

A Fast Algorithm for Multicast Routing Subject to Multiple QoS Constrains in WMNs

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Abstract—The problem of optimal multicast routing tree in WMNs subject to multiple QoS constraints, which is NP-complete, is studied in this paper. As far as we know, the existing algorithms for finding such a multicast routing tree are not very efficient and effective in wireless mesh networks. Combining the previous effective algorithms, this paper devises a fast multicast path heuristic (FMPH) algorithm to deal with it. The theoretical validations for the proposed algorithm show that its approximation ratio is $2K(1-1/q)$ and the time complexity is $O(Km+qn^2)$. The simulation results on the special network show that the FMPH algorithm is as simple as Dijkstra algorithm in the way of implementation, which is fit for application in wireless routing protocols.

Index Terms—Wireless mesh networks, multicast routing, multiple QoS constrains, approximation algorithm

I. INTRODUCTION

The growth of Wireless Mesh Networks (WMNs) has been witnessed with widespread deployment of the high-speed network technology for the last few years [1], [2]. Rapid progress and inspiring numerous deployments are generating in WMNs. In personal, local, campus and metropolitan areas, it is intended to deliver wireless services for a large variety of applications. At the same time, new challenges to current high-speed packet switching wireless networks is also raising, one of which is Quality-of-Service (QoS) routing. In order to guarantee various applications subject to multiple QoS constrains in WMNs, it is intended to find the optimal multicast routing tree from the source to the destination nodes set.

Previous works in wired networks are focused on many applications, which are taking into account the routing subject to multiple QoS metric [3], [4]. Compared with previous works, more details should be taken in account for the multi-constrained routing in WMNs [5]. First of all, it is important for energy consumption which affects the cost of the multicast tree from source s to destination nodes set [6]. Secondly, it is equally important that the network lifetime charged by the

intermediate nodes providing forwarding service [7], [8]. It is known to all that finding such a multicast tree subject to multiple QoS constrains is an NP-complete problem [9]. More recently, many researches are focused on optimal deterministic algorithms and heuristic approximation algorithms for multi-constrained routing so that great breakthroughs have been achieved [9], [10]. On the one hand, deterministic algorithms such as the genetic algorithm, the ant colony algorithm and so on are making great progress recently [11], [12], such that the optimal solutions could be found finally by these algorithms without any time constrained. However, the time complexity grows exponentially with the increase of wireless network nodes, thus requiring an extremely fast computing and processing rate. As we know that wireless network nodes are restricted in energy consumption and computing power, so the most previous algorithms are not very suitable in WMNs. On the other hand, heuristic algorithms and approximation algorithms can find the approximate optimal solutions in shorter and more reasonable time [13], [14], thus they are more valuable and meaningful in wireless network application.

In terms of research on approximation algorithms, compared to optimal solutions, the approximate optimal solution found by the earliest heuristic algorithms were less than 2 in the worst situations. Later on, X. Yuan did the research and put forward the approximation algorithm in 2002 [15]. Based on that G. Xue and others presented novel algorithms for the MCOP problem [16],[17], which guaranteed that the approximate rate of solution remained at $(1+\epsilon)$ by rounding and scaling. As recent as 2013, Hwa-Chun Lin and others devised a multicast tree approximation algorithm dependent on node weight [18]. In 2014, Guan hong Pei did research on the maximal handling capacity of delay-constrained wireless networks and proposed a new type of approximation algorithm [19]. At the same time, famous Prof. Athanasios Vasilakos and his coauthors have done extensive studies on approximation algorithms in the literature [20], [21], which are in the scope of WMNs. Weijun Yang and Yun Zhang did research on the optimal constrained path routing in WMNs and devised a fast approximation algorithm to deal with it [22]. Recently, Jianqi Liu et al. proposed the cross-layer protocol to decrease the delay [23] and devised an novel energy-saving algorithm [24], [25]. However, to the best knowledge, the previous

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algorithms for the optimal Steiner tree subject to multiple QoS constrains in WMNs were still not very effective and fast for implementation. Thus this problem is studied in this paper.

The rest of this paper is organized as follows. In Section II, We refer to the WMNs in the literature [22] and denote the function modules of the system that will be used in later sections. We introduce the related algorithms for multicast routing in Section III. We present the novel algorithm and its detailed steps for multicast routing subject to multiple QoS constrains in WMNs, then an example is used to illustrate the steps of the algorithm in Section IV. We present its theoretical analysis and experimental results obtained from the special networks in Section V and Section VI, respectively. In the end, we conclude this paper in Section VII.

II. PRELIMINARIES

A wireless mesh network with K QoS constraints can be represented by a directed graph $\mathbf{G}(\mathbf{V}, \mathbf{E}, \bar{\mathbf{W}}, \bar{\mathbf{L}})$, where the set of vertices $|\mathbf{V}| = n$ and the set of edges $|\mathbf{E}| = m$. Each edge in \mathbf{G} is associated with $K(K \geq 2)$ weights, denoted as $\bar{\mathbf{W}} = \{w_i(e) | e \in \mathbf{E}, 1 \leq i \leq K\}$. $w_i(e)$ is the i th weight of edge e . Let \mathbf{P} be a path from source s to destination d_i in \mathbf{G} . Denote $w_i(\mathbf{P})$ as the sum of the i th weight on edges along path \mathbf{P} . Based on previous related work, the authors have studied the constrained path routing in the literature [22], therefore we have the definitions as follows.

Definition 1. The set of multicast destination nodes is $\mathbf{D} = \{d_i | 1 \leq i \leq q\}$. Let $\mathbf{T}(\mathbf{V}_T, \mathbf{E}_T)$ be a multicast routing tree (MRT) from source s to the set of destination nodes \mathbf{D} in \mathbf{G} , where $\mathbf{D} \subseteq \mathbf{V}_T \subseteq \mathbf{V}$, $\mathbf{E}_T \subseteq \mathbf{E}$. Denote $w_i(\mathbf{T})$ as the sum of the i th weight on edges along multicast routing tree \mathbf{T} . The minimal cost of MRT is called as minimal spanning tree (or Steiner tree). In the multicast routing tree \mathbf{T} , the nodes in the set $\bar{\mathbf{D}}$ (s.t $\bar{\mathbf{D}} \subseteq \mathbf{V}_T$ and $\bar{\mathbf{D}} \cap \mathbf{D} = \emptyset$) are called non-multicast nodes, or Steiner nodes.

Definition 2. Multiple Constrained Multicast Routing (MCMR) Problem. In the graph \mathbf{G} , each edge is associated with K positive real-valued edge weights $\{w_i(e), 1 \leq i \leq K\}$, with $\bar{\mathbf{L}} = (L_1, L_2, \dots, L_K) | L_i \in \mathbf{R}^+$ as the K constraints. It is to find a multicast routing tree \mathbf{T}_j from s to \mathbf{D} for MCMR, such that $w_i(\mathbf{T}_j) \leq L_i$.

\mathbf{T}_j is said to be a feasible multicast routing tree which satisfies $w_i(\mathbf{T}_j) \leq L_i$. All the feasible multicast routing trees in \mathbf{G} are denoted as $\{\mathbf{T}_j\}$.

Definition 3. Multiple Constrained Optimal Multicast Routing (MCOMR) Problem. The problem is looking for an optimal multicast routing tree \mathbf{T}^{opt} among feasible $\{\mathbf{T}_j\}$ in graph \mathbf{G} for MCOMR problem, and the

corresponding smallest value $\eta \in (0, 1]$, which satisfies $w_i(\mathbf{T}^{opt}) \leq \eta \cdot L_i$.

Definition 4. α -approximation algorithm ($\alpha \geq 1$). An algorithm is an α -approximation algorithm for MCOMR if the algorithm generates a path \mathbf{T}^* from s to t such that $w_i(\mathbf{T}^*) \leq \alpha \cdot \eta \cdot L_i$.

(1) When $\mathbf{D} = \mathbf{V}$, the problem of the Steiner generating tree is finding the minimum cost tree of graph \mathbf{G} . The famous Multicast Routing Tree (MRT) algorithm can get the optimal solution with time complexity $O(n^2)$.

(2) When $q=2$, the problem is to find the shortest path between two points. An algorithm like Dijkstra can provide the optimal solution in polynomial time.

Apart from the above two cases, the Steiner tree ($\mathbf{D} \neq \mathbf{V}$, $q \neq 2$) problem has been proved to be an NP-complete problem. Aimed at this problem, this article further discusses and puts forward the MCOMR problem based on minimum cost path heuristic algorithm. Table I lists frequently used notations.

TABLE I: FREQUENTLY USED NOTATIONS

s	the source node
\mathbf{D}	the set of destination nodes
K	the number of QoS requirements
$w_i(e)$	i th link weight of edge e
$w'_i(e)$	i th normalization link weight of edge e
L_i	i th QoS requirement
\mathbf{T}_j	j th multicast routing tree from s to \mathbf{D}
$w_i(\mathbf{T}_j)$	i th link weight from s to t along \mathbf{T}_j
\mathbf{T}^{opt}	the optimal multicast routing tree in graph \mathbf{G}
$\hat{\mathbf{T}}^{opt}$	the optimal multicast routing tree in graph $\hat{\mathbf{G}}$
\mathbf{T}^*	the approximation optimal multicast routing tree
α	the approximation value to \mathbf{T}^{opt}
η	the ratio of cost of \mathbf{T}^{opt} with the QoS constraints
$\hat{w}(e)$	the maximum link weight of edge e

III. MULTICAST ROUTING ALGORITHMS AND APPROXIMATION ALGORITHMS

A. Description of the MPH Algorithm

To help solve the Steiner tree problem in 1980, Takahashi and Matsuyama put forward the Multicast Path Heuristic (MPH) algorithm for Steiner tree problem, which was proved that the approximation ratio between the cost and the optimal cost was less than $2-2/q$. Furthermore, it has been found in many network simulation experiments that the MPH algorithm offered better average performance in most cases. Therefore, the MPH algorithm was a comparatively more excellent heuristic algorithm with which to address the Steiner tree problem in terms of time complexity and performance. Its steps are as follows:

Step 1: Initialize the generation tree $\mathbf{T}_1 = \{s\}$, $\mathbf{V}_{\mathbf{T}_1} = \{s\}$;

Step 2: Find out the minimum value $\hat{w}(d_t, \mathbf{T}_{j-1})$ by comparing the cost from every destination node to the existing spanning tree, then connect d_t to \mathbf{T}_{j-1} , it can get the result of $\mathbf{T}_j = \mathbf{P}(d_t, \mathbf{T}_{j-1}) \cup \mathbf{T}_{j-1}$ for the updated tree.

Step 3: Until $t > q$, the final multicast routing tree is found out; otherwise, let $t = t + 1$. Then repeat **Step 2**.

B. Description of KAMCOP Algorithm

Recently, Weijun Yang and others presented a novel approximation algorithm KAMCOP [22], which was to find an approximation optimal path from source s to destination d subject to multiple QoS requirements. It was a novel solution to the unicast routing obviously, different from the problem for multicast routing in this paper. The primary steps of KAMCOP are shown as follows:

Step 1: Initialize weights $w_i(e)$ for every edge in graph \mathbf{G} by $w_i(e) / L_i$;

Step 2: Obtaining the maximum value $\hat{w}(e)$ of each edge, it can get the new graph $\hat{\mathbf{G}}$ from the original graph \mathbf{G} by replacing all other values with $\hat{w}(e)$;

Step 3: Find the approximation optimal path \mathbf{P}^* from s to t by the Dijkstra algorithm.

IV. A FAST MULTICAST PATH HEURISTIC ALGORITHM (FMPH)

Given that the MPH algorithm is excellent in solving the Steiner tree problem, and the authors have studied the approximation optimal constrained path, combining the MPH algorithm and the KAMCOP algorithm presented by the authors previously, a fast multicast path heuristic algorithm is proposed to solve the MCOMR problem from the perspective of approximation in WMNs as fast as possible. The details of the algorithm FMPH are shown as follows.

A. Description of FMPH Algorithm

Step 1: Obtain the normalization weights $w_i(e)$ for every edge in \mathbf{G} by $w_i(e) = w_i(e) / L_i$;

Step 2: Let the new weight $\hat{w}(e) = \max_{1 \leq i \leq K} w_i(e)$, then the original graph \mathbf{G} is changed into the new graph $\hat{\mathbf{G}}$ with only one weight for each edge.

Step 3: Let $t=1$, and initialize the spanning tree $\mathbf{T}_1 = \{s\}$ and $\mathbf{V}_{\mathbf{T}_1} = \{s\}$;

Step 4: For every destination node $d_t \in \overline{\mathbf{D} \cap \mathbf{V}_{\mathbf{T}_{j-1}}}$, it calculates the corresponding value $\hat{w}(d_t, v_k) | v_k \in \mathbf{V}_{\mathbf{T}_{j-1}}$ from d_t to the node in existing multicast routing tree \mathbf{T}_{j-1} by Dijkstra algorithm. By comparing all the value $\hat{w}(d_t, v_k)$ for each node d_t in $\overline{\mathbf{D} \cap \mathbf{V}_{\mathbf{T}_{j-1}}}$, it can reach the minimum value $\hat{w}(d_t, \mathbf{T}_{j-1}) = \min\{\hat{w}(d_t, v_k) | v_k \in \mathbf{V}_{\mathbf{T}_{j-1}}\}$ from d_t to \mathbf{T}_{j-1} .

Step 5: Compared with the value $\hat{w}(d_t, \mathbf{T}_{j-1})$ for all the nodes d_t in $\overline{\mathbf{D} \cap \mathbf{V}_{\mathbf{T}_{j-1}}}$, the minimum value $\hat{w}(d_{\min}, \mathbf{T}_{j-1}) = \min\{\hat{w}(d_t, \mathbf{T}_{j-1}) | d_t \in \overline{\mathbf{D} \cap \mathbf{V}_{\mathbf{T}_{j-1}}}\}$ could be obtained. By connecting d_{\min} to \mathbf{T}_{j-1} through the shortest $\mathbf{P}(d_{\min}, \mathbf{T}_{j-1})$, the updated tree can get the result of $\mathbf{T}_j = \mathbf{P}(d_{\min}, \mathbf{T}_{j-1}) \cup \mathbf{T}_{j-1}$. The corresponding $\mathbf{P}(d_{\min}, \mathbf{T}_{j-1})$ is the shortest in new graph $\hat{\mathbf{G}}$.

Step 6: Until $t > q$, the final generating tree $\mathbf{T}^* = \mathbf{T}_q$ is found out; otherwise, let $t = t + 1$. Then repeat **Step 4**.

B. The Proposed FMPH Algorithm

The detailed steps of FMPH are presented as follows:

Algorithm 1: the FMPH algorithm

Input: $\mathbf{G}(\mathbf{V}, \mathbf{E}, \overline{\mathbf{W}}, \overline{\mathbf{L}})$, s , \mathbf{D}

Output: \mathbf{T}^*

1. for every $e \in \mathbf{E}$, do
 2. $w_i(e) = w_i(e) / L_i$;
 3. $\hat{w}(e) = \max_{1 \leq i \leq K} w_i(e)$;
 4. end for
 5. $\mathbf{T}_1 = \{s\}$ and $\mathbf{V}_{\mathbf{T}_1} = \{s\}$;
 6. for $j=1:q$ do
 7. for each $d_t \in \overline{\mathbf{D} \cap \mathbf{V}_{\mathbf{T}_{j-1}}}$ do
 8. for each $v_k \in \mathbf{V}_{\mathbf{T}_{j-1}}$ do
 9. $\mathbf{P} \leftarrow \emptyset, \mathbf{Q} \leftarrow \mathbf{V}_{\mathbf{T}_{j-1}}, \hat{w}(\mathbf{P}) = 0, \mathbf{D}(\mathbf{V}_{\mathbf{T}_{j-1}}) \leftarrow \infty, u = d_t$;
 10. while $v_k \notin \mathbf{P}$ do
 11. $u \leftarrow \text{Extract}(v_k) | \min\{\mathbf{D}(v_k)\}, v_k \in \mathbf{Q}; \mathbf{Q} \leftarrow \mathbf{Q} - \{v_k\}$;
 12. $\hat{w}(\mathbf{P}) = \hat{w}(\mathbf{P}) + \hat{w}(u, \mathbf{P})$;
 13. $\mathbf{P} \leftarrow \mathbf{P} \cup \{u\}$;
 14. for every link $(u, v) \in \mathbf{E}, v \in \mathbf{Q}$ do
 15. if $\mathbf{D}(v_k) > \mathbf{D}(u) + \hat{w}(u, v_k)$ then
 16. $\mathbf{D}(v_k) = \mathbf{D}(u) + \hat{w}(u, v_k)$
 17. end if
 18. end for
 19. end while
 20. end for
 21. $\hat{w}(d_t, \mathbf{T}_{j-1}) = \min\{\hat{w}(d_t, v_k) | v_k \in \mathbf{V}_{\mathbf{T}_{j-1}}\}$
 22. end for
 23. $\hat{w}(d_{\min}, \mathbf{T}_{j-1}) = \min\{\hat{w}(d_t, \mathbf{T}_{j-1}) | d_t \in \overline{\mathbf{D} \cap \mathbf{V}_{\mathbf{T}_{j-1}}}\}$
 24. $\mathbf{T}_j = \mathbf{P}(d_{\min}, \mathbf{T}_{j-1}) \cup \mathbf{T}_{j-1}$
 25. end for
 26. $\mathbf{T}^* = \mathbf{T}_j$;
 27. if $\hat{w}(\mathbf{T}^*) \leq 1$ then
 28. **OUTPUT** \mathbf{T}^* ;
 29. else **OUTPUT NO feasible** \mathbf{T}^* ;
 30. end if
-

C. An Example of the FMPH Algorithm

An example of the FMPH algorithm is shown as follows. Fig. 1(a) shows a simple topology graph G of a directed network, in which the node in red is the source node, the nodes in green are the multicast destination nodes and others in blue are intermediate nodes. Numbers marked between two nodes are the link costs, distances and delay. Given the QoS requirements $\bar{L} = (10, 20, 10)$, the topology graph G is transformed to Fig. 1(b) in the first step of the FMPH algorithm. Then it is simplified to Fig. 2(a) with only one value by choosing the maximum value for each edge in the second step. In the fourth step of the FMPH algorithm, the node first added to multicast generating tree is node D1, as shown in Fig. 2(b). Following node is the node D2 shown in Fig. 3(a). Destination nodes D3 is added to the tree finally, and the final multicast tree obtained is shown in Fig. 3(b). Its total value is 0.9, which is less than the constraint 1. Therefore the multicast routing tree by the FMPH algorithm is feasible.

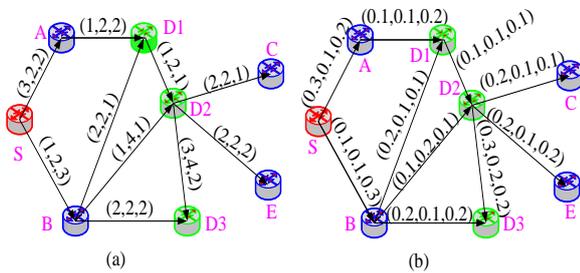


Fig. 1. A directed network topology graph G

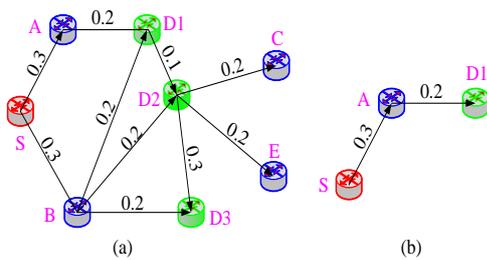


Fig. 2. Implementation of the FMPH algorithm

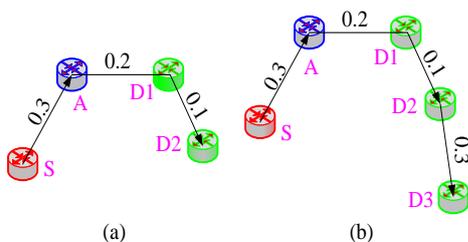


Fig. 3. The final multicast routing tree T^*

V. ANALYSIS OF FMPH ALGORITHM

Theorem 1. The FMPH algorithm obtains a feasible multicast routing tree T^* in graph G from source s to the set of destination nodes D for MCMR problem.

Proof. To the multicast routing tree T^* in graph \hat{G} , we have

$$\sum_{e \in T^*} \hat{w}(e) = \hat{w}(T^*) \leq 1 \quad (1)$$

By the definition of $\hat{w}(e)$, we have

$$\hat{w}(e) = \max_{1 \leq i \leq K} \frac{w_i(e)}{L_i} \geq \frac{w_i(e)}{L_i} \quad (2)$$

This implies that

$$\sum_{e \in T^*} \frac{w_i(e)}{L_i} \leq \sum_{e \in T^*} \hat{w}(e) \leq 1 \quad (3)$$

Then we have

$$w_i(T^*) \leq \sum_{e \in T^*} w_i(e) \leq L_i \quad (4)$$

Thus, T^* is a feasible multicast routing tree in graph G , and the theorem 1 is proven.

Theorem 2. The multicast routing tree T^* minimizes all the multicast routing trees $\hat{w}(T_j)$ in graph \hat{G} . Algorithm FMPH finds a $2K(1-1/q)$ -approximation MRT for MCOMR problem.

Proof. To the optimal path T^{opt} in G , we have

$$w_i(T^{opt}) \leq \eta \cdot L_i \quad (5)$$

This implies that

$$\frac{w_i(T^{opt})}{L_i} \leq \eta \quad (6)$$

Then we have

$$\sum_{i=1}^K \frac{w_i(T^{opt})}{L_i} \leq K \cdot \eta \quad (7)$$

Here we obtain every edge for the path P^{opt} , which implies the following:

$$\sum_{e \in T^{opt}} \sum_{i=1}^K \frac{w_i(e)}{L_i} \leq K \cdot \eta \quad (8)$$

By the definition of $\hat{w}(e)$, we have

$$\hat{w}(e) = \max_{1 \leq i \leq K} \frac{w_i(e)}{L_i} \quad (9)$$

It seems to be clear that

$$\max_{1 \leq i \leq K} \frac{w_i(e)}{L_i} \leq \sum_{i=1}^K \frac{w_i(e)}{L_i} \quad (10)$$

According to inequality (4), (5) and (6), it implies the following:

$$\hat{w}(T^{opt}) = \sum_{e \in T^{opt}} \hat{w}(e) \leq \sum_{e \in T^{opt}} \sum_{i=1}^K \frac{w_i(e)}{L_i} \leq K \cdot \eta \quad (11)$$

In the related literature, H. Takahashi and others proved that there is corresponding relationship between each i and node's pair (t_{j-1}, t_j) , in which $i, j=2, 3, \dots, q$, and v_1, v_2, \dots, v_k is from 1 to k [15]. Let i and number pair $[t_{q(i)-1}, t_{q(i)}]$ have a one to one relationship, and we have

$$\min\{t_{q(i-1)}, t_{q(i)}\} < i \leq \max\{t_{q(i-1)}, t_{q(i)}\} \quad (12)$$

$$\hat{w}(v_i, \mathbf{V}_{i-1}) \leq \hat{w}(v_{q(i-1)}, v_{q(i)}) \quad (13)$$

To the optimal multicast routing tree $\hat{\mathbf{T}}^{opt}$ in graph $\hat{\mathbf{G}}$, we have

$$\hat{w}(v_{t_q}, v_{t_i}) \geq (2/q) \cdot \hat{w}(\hat{\mathbf{T}}^{opt}) \quad (14)$$

By inequality (12), (13), and (14), then we have the following:

$$\hat{w}(\mathbf{T}^*) = \sum_{i=2}^q \hat{w}(v_i, \mathbf{V}_{i-1}) \leq \sum_{i=2}^q \hat{w}(v_{t_{q(i-1)}}, v_{t_{q(i)}}) \quad (15)$$

$$\sum_{i=2}^q \hat{w}(v_{t_{q(i-1)}}, v_{t_{q(i)}}) = \sum_{j=2}^q \hat{w}(v_{t_{j-1}}, v_{t_j}) \leq 2(1-1/q) \cdot \hat{w}(\hat{\mathbf{T}}^{opt}) \quad (16)$$

To the approximation optimal multicast routing tree \mathbf{T}^* in graph $\hat{\mathbf{G}}$, we have

$$\hat{w}(\mathbf{T}^*) \leq 2(1-1/q) \cdot \hat{w}(\hat{\mathbf{T}}^{opt}) \quad (17)$$

The multicast routing tree $\hat{\mathbf{T}}^{opt}$ found by Dijkstra algorithm in new graph $\hat{\mathbf{G}}$ minimizes all the multicast routing trees $\hat{w}(\hat{\mathbf{T}}_j)$, while \mathbf{T}^{opt} is the optimal value in original graph \mathbf{G} . It implies that

$$\hat{w}(\hat{\mathbf{T}}^{opt}) \leq \hat{w}(\mathbf{T}^{opt}) \quad (18)$$

Thus we have

$$\hat{w}(\mathbf{T}^*) \leq 2(1-1/q) \cdot \hat{w}(\mathbf{T}^{opt}) \quad (19)$$

According to inequality (17) and (19), it implies that

$$\hat{w}(\mathbf{T}^*) \leq 2K(1-1/q) \cdot \eta \cdot 1 \quad (20)$$

Thus, Theorem 2 is proven.

Theorem 3. The time complexity of the FMPH algorithm is $O(Km + qn^2)$

Proof. It normalizes each edge with the time complexity $O(m)$ in **Step 1** and obtains the maximum value $O(K)$ in **Step 2** by the FMPH algorithm. **Step 3** initials the spanning tree with the constant time complexity. **Step 4** searches for the shortest path between any destination nodes. **Steps 5** and **6** find the shortest paths to multicast tree \mathbf{T} for q nodes respectively. The time complexity of the path of a node to multicast tree is $O(n^2)$, therefore the total time complexity from **Step 4** to **Step 6** is $O(qn^2)$.

According to the above six steps, the time complexity of FMPH is $O(Km + qn^2)$, and Theorem 3 is proven.

VI. SIMULATION EXPERIMENT

This section shall evaluate both the performance of FMPH and the performance of an experimentally obtained approximation optimal multicast routing tree. Special network namely NTT is used in these experiments [2], which is run on an Intel Core Duo CPU 1.66GHz PC with 2GB memory. There are 57 nodes and 81 edges in this network topology shown as Fig. 4. Moreover, other parameters can be found in the URL:

<http://code.google.com/p/efptas/downloads/list>. Each link in this network has three weights, which corresponds to Cost, Delay and Jitter.

All the red points are denoted as nodes of the network, the black wires as the links, and the green circle as the source node s and the green star as the destination nodes set \mathbf{D} in the network for Fig. 4. The blue paths in these figures indicate the approximation optimal paths from source s to destination nodes set \mathbf{D} . As expected, the approximation optimal MRT with three constrains by the FMPH algorithm are able to be found, and they show the corresponding results.

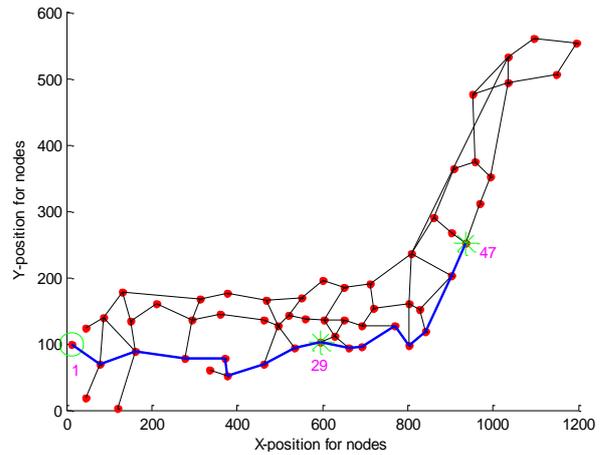


Fig. 4. The approximation optimal multicast tree with $\bar{\mathbf{L}} = (112, 735, 0.19)$

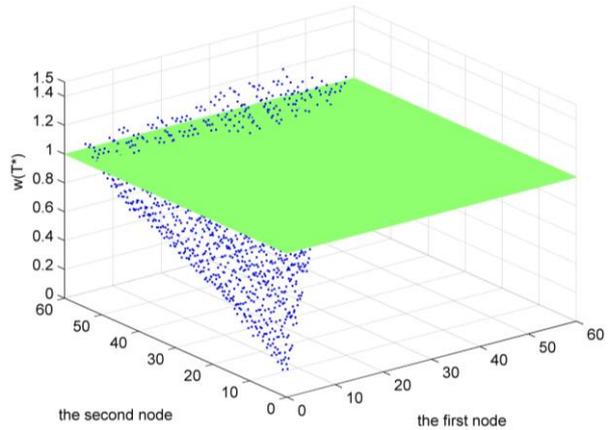


Fig. 5. All the multicast routing trees with $\bar{\mathbf{L}} = (112, 735, 0.19)$ in NTT

The approximation optimal MRT in NTT are shown in Fig. 4. The source s is No.1 node, the destination nodes are No.29 and No.47 node, and QoS requirements are $\bar{\mathbf{L}} = (112, 735, 0.19)$, respectively. The approximation optimal value $\hat{w}(\mathbf{T}^*)$ found by the FMPH algorithm is 0.90307, which is less than 1, thus the corresponding multicast routing tree is feasible.

With a three dimensional diagram, Fig. 5 shows the solution of all MRTs in which there are two destination nodes. The parameters in Fig. 5 include the source node s (No.1), destination nodes set \mathbf{D} (No.2-No.57) and the corresponding solution $\hat{w}(\mathbf{T}^*)$. The green plane is

regarded as the QoS requirements $\bar{L}=(112,735,0.19)$, and the blue point as the solution $\hat{u}(\mathbf{T}^*)$ of each MRT in Fig. 5. As the figure shows meaning, we could easily conclude that all the blue points below the green plane are feasible and reverse are infeasible.

In these simulation experiments, Fig. 5 shows that the approximating Steiner tree could be found by the FMPH algorithm presented in this paper. Following that the performance and efficiency of the FMPH algorithm would be verified. Table II shows the comparisons of Steiner trees generated via the MPH and FMPH algorithm in the simulation experiment, respectively. With the two algorithms, q destination nodes in the two networks were randomly generated, then the Steiner trees were obtained and the corresponding time were recorded. The simulations experiments were run to calculate the average values for ten times. In order to evaluate the performance of two algorithms, we define the following metrics:

$$\text{Average Time for the Steiner tree (ATS)} = \frac{\text{Total time for each Steiner tree}}{\text{Number of runs}}$$

TABLE II A COMPARISON OF THE PERFORMANCE OF TWO ALGORITHMS ON THE NTT NETWORK

NO.	q=2	q=5	q=8	q=11	q=14
MPH	16.5482	16.7255	16.5161	16.9853	18.0453
FMPH	16.5812	16.7582	16.5485	17.0179	18.0787
NO.	q=17	q=20	q=23	q=26	q=29
MPH	18.4433	19.7361	20.0296	21.0046	21.9456
FMPH	18.4783	19.7691	20.0648	21.0370	21.9802
NO.	q=32	q=35	q=38	q=41	q=44
MPH	23.6829	25.2554	27.7329	30.3103	32.9809
FMPH	23.7150	25.2881	27.7659	30.3430	33.0133
NO.	q=47	q=50	q=53	q=55	q=56
MPH	36.3696	38.9639	43.1503	46.4829	47.8729
FMPH	36.4123	38.9973	43.1827	46.5153	47.9063

The unit of ATS in Table II is millisecond. Analyzing the experimental results, it shows that the consuming time by FMPH is a little larger than that by MPH, because the novel FMPH algorithm in this paper is devised to deal with the MCOMR problem, different from previous MPH algorithm. At the same time, it could be easily found that when the value of q is getting larger from 2 to 56, the two algorithms are extremely neck and neck. The simulation experimental results also show that, in most cases, both the two algorithms have the same time complexity level.

VII. CONCLUSION

This paper discusses the problem of MCOMR in WMNs. A fast approximation algorithm called FMPH is proposed, which intends to find the approximation optimal MRT from the perspective of approximation as fast as possible. The algorithm could obtain the approximation optimal solution in the shortest time, according to the time-varying characteristics of wireless

networks. Experiments on the special network show that the FMPH is a fast approximation algorithm, which is fit for the multiple QoS constraints routing in WMNs.

As for future research, we plan to improve the solution for the constrained multicast routing according to the time-varying characteristics of wireless networks, and investigate a novel and more excellent solution for WMNs based on our current research.

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