Efficient Routing Algorithm Based on Decision-making Sequence in Wireless Mesh Networks

Yingying Qin, Rongbo Zhu*
College of Computer Science, South-Central University for Nationalities, Wuhan, China

Abstract—The ultimate goal of routing in wireless mesh networks (WMNs) is to find the “good” paths between the source and destination. Considering of the characteristics of this new networking paradigm, such as low mobility and less restriction from the energy effect, the focus is on the design and optimization of the technology to establish the path that can reflect this network feature. In this paper, an efficient routing algorithm is proposed based on decision-making sequence in WMNs, and the routing process is mapped into multi-stage decision process. We construct a mathematical model for it and present a multi-decision sequential routing method taking use of the idea of dynamic programming. In addition, a new metric (EEDT) for routing based on the information of MAC layer in WMNs is given, which optimized the two objectives—end to end delay and throughput. In the end, the multi-decision sequential routing algorithm (MDSR) is proposed that synthesized the suggesting method and new metric. The path selected by MDSR would be better based on the mathematical model, and it has lower delay of routing building. At the same time, EEDT can accurately capture the quality of the network links. Simulation results show that the proposed routing algorithm significantly improves the performance of the WMNs in terms of end-to-end delay and throughput.

Index Terms—wireless mesh networks, multi-stage decision, dynamic programming, end to end delay, throughput

I. INTRODUCTION

With the development of wireless communication technology, wireless mesh networks (WMNs) [1, 2] have emerged as a promising technology for next generation wireless networking, which integrates the advantages of wireless local area network (WLAN) and ad hoc network. WMNs have self-organizing self-configuring, and self-healing features with simple maintenance at a low cost offering high scalability and reliable services as well as enhancing capacity, connectivity, and resiliency of the existing network. Because of these advantages, WMNs have been widely accepted in the traditional application, which will have an important role in future generations of wireless communication and receive considerable attention recently. So it is very meaningful for WMNs to investigate all of crucial techniques deeply. Despite the rapid progress making in researching for WMNs, many topics have no satisfied solutions. Especially, routing is still challenging.

Because WMNs is similar to a mobile ad hoc network, in that the node connection is a wireless multi-hop connection, many routing technologies applied to WMNs derived from some traditional routing protocols of ad hoc network. However, the particularity of routing schemes in WMNs may be specially taken into account. WMNs consist of mesh routers (MRs) and mesh clients (MCs). Where mesh routers are mainly stationary and provide wireless access to clients. Also, MRs forms a multi-hop environment by forwarding and relaying data packets from one mesh router to another. In such networks, most of nodes are either stationary or minimally mobile and do not rely on batteries. Thus, routing protocols must deal with reliability and improvement of the overall network performance rather than mobility or power saving. Up to now, most ad hoc routing protocols regard minimum hop counts as the only routing metric, which has been proved not good for WMNs. Moreover, in ad hoc network [3], in order to adapt to the dynamic topology of network, the paths established by some routing protocols may not be the optimum.

To solve these problems, we suggest a multi-decision sequential routing algorithm (MDSR), which makes use of the idea of dynamic programming to find the optimal path from source to destination, and introduce a new metric for routing. The paper formulates the problem of routing as a multi-stage decision problem, and, constructs a mathematical model for it, then we present a dynamic programming algorithm to solve problem of the optimal path. At the same time, the new metric (EEDT) is given in consideration of the delay-sensitive multimedia services and network throughput, and applied to the dynamic programming algorithm. In the end of MDSR, the final decision-making sequence is the optimal routing. It will obtain the better performance path in terms of end to end and throughput.

The remainders of this paper are organized as follows: In section II, related work is introduced. In section III, describe details of the routing problems and construct the mathematical model. In section IV, introduce a new routing metric for the end to end delay and network throughput. In section V, present the proposed routing algorithm. Section VI summarizes the simulation results, and section VII concludes the paper.

II. RELATED WORK
Network routing plays a critical role in determining the performance of a wireless mesh network. A significant amount of research has been made in the past years regarding the best routing protocol that can maximize the network throughput while satisfying other constraints. Most of the existing literatures improved the performance of routing by concerning with the routing metric and routing algorithm.

A lot of popular routing protocols were designed to simply get the shortest path from the minimum hop metric between the given source and destination. In most cases, the optimal path can’t be acquired. Recently, the most popular routing metrics such as blocking metric, expected transmission count (ETX) [4], expected transmission time (ETT) [4], modified ETX (mETX), network allocation vector count (NAVC), and metric of interference and channel-switching (MIC) are used in WMNs. Also, [5] made overall comparison of these metric, and analysis their performances in WMNs. The authors of [6] consider the effects of underlying layers and introduce a new cross-layer metric for ad hoc on demand distance vector (AODV) routing in WMNs. In [7], a multiple-metric approach was presented to improve throughput and transmission delay. And, other works has been published regarding route metrics that could identify high quality paths in WMNs [4, 8, 9, 10], and significant performance improvements have been demonstrated by using suitable metrics to estimate the link quality and other related factors.

Beyond that problem, routing algorithm should also be carefully designed taking into account the specific characteristics of WMNs. To avoid the bottleneck of access-point (AP) communications, the authors of [11] formulated the routing tree problem for AP communications and proposed the greedy heuristic algorithm of sequentially selecting one link that minimized the delay of the predicted tree. In order to efficiently support diverse applications in WMNs, [12] suggested a simple solution, namely, the service-oriented routing algorithm which worked in a similar manner as the domain name system (DNS), and could efficiently provide distributed services in WMNs. In [13], a feasible method to solve wireless mesh network routing problem with QoS constraint was used by introduce the novel dynamic ant genetic algorithm. And another dynamic routing method based on genetic algorithm is used in [14] that aimed to reduce network overhead. There are many other considerations, such as lower mobility and less restriction from energy effect, in case of setting and maintain the path of network. The routing algorithm should be designed or optimized that could reflect this network features. Then, the linear programming or dynamic programming approach for routing in WMN will be a good choice, that has been used several studies in recent years. In [15], the authors formulated the problem of routing as a network optimization problem, and presented a general linear programming (LP) formulation for modeling the problem, that could effectively incorporate the traffic demand uncertainty in routing optimization. In [16], the paper gave a QoS routing algorithm based on dynamic programming solution that solved multi-parameter routing problem with the nature of NPC in WMNs. J. Crichigno et al. also proposed a mesh routing algorithm, a dynamic programming approach to compute high capacity paths while simultaneously bounding the end to end delay [17]. In [18], a dynamic programming based link scheduling algorithm was presented to provide an optimal resource allocation in WiMAX mesh networks. Talmai Oliveira et al suggest a stochastic approximate dynamic programming solution that is capable of utilizing limited network knowledge and stochastic elements [19].

Based on mentioned above achievements in routing optimization, the paper view the route setting process as a multi-stage decision process, and dynamic programming solution is introduced to obtain the optimal path in WMNs. In addition, A new routing metric for end to end and network throughput is used. Different from previous works, we focus on the process of establishing routing by using dynamic programming algorithm, which will be benefit of finding the optimal path and reduce the delay of path setting, and lead to the better performance of network in WMNs.

III. NETWORK MODEL

A. Problem Description

WMNs communicate by the way of multi-hop mode in the whole wireless networks, where routing process between nodes within the network accomplish in a collaborative manner. Parameters like link bandwidth, end to end delay, and packet loss rate between neighbor nodes are obtained and maintained by the appropriate routing protocol, then getting the optimal path based on this criterion, which consistent with multi-stage decision problems. The selection of decision at every stage, and affects the future development at the same time. When all stages of decision-making is determined to form a decision-making sequence. Then, an effective path for an entire process will be presented. Such an interrelated chain structure is also seen as sequential decision-making process (Fig. 1).

Figure 1. Sequential decision-making process

Dynamic programming algorithm is an effective solution to solve multi-stage decision problems that has linear time complexity $O(n^2 k)$, the worst is $O(n^3)$ . Where $n$ is the scale of the problem, and $k$ is the number of decomposed sub problems. Then, the dynamic programming model based on WMNs will be shown in the following.

B. System model

We assume that the nodes are stationary, and the physical layer supports bidirectional links in WMNs.
Then, let \( G(V, E) \) be the weighted undirected graph representing the WMNs, where \( V \) is the set of nodes (MRSs) and \( E \) is set of links. \( n = |V| \) is the number of nodes (the scale of the problem).

In this paper, we formulate the routing problem in WMNs as a multi-stage decision problem. Multi-hop routing in WMNs will be decomposed into single-hop, in other words, a single-hop routing between the two adjacent nodes is defined as one stage for dynamic programming solution. And, we will use the following notation in our mathematical formulation.

\( k \): Stage variable.

\( S_k \): The set of effective states in the stage of \( k \). Apparently, \( S_k \subset V \), \( |S_k| \) is the number of nodes in stage \( k \).

\( L_k(i, j) \in E \): The value of weighted link in the stage of \( k \) from node \( i \) to \( j \).

\( x'_k \): The node \( i \) in the stage of \( k \), the value of \( i \) will range from \([1, |S_k|]\). And, \( S_k = \{x'_k\} \).

\( u_k(x'_k) \): A strategic decision-making by the node \( x'_k \) in the stage of \( k \).

\( Q_{k-1}(x'_k) \): The sequence of decision function arranged in order starting from the stage of \( k \).

In this network model, there is \( u_k(x'_k) \in S_{k-1} \). When the current stage is \( k \), and the decision is \( u_k(x'_k) \), we say the cost of routing is \( L_k(u_k(x'_k), x'_k) \). We first define the objective function of \( k \) sub-process as follows:

\[
\phi_{k-1}(x_k, u_k, ..., x_{n+1}) = \sum_{j=1}^{n} L_j(u_j(x'_j), x'_j).
\]

Then, select the one with the smallest cost, which results from finding the minimum in the following equation:

\[
F_k(S_k) = \min_{(u_k, ..., u_{n+1})} \phi_{k-1}(x_k, u_k, ..., x_{n+1}),
\]

\[
= \min_{x_k \in S_k} \left[ L_k(S_{k-1}, x_k) + F_{k-1}(S_{k-1}) \right].
\]

\( F_k(S_k) \) is the optimization objective of \( k \) sub-process which is shown in the optimality theorem \([20]\). As shown in (2), routing decisions are ranked based on the present cost and anticipated future sum at every stage.

As \( k=1 \), it is the optimum value of the entire of the proceeding. And the homologous optimal strategy is the optimal solution of the routing protocol.

We start by showing how the algorithm operates on the topology of Fig. 2, where the weight of link has been given. Suppose first we want to find the path from \( u \) to \( w \) with minimum weighted sum. We adopt reverse dynamic programming solution on it. Then, \( S_1 = \{c, d\} \), \( F(c) = 1 \), \( F(d) = 2 \). In the stage 2, we need to compute these two equations:

\[
F_z(a) = \min \left\{ \frac{\text{link}(a, c) + F_z(c)}{\text{link}(a, d) + F_z(d)} \right\},
\]

\[
F_z(b) = \min \left\{ \frac{\text{link}(b, c) + F_z(c)}{\text{link}(b, d) + F_z(d)} \right\},
\]

So, in the last stage,

\[
F_z(u) = \min \left\{ \frac{\text{link}(s, a) + F_z(a)}{\text{link}(s, b) + F_z(b)} \right\}.
\]

In the end of algorithm, we could find an optimal path: \( u \rightarrow b \rightarrow d \rightarrow w \).

![Figure 2. A network with weighted link](image)

### IV. A NEW ROUTING METRIC

A good routing metric can accurately capture the quality of the network links and is capable of ranking all those parameters that constitute the best path \([21]\). As noted by references in \([4, 22]\), the hop count metric has been proved that is not efficient. In WMNs, paths with the fewest number of hops mean the length of each hop link is maximized. However, it has also been equated with the maximum of link packet loss rate. In a dense network, the objective such as data packet loss rate, end to end delay, and throughput can not be guaranteed. Furthermore, effective WMNs routing metric needs to consider more about end-to-end delay and network throughput to take the delay-sensitive multimedia services into account.

To the best of our knowledge, the only technique proposed to simultaneously minimize the end to end delay and maximize the throughput is the weighted sum \([4, 23]\), whereby an objective function \( f = \beta_f \cdot (\text{end to end delay}) + \beta_t \cdot (\text{throughput}) \) is optimized \([4, 23, 24]\). Therefore, we present a metric adapted thought of weighted cumulative.

\[
EEDT = (1 - \beta) \cdot \frac{1}{TBT} + \beta \cdot PTT
\]

Where:

- \( TBT \) is the link bandwidth transmission time. This reflects the total throughput of the routing. The parameter will be obtained by virtual carrier sense (NAV method) in the MAC layer \([25]\), periodically sensing the busy state of node transmission channel, and then estimating by...
moving weighted average method. MAC layer will believe the node transmission channel is idle, when the following three conditions are met: the value of NAV is less than the current time value, that is NAV has returned to idle; sending state is idle; sending state is idle. Correspondingly, MAC layer will believe the node transmission channel is busy. When any one of the following conditions are met: NAV is assigned a new value; receiving state convert from idle to any other state; send state convert from idle to any other state. 

\( \beta \) is the practical transmission time. It measures the actual link time during the route request packet RREQ transferred from the source node to its adjacent nodes in the process of route discovery. That reflects the corresponding channel transmission rate and delay. 

\( \beta \) is an adjustable system parameter. The greater the value of \( \beta \), the metric will be inclined to choose the path with faster transmission rate and less delay. The smaller the value of \( \beta \), it will be inclined more high throughput routing.

Considering the precise parameter requires the path with maximum value of TBT among all the candidate paths, Whereas, in terms of the PPT, it requires to choose the one of the minimum of the practical transmission time from all paths, Then, This article adopt the reciprocal value of TBT, ensuring the monotonicity consistency of the two parameters.

Both objectives take different orders of magnitude. Their weights depend on the importance of the relative objective to the problem at hand. And adjustable coefficient \( \beta \) plays a balancing role in the weight distribution, so that the system achieved an optimal trade-off solution with the two objectives.

V. PROPOSED ROUTING ALGORITHM

In comparison with a wireless ad hoc network consisting of arbitrarily deployed nodes with the power constraints, the low mobility of nodes and relatively static topology in WMNs is the peculiarity. Classic routing protocol AODV in ad-hoc wireless networks can not satisfy the need of the systems any more. Additionally, routing paths established after the process of routing discovery may not be the optimum. due to the method finding the “good” path of AODV, several problems will occur now and then, (1) in the routing discovery process, the path established by sending the routing response packet (RREP) through intermediate nodes does not always mean the global optimum. (2) The processing method of the protocol may result in the data packet loss, while the link failures occur. To solve these problems, dynamic programming was adopted in the AODV protocol in this paper, and the new metric was seen as the weight of the link. Then, we presented the multi-decision sequential routing algorithm (MDSR).

A. Route metric table formation

In this paper, the hop count metric will be substituted by a new metric EEDT in the protocol AODV. The

In the specific operation, the node send a RREQ packet including only the value of T and K, in the beginning, the value of K will be initialized to 0. As the RREQ packet is sent to its neighbors, K values will increase by 1. Another two values of parameter are not included in RREQ packet in the beginning of sending. These fields will be initialized to the value 0, the TBT value of the forward link will not be added into the RREQ packet until the neighbors receive the RREQ packet. At the same time, neighbor nodes will record the receiving time of RREQ. The value of PPT will be obtained by the receiving time of RREQ in neighbors minus the sending time (T). Then, the value of metric EEDT can be calculated to accumulate to the field of EEDT in the RREQ packet. When neighbor nodes continue to forward RREQ packets to there neighbors, The value of TBT will be set to 0 again, also, the value of T need to be updated to the current sending time.

B. Routing process

Contrary to AODV protocol, routing discovery process is aroused by the destination node in the dissertation. Correspondently, MDSR adopt reverse dynamic programming solution to establish the rout path. Besides, nodes forward the RREQ request packets to their neighbors in turn, updating some parameters of the RREQ packets constantly, so that the weights of link could be captured accurately (that is routing metric).

Routing discovery occurred in case that a node needs a route path to destination and the current route is not available. The process started by the destination node. Prior to this, the destination node will receive the source node’s notification on initiating a route discovery process. Intermediate nodes will do some calculations and deal with the request packet. In the meantime, they choose the optimal route path based on the model of dynamic programming algorithm and record the relative previous hop node. Then, a forward path is established from source to destination, which is shown in Fig. 4.

© 2012 ACADEMY PUBLISHER
Routing Algorithm MDSR

Input: source node S, destination node D

Output: optimal decision u(S)

1. Source node notify destination of start route discovery by broadcasting message
2. Destination node receive notice, and start route discovery process
3. /*destination node initializing RREQ packet*/
4. k=0, T= current time; TBT=0, EEDT=0
5. Send RREQ packet to all it's neighbors
6. /*main loop*/
7. for each neighbor node do
8. if <IP address, RREQ ID> exists in the list of node rout table then
9. Discard RREQ packet
10. end if
11. if stage variable k value of RREQ ≥ the counterpart of node then
12. Discard RREQ packet
13. end if
14. if the value of EEDT in current received RREQ ≤ the counterpart in former RREQ then
15. Receive RREQ, record the IP address of previous-hop route node
16. else
17. Discard RREQ packet
18. end if
19. Node update parameters of RREQ packet: k=k+1, T= current time; TBT=0
20. Node forward RREQ packet to its neighbors
21. until <node=source node>
22. if source node received RREQ packet then
   Choose the path with minimum accumulate value of EEDT, and record the previous-hop route
23. end if
24. return optimal decision u(S)

Figure 5. MDSR algorithm description

Arbitrary sub-path included the optimal path is also optimal. Additionally, intermediate nodes constantly update the previous-hop node on optimal path during the building process of the forward path in MDSR. Therefore, all intermediate nodes established the optimal path to the destination node accompanied by the building process of the forward path, which is shown in Fig. 3, that be benefit of decrease the number of route discovery. It also has another advantage. If link failed during data transmission, the route node can temporary transfer data to its neighbor nodes, then transfer data through the optimal path from adjacent node to destination node. That reduced the packet loss rate.

VI. SIMULATION RESULTS

Extensive experiment was performed to evaluate the performance of MDSR. As MDSR is modified based on AODV, and is an essential outgrow of AODV in theory. We have compared results with the AODV protocol, and the main goal of simulation experiment was to verify our proposed decision-making sequence approach have the expected improvements over the ancestor protocol. In addition, the simulation tool was OPNET Modeler (version 14.5), that was selected because of its growing reputation and its universality in performing the routing algorithm. It enabled testing different telecommunication areas, including routing protocols and modeling network in great detail. Especially, it’s convenient to simulation some major routing protocols in wireless network, because it comes with the whole implementation of some classical routing protocols, including AODV, DSR, and OLSR.

We recognized that the efforts made about the problem of selecting the best path for routing in wireless mesh network have led to the publication of many different protocols. While more comparisons with other routing protocols would be preferred, given the selected routing metric or proposed algorithm, we pay more attention to the integral performance of the new metric and proposed algorithm. In order to properly verify the effectiveness of the proposed method, our experiment simulations were performed under several scenarios with different configurations including the traffic load, mobility, and network size and network density. The objective is to compare the performance of MDSR and AODV in these different scenarios. To achieve this objective, end to end delay and network throughput are used as the major evaluation metrics. In all simulations, source node and the destination were specified. At the MAC layer, 11Mbps IEEE 802.11 with direct sequence physical layer technology is used, and the transmit power was set to 0.005 w.

A. Scenario I

The network topology of 10 nodes was building in the first scenario, and each node is fixed, that is shown in Fig. 5.
First, we collect the network throughput in this scenario. The following settings were common to simulation experiments reported in this scenario.

a) The simulation duration was 12050 seconds, and the seed was set to 128.
b) Traffic load was 200.
c) Communication range of each node was set to 50.

In addition, the interval time of packet sent by source node is set to exponential distribution function; its parameter is 0.5, 0.3, 0.2, 0.1, 0.05, 0.01…, and 11 runs in total. The result of simulation is shown in Fig. 6.

In Fig. 6, X-direction is channel traffic G, and Y-direction is channel throughput S. The curve describes the developing trend of network throughput varying with the traffic load. At low traffic levels, the throughput take on ascend trend along with the rising traffic load, then, at high traffic levels, throughput fell off sharply after the maximum throughput. This behavior is amply demonstrated by the simulation results. In particular, the maximum throughput of AODV is achieved near G=17 and is close to the value of 6.5, and for MDSR, the maximum throughput is about 7.5 achieved near G=18. Apparently, the maximum network throughput of MDSR in WMNs is greater than AODV protocol. The most likely reason for this is that the smaller delay of routing building comparing AODV, and the better path selected by MDSR. It shows that the proposed approach is efficient algorithm.

Then, we set the interval time of source to be distribution constant (2); traffic load is 100; and the duration is 300. We obtain the simulation result of end to end delay that is shown in Fig. 7.

In demonstrations, the average delay of the two datagram is almost equal. But, from the delay curve it can be seen that the amplitude of fluctuation of MDSR is small. It shows that MDSR is better than AODV in terms of delay jitter, an important parameter of QoS. In the delay-sensitive multimedia services, MDSR will make transfer performance more superior.

B. Scenario II

In this scenario, the network topology is the same as Fig. 4. Different with the former, we randomly selected 4 nodes from the 10 nodes, and set these 4 nodes to movement. We simulate in the mobile environment, and the result curve of throughput is shown as in Fig. 8, and the delay curve in Fig. 9.
In the mobile environment of WMNs, MDSR still have the same effect on the network throughput and end to end delay. In Fig. 7, the maximum throughput of MDSR can achieve 7.5 near $G=18$ and AODV is only close to the value of 7. And, In Fig. 8, the curve fluctuates of MDSR tends to stabilize in terms of end to end delay. The result of tests indicates that MDSR algorithm is not only outperforms the AODV protocol in general but also be stable to changes in movements.

C. Scenario III

In the third scenario, we increase the number of nodes to 50. The simulation field was 220*140 (m) wide, the nodes randomly deployed in his rectangle grid. The traffic load is set to 800, and other simulation configurations adopt the parameters in the scenario 1.

Then, we collected the throughput statistic, and the result curve was shown in Fig. 10.

The above simulation result indicates that our proposed reaches the prospective effect. Comparing AODV routing protocol, it could increase the network throughput and obtain the smaller delay jitter whether in a small and big network or in a static and dynamic environment. MDSR is a stable and efficient algorithm in WMNs, especially in an WMNs with QoS constrained.

VII. CONCLUSION

In this paper, we have developed dynamic programming solving the routing problem depend on the characteristics of WMNs. The nodes of network are divided into multi-stage during the process of building route path, and the new routing metric is adoped to identify high quality paths. We have compared MDSR with AODV protocol and found that our proposed algorithm provides superior performance, especially in the delay-sensitive multimedia services. At the same time, it is simple and easy to be implement. As for future works, we will extend our proposed model to support multi-radio multi-channel WMNs environment.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (No. 60902053), the Natural Science Foundation Hubei Province of China (No. 2008CDB339), and the Science and Technology Research Planning of Educational Commission of Hubei Province of China (No. B20110803). The authors
gratefully acknowledge the helpful comments and suggestions of the reviewers.

REFERENCES

Yingying Qin received the B.S. degree in Computer Science from South-Central University for Nationalities, China, in 2009. She is currently a graduate in College of Computer Science of South-Central University for Nationalities. Her main research interest is in protocol design in WMNs.

Rongbo Zhu received the B.S. and M.S. degrees in Electronic and Information Engineering from Wuhan University of Technology, China, in 2000 and 2003, respectively; and Ph. D degree in communication and information systems from Shanghai Jiao Tong University, China, in 2006. He is currently an Associate Professor in College of Computer Science of South-Central University for Nationalities.

He has published over 50 papers in international journals and conferences in the areas of wireless communications, covering 3G mobile systems and beyond, MAC and routing protocols, and wireless ad hoc, sensor, and mesh networks. He received the Outstanding B. S. Thesis and M. S. Thesis awards from Wuhan University of Technology in 2000 and 2003, respectively. His current research interests are in the areas of wireless communications, protocol design and optimization. The research activities have been supported by the Natural Science Foundation of China, the Natural Science Foundation of Hubei province and the Natural Science Foundation of South-Central University for Nationalities.

He is the Editor-In-Chief of International Journal of Satellite Communications Policy and Management, Associate Editor of International Journal of Radio Frequency Identification Technology and Applications. He serves as a guest editor for several journals, such as, Future Generation Computer Systems, Telecommunication Systems, and as a reviewer for numerous referred journals such as IEEE System Journal etc. He has been actively involved in around 10 international conferences, serving as TPC Chair of GCN’11, General Co-chair of ICICA’10 and so on. Dr. Zhu is a member of the ACM and IEEE.