower-cost Minimum Relay Tree Problem.** The multicast tree sets $\{T_1, T_2, L, T_n\}$ that can completely cover $S$ and $D$ with minimum number of relay nodes meet the demand that:

$$\text{cost}(T_1) J \text{cost}(T_2) J L J \text{cost}(T_n),$$

where $\text{cost}(T_i)$ denotes the sum of cost of edges in $T_i$ and $T_i$ is the lowest-cost tree among $\{T_1, T_2, L, T_n\}$. We call $T_i$ the lower-cost minimum relay tree.

**Definition 4. Minimum Covering Set.** Given a bipartite graph $G_b = (A, E_b, B)$. $A$ and $B$ are two mutually disjoint subset. $\text{Chi}(k)$ denotes the children set of $k$ and $\text{Par}(k)$ denotes the parent set of $k$. The subset $F$ selected from $A$ that can cover $B$ and has the minimum number of nodes is called the minimum covering set.

The LCMRT algorithm consists of two parts: the construction algorithm and the channel assignment algorithm.

### 3. The LCMRT Construction Algorithm

#### 3.1. The idea of the Construction Algorithm

The LCMRT algorithm builds a minimum relay tree based on MCM algorithm which has a lower cost and a non-incremental relay nodes number than MCM tree by optimizing the searching process of DDSP. LCMRT algorithm optimizes the multicast tree in the following two cases:

1) The minimum covering set $F$ is unique but more than one parent of the current node belongs to $F$ which means that there are more than one alternative path in the network. Thus, LCMRT selects the path with minimum cost among that to build the lower-cost tree.

2) The minimum covering set $F$ is unique and more than one parent of the current node belongs to the intersection of all $F$. This means that there are many construction methods that can cover all the under layer nodes, i.e. there exists many multicast trees meeting the ‘minimum number of relay nodes’ demand. Therefore, LCMRT selects the minimum cost tree among them in order to optimize the multicast tree.

**Theorem 1.** $F_i (i = 1, 2, L, n)$ denotes the minimum covering sets of node $k$ in $k$'s level. For $k \in O$ if $\text{Par}(k) \cap \bigcup_{i=1}^{n} F_i$, then select arbitrary $u$ $O$ $\text{Par}(k)$ as the parent of $k$ will not increase the number of relay nodes in the network. When $i = 1$, the minimum covering set is unique.

**Proof.** Proof by contradiction. Suppose to select arbitrary $u_0$ $O$ $\text{Par}(k)$ as the parent of $k$ will increase the number of relay nodes in the network, then there must exists a node $u_i$ $O$ $\text{Par}(k)$ such that when $u_i$ is chosen to be the parent of $k$, the number of relay nodes is less than the $u_0$’s situation. Therefore, there is a minimum covering set $F$, $u_1$ $O$ $F$ and $u_0$ $\Pi$ $F$, i.e. there exists $u_0$ $O$ $\text{Par}(k)$ and $u_0$ $\Pi$ $\bigcup_{i=1}^{n} F_i$, then $\text{Par}(k) \cap \bigcup_{i=1}^{n} F_i$. From the above the theorem holds.

According to theorem 1, the number of relay nodes of LCMRT tree is not more than that of MCM tree and the total cost of LCMRT tree is lower than that of MCM tree.

The process of LCMRT algorithm is as follows.

(1) Take a breadth-first search (BFS) on the graph $G = (V, E)$ to mark the level every node belongs to.

(2) The source node belongs to level 1.

(3) Starting from the bottom the upper layer of two level-adjacent nodes is $S_i$ and the under layer of them is $S_j$.

(4) Select $i_0$ from $I$ subject to $\min \{\text{cost}(i_0, j)\}$.

Connect all $k$ $O$ $\text{Chi}(i_0)$ to $i_0$, i.e. $\text{Pri}(k) = i_0$ and mark the state of $k$ as 1 which means the node has been computed. For all children nodes of $i_0$ that have been computed, compare $\text{cost}(k, i_0)$ and $\text{cost}(k, \text{Pri}(k))$ then choose the lower-cost one as parent of $k$. Update $S_i$ and $S_j$ according to (2).
5) Repeat (3) and (4) until S_j is empty.
6) Repeat (2) (5) until the value of level is equal to 2.

3.2. Algorithm Description

The pseudocode of the channel assignment algorithm is described as follows:

Input: Graph G, Source node s, Destination nodes D;
Output: Multicast tree T;
Initial the network with tree T ← Null, the source node s and the destination nodes D;
BFSTraverse[Graph G, int k];
If k ∉ D then
CST[k] ← 0; Pri[k] ← Null; nState[k] ← 0;
IsDest[k] ← True;
Else
CST[k] ← 0; Pri[k] ← Null; nState[k] ← 0;
IsDest[k] ← False;
End if
For l=LevelNum; l>=2; l--; Do
Si ← {node i| i belongs to level l-1};
Sj ← {node j| j belongs to level l&& IsDest[j]=True};
While Sj!=Null
Pick up J in Sj which have the minimal number of parents;
Among the parents of J, pick up I which have the maximal number of destination children;
Pick up 0_i in I which minimize the total cost in current level;
For all k in {children of 0_i} Do
If nState[k] =0 then
Pri[k]← 0_i ; nState[k]← 1;
Else if nState[k]=0 & & cost[k, 0_i ]<cost[k, Pri[k]]
Pri[k]← 0_i ;
End If-Else
End For
IsDest[0_i ]←True;
Si←Si\{0_i \};
Sj←Sj\{children of 0_i \};
End While
End For

3.3. Algorithm Complexity Analysis

n and e denote the number of vertices and edges of graph G respectively. The algorithm complexity of BFS relates with the storage structure of the graph. We adopt adjacency list to storage it, thus the algorithm complexity of BFS is O(n + e). The initialization time of this algorithm is T_1 = O(n).

The selection algorithm compares the number of parents and children of the nodes to choose the biggest or smallest one. The comparison algorithm adopts Fibonacci searching method so the worst situation of it has a O(log n) complexity. Each node compares two times when it acts as a parent and a child. Therefore, the complexity of comparison algorithm is T_2 = 2nO(log n) = O(n log n). The updating algorithm requires ergodic of all children of the selected node 0_i, the number of children of 0_i is |Chi(0_i)|, so the complexity of updating algorithm is T_3 = c \sum_{0_i} |Chi(0_i)|.

From all the above, we can get the complexity of LCMRT is:

\[ T = T_1 + T_2 + T_3 = O(n) + O(n log n) + \sum_{0_i} |Chi(0_i)| = O(n + n log n + e) = O(n log n + e) \] (1)

As we can see from equation (1), the complexity of LCMRT is the same as that of MCM, but it is lower than that of DDSP (O(e log n)).

4. The LCMRT Channel Assignment Algorithm

4.1. Interference Degree Analysis

The channel assignment strategy of WMN is minimizing the interference of links to improve system throughput. The LCMRT trees generate three kinds of interference: interference of nodes within the same level, interference of nodes within adjacent levels and interference of nodes whose level separation is more than one. We call them the same-level interference, the adjacent-level interference and the separate-level interference respectively.

The more intensive the distribution is, the more significant the impact of separate-level interference is. We evaluate this impact through the experiment with WMN devices of Strix company. The IWS (indoor Wireless System ) [12] devices can be used indoor and have the forward, access and cover functions. IEEE 802.11g is the most common WLAN protocol, so we set the center frequency of the radio as 2.4 GHz. The radius of device is 30 m under IEEE 802.11g protocol, so we display devices in a 10 m interval. The device receiver sensitivity is 90 –dBm. There are three non-overlap channels in IEEE 802.11g, 1, 6 and 11. The channel assignment and network topology are depicted in Fig. 3. S serves as the server, and composes a chain-link topology with node a, b and c. The scene 1 is the ideal channel.
assignment strategy with orthogonal channels while in scene 2, channel 1 assigned to link S→a, b→c and channel 6 assigned to link a→b.

The results are shown in Table 1. loc, rem, delay, upstream and downstream denote the sender received signal strength (dBm), the receiver received signal strength (dBm), the delay from gateway to the receiver (ms), the upstream bandwidth (Mbps) and the downstream bandwidth (Mbps).

The signal strength of link S→a and b→c in scene 1 are 10 dBm and 9 dBm less than that in scene 2 respectively. The average delay of link S→a and b→c in scene 1 are 0.9 ms and 2.8 ms smaller than that in scene 2. The total bandwidth of link S→a and b→c in scene 1 are 1.5 Mbps and 2.3 Mbps bigger than that in scene 2. As we can see from the above, the separate-level interference has a significant impact on wireless network performance.

To further reduce impact of the interference of adjacent link on network performance, we introduced a more precise parameter than interference factor [13] called interference degree.

Definition 5. Interference Degree \( d(t) \). On the condition of certain degrees of separation, interference degree is defined as a linear function of the size of overlapping section \( S \tilde{Y} \), i.e.

\[
d(t) = aS\tilde{Y} + b, 
\]

where both \( a \) and \( b \) are constant.

As depicted in Fig. 4, \( A \), \( B \) are the senders on links \( AC \) and \( BD \) respectively. When \( d \leq r \), \( A \), \( B \) are within each other’s interference range, so \( A \), \( B \) interfere each other despite adjacent or not. The size of the overlapping section, the bigger the interference is. The size of overlapping section can be expressed as \( S\tilde{Y}O(2/3\Psi r^2 - \sqrt{3}/2\Psi^2, pr^2) \) when \( dO[r,0) \). That is because when \( d \) varies uniformly from \( r \) to 0, \( S\tilde{Y} \) varies uniformly from \( 2/3\Psi r^2 - \sqrt{3}/2\Psi^2 \) to \( pr^2 \) at the same time. Therefore,

\[
S\tilde{Y} = r(r - d)(\rho/3 + \sqrt{3}/2) 
\]

The common expression of interference factor is \( d_i = r / R \) [13] where \( t \) is the separation degree of channels, \( r \) and \( R \) are the interference range and distance of links respectively.

Take the equation (3) into (2) we can get

\[
d(t) = a\tilde{Y}^2R^2(1 - d/r)(\rho/3 + \sqrt{3}/2) + b 
\]

Take the equation \( d_i = r / R \) into (4) we can get

\[
d(t) = a\tilde{Y}^2R^2 - a\tilde{Y}(\rho d + b) 
\]

where \( d \in \Delta \), \( \Delta = \{D, \sqrt{2}D, 2D, \sqrt{5}D, \ldots\} \) and \( \Delta \) is the unit distance of a mesh grid.

When the sender channel of node \( u \), \( i_u \), satisfy

\[
\min_{i \in V(Y)} d(i_u - i) \text{, where } V(Y) \text{ denotes the set of nodes which have been assigned channels.} 
\]
4.2. Channel Assignment Algorithm

Suppose all mesh nodes have the same transmission range and two interfaces. One is used for sending, the other is used for receiving.

The pseudocode of the channel assignment algorithm is described as follows.

Input: Multicast tree T, Output: Channel assignment strategy
For l=1; l<LevelNum-1; l++ Do
    For all u satisfy level[u]=l Do
        \( V^\prime \leftarrow \{\text{all nodes have been assigned channels for send interface}\}; \)
        Choose \( i_u \) for node u which satisfy \( \min_{v \in V^\prime} d(v, i_u) \);
        u’s send interface\( \leftarrow i_u \);
        Receive interface of u’s children\( \leftarrow i_u \);
    End For
End For

5. Simulation Results and Analysis

We adopt NS3 (Network Simulator Version 3.10) [14] to do the simulation. It performs NS2 in terms of completeness, modularization and scalability. It also abstracts every component of the real network into modules and to the greatest extent implement the actual network environment. Therefore, NS3 gives more objective results [15].

We consider a wireless mesh network with 8×8 mesh routers randomly distributed within a 900 m × 900 m rectangular region. The transmission range of every mesh router is 250 m. The source node locates at top-left and acts as a gateway. The destination nodes are randomly selected within remain nodes. Every node has two interfaces with Packet Capture Library (PCAP) activated. The data rate is set to 2 Mbps, end to end delay is 2 ms and the simulation time is 100 s. 10 topologies are generated randomly. The results of these 10 topologies are averaged.

The number of relay nodes and the total cost are illustrated in Fig. 5 and Fig. 6 respectively.

As we can see from Fig. 5 and Fig. 6, the relay nodes number of the LCMRT tree is not increased compared with that of the MCM tree. When there are 15, 25 and 35 destinations the former is 1-2 less than the latter. The total cost of the LCMRT tree is 13.33 % less than that of the MCM tree. When number of destination nodes is between 25 % and 70 %, i.e. the proportion of destination nodes is moderate, the advantages of LCMRT is particularly significant. This is due to the thoughts of selecting the optimal path from multiple alternative paths. When the number of destination nodes is too small or too large, it only has few choices of paths which limit the algorithm performance.

The results of throughput and average delay are depicted in Fig. 7.

As depicted in Fig. 7, the average delay of LCMRT algorithm is 6.15 % less than that of MCM algorithm, at the same time, the throughput of the former is 4.29 % larger than that of the latter. There are two reasons to explain it. First, decreasing the total cost of multicast trees makes the end to end delay reduce, which reduces the average delay. Second, through the analysis of interference degree, the optimal dimension of interference is enlarged, which improves the performance of link transmission and also the system throughput. Thus, LCMRT algorithm overwhelms MCM algorithm in terms of throughput and average delay. At the same time, a more precise parameter of interference degree is introduced which decreases the interference between links and improves the system throughput. The simulation results show that the total cost of the LCMRT tree is 13.33 % less than that of the MCM tree and the average delay of LCMRT algorithm is 6.15 % less than that of MCM algorithm, at the same time, the throughput of the former is 4.29 % larger than that of the latter.
6. Conclusions

Wireless Mesh networks have been widely used in special areas of a city, school, hospital, public entertainment place, business areas and enterprise. It provides seamless roaming in spite of indoor or outdoor. To adopt multicast technology improves users’ quality of experience. The thoughts of selecting the optimal path from multiple alternative paths are used in this paper, which optimizes the performance of multicast trees on the condition of not increasing the number of relay nodes. Therefore, a lower-cost minimum relay tree algorithm for wireless mesh networks is proposed in this paper, the simulation results show that the total cost of the LCMRT tree is 13.33 % less than that of the MCM tree and the average delay of LCMRT algorithm is 6.15 % less than that of MCM algorithm, at the same time, the throughput of the former is 4.29 % larger than that of the latter.

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