A Study of Root Driven Routing Protocol for Wireless LAN Mesh Networks

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ABSTRACT

Wireless LAN mesh networks (or Mesh WLANs) are being widely deployed as a new wireless access network that employs a key technology of multihop communications to link the edges of the mesh to a mesh portal, which connect to other wired networks. In such deployment, the Mesh WLAN backbone topology can be efficiently constructed among the mesh nodes by using a proactive routing protocol due to low or no mobility in mesh nodes. A tree-based routing (TBR) protocol is a viable proactive routing protocol for the Mesh WLAN, because it is well-suited for the user traffic that is directed to/from a wired network via the mesh portal (i.e., the root). However, the performance of TBR protocol is rapidly degraded when the user traffic is mostly dominated by the intra-mesh traffic, since the traffic within the Mesh WLANs must also bypass the root, which unnecessarily overloads the root by routes without using the best-metric route. Especially, it becomes more serious if the network size is significantly large whereby the amount of traffic inside mesh network increases dramatically. To mitigate this shortcoming, in this paper we propose a root driven routing protocol to enable the root to quickly provide the best-metric route for any source-destination pair of intra-mesh traffic. Furthermore, we combine the proposed protocol for intra-mesh traffic and the original TBR protocol for inter-mesh traffic as a hybrid routing protocol to achieve the best performance in the Mesh WLAN networks. Our simulation results reveal that the proposed protocol outperforms the TBR protocol with much lower average end-to-end delay and much higher packet delivery ratio.

Categories and Subject Descriptors

C.2.2 [Computer-Communication Networks]: Network Protocols—Routing protocols

General Terms

Design, Simulation, Performance

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Keywords

Wireless LAN mesh network, Root driven, Tree-based, Routing protocol

1. INTRODUCTION

Wireless LAN mesh networks (or Mesh WLANs) are mesh networking implemented over a wireless local area network (WLAN). The Mesh WLANs are mainly targeted for residential, office, public safety, military, campus, community, small to medium businesses, public access, emergency, municipality, and rural networks. Most of the above-mentioned networks needs to connect to the infrastructure networks. For example, an ambulance ad hoc network on an emergency call may connect to the hospital infrastructure as necessary for communicating with the doctor. In this kind of mesh topology, at least one node directly connects to the infrastructure networks. Moreover, nodes in this mesh network have minimal or no mobility. Thus, a proactive routing protocol is deemed more suitable for such a mesh network.

The aforementioned features can be well captured by a tree-based routing (TBR) protocol [1, 2], which is attaining increased attention as a viable routing protocol for the Mesh WLANs. Based on the TBR protocol, the root (mesh portal) constructs tree-type paths efficiently and quickly in the Mesh WLAN, whereby all the participating nodes are linked to it. In addition, the TBR protocol is proposed based on the premise that traffic are mostly directed to/from an infrastructure network through the root, in which it works effectively in handling the traffic communications towards the root. However, when the amount of traffic inside mesh network increases significantly, the intra-mesh traffic around the root of the Mesh WLAN becomes so heavy that the overall network performance can be degraded rapidly. Routing intra-mesh traffic through the root not only aggravate the said weak point of TBR protocol, but also waste efficient usage of network resources due to the physical characteristics of wireless constraints. Indeed all this forwarding of intra-mesh traffic through the root might flow over the routes without using the best-metric.

To address these problems, in this paper we propose a root driven routing protocol, which enables the root to provide the best-metric route for any source-destination pair rather than go through itself when an inevitability intra-mesh traffic volume occurs at the root. In other words, the proposed protocol extends and significantly enhances the capability of the TBR protocol in regards to self-traffic-dispersing protocol and provides the best-metric route for all the source nodes. Furthermore, the proposed protocol advantageously improves the network performance without having any impact on the TBR protocol operation. The main objective of the proposed protocol is to design an efficient and effective scheme that is simple enough for combining the TBR protocol to achieve the best performance in the Mesh WLAN networks.

The arrangement of this paper is organized as follows. Section 2 briefly reviews the background of Mesh WLAN and the related work. An overview of TBR protocol is presented in Section 3 and the motivation of this paper is highlighted in Section 4. Section 5 describes a core idea of the proposed routing protocol. Section 6 gives the simulation setup, scenario, and results. Finally, this paper is concluded in Section 7.

2. BACKGROUND AND RELATED WORK

This section discusses the architecture of Mesh WLAN and reviews the related work on tree-based approaches in disseminating information of a network.

2.1 Mesh WLAN Architecture

In order to grasp the network architecture of Mesh WLAN as specified in [3], we first explain the original wireless local area network (WLAN) [4]. Two types of WLAN are classified based on the combination of an access point and a station. The simplest WLAN type consists of a minimum of two stations, wherein each station operates with the same protocol. This is also known as a wireless ad hoc network. Another WLAN type consists of a minimum of one station and one access point. It is represented as a wireless access network, in which the access point can act as a bridge or a gateway to other wired networks. To address the need of wireless mesh in WLANs, the access point links are unwired and their links are connected to each other via radio links resulting in a ‘mesh of connectivity’ among the access points. Such an enhanced architecture is known as a wireless LAN mesh network (or Mesh WLAN). An example of Mesh WLAN architecture with legacy stations (STAs) as specified in the IEEE 802.11s [2] that is depicted in Fig. 1. In such a Mesh WLAN architecture, different entities in the Mesh WLAN play different roles according to the functionalities they provide. Basically, the Mesh WLAN architecture consists of three entities; a mesh point (MP), a mesh portal point (MPP), and a mesh access point (MAP). The ad hoc link formation formed by the MPs, which provides the backbone for the Mesh WLAN infrastructure, whereas the MPP works as a repeater or a gateway. The MP that supports the associated STAs is usually called as MAP. The MPs can be either stationary or mobile. However, the MPP and MAPs are mostly immobile. The STAs are usually regular devices that do not contribute to the Mesh WLAN services, such as routing and forwarding for multi-hopping packets. Therefore, the STAs simply connect to one of the MAPs in order to access the network resources. Since we intend to focus on the routing protocol in the Mesh WLAN networks, STAs access to MAPs is not considered in this paper. We also use the terms of node and root to represent MP and MPP, respectively.

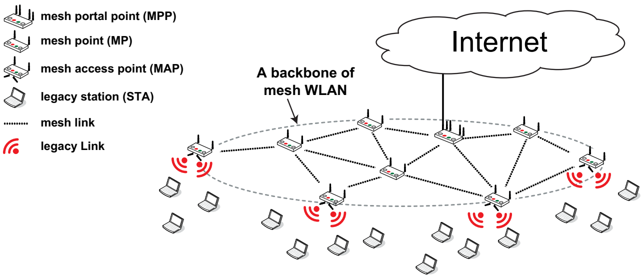


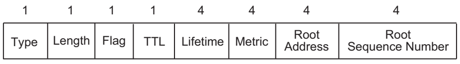
Figure 1: An architecture of Mesh WLAN.

2.2 Related Work

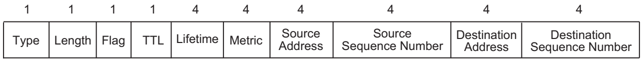
Broadcasting protocols play an importance role in disseminating information to all network nodes in the wireless multihop networks [5]. For simple and reliable dissemination, a simply flooding or flooding-like approach is used. Despite its simplicity and reliability, flooding involves unnecessary communications, causing inefficient use of resources. To minimize the hefty communication overhead and reduce the number of collisions, the dissemination information is distributed over a tree path, instead of flooding it. In literature, the tree path broadcasting appears in two forms; a single root broadcast tree and multiple root broadcast trees. In the single root broadcast tree approach, Chlamtac and Kutten [6] have proposed two algorithms; distributed and centralized in order to increase the distribution efficiency for maintaining the tree. In [6], both algorithms are based on a set of time oriented channel allocation rules, which results in a collision free forwarding along the tree. In the distributed algorithm a message called TOKEN is generated at the root and routed through the network nodes. Upon TOKEN reception, a node becomes the focus of the tree construction activity and timeslot assignment. In the centralized algorithm however a node’s timeslot assignment is determined by the root only.

In the multiple root broadcast trees, Ogier et al. [7] considered the idea behind reverse-path forwarding (RPF) in [8] and proposed a new topology dissemination protocol called topology dissemination based on reverse-path forwarding (TBRPF) protocol, in which broadcast trees are computed based on full topological information received over the broadcast trees themselves. In TBRPF, every node executes Dijkstra’s algorithm to determine a reverse minimum-hop tree, and then exchanges some information with neighbors to determine its parent and children from the standpoints of other nodes. Once the topology is changed, TBRPF suffers from the overhead associated with computing the trees and communicating with neighbors.

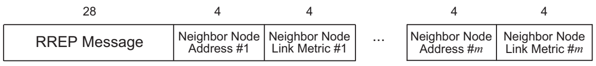
The idea of tree-based is also applied to the routing protocols for multicast (group-oriented) communication. An example of tree-based multicast protocols is multicast ad hoc on demand distance vector (MAODV) protocol [9]. The MAODV protocol maintains a shared tree for each multicast group, consisting of only receivers and relays. Sources wishing to send message to destinations in particular multicast group acquire on demand routes corresponding to the destinations in a way similar to the AODV protocol [10]. Each multicast group has a group leader. The group leader periodically transmits a HELLO packet to the receivers and relays. Upon HELLO packet reception, the receivers and relays reply with a special route request (RREQ) to the group leader in order to keep themselves as a member of shared tree. The primary drawback of MAODV is high delay and



(a) RANN message format

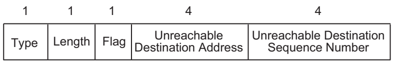


(b) RREP message format



m denotes number of neighbor nodes

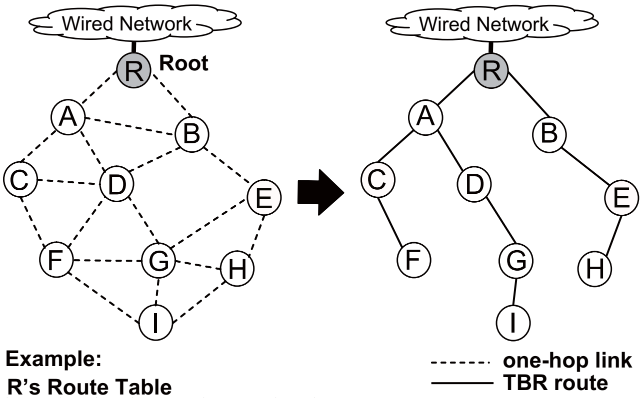
(c) RREP message format with neighbor information



(d) RERR message format

Note: all the figures denote in Octets

Figure 2: RANN, RREP without and with neighbor information, and RERR message formats.



Example:

R's Route Table

DST	NH	LM	SN	TS	NF
A	A	1	655	1.0345	N
B	B	1	655	1.1355	N
C	A	2	655	1.3740	N
D	A	2	655	1.6241	N
E	B	2	655	1.5585	N
F	A	3	655	1.7925	N
G	A	3	655	1.8252	N
H	B	3	655	1.8511	N
I	A	4	655	1.9236	N

Node A's Route Table

DST	NH	LM	SN	TS	NF
R	R	1	655	1.0125	R
D	D	1	655	1.1075	N
C	C	1	655	1.2930	N
F	C	2	655	1.5430	N
G	D	2	655	1.4893	N
I	D	3	655	1.7632	N

Figure 3: A root and all participating nodes form a tree-topology network using the TBR protocol. The examples of route table for the root and node A are also provided.

overhead in fixing broken links under high network mobility and traffic load. It may be argued that its dependence on a unicast routing protocol makes it less flexible.

Besides the wireless networks, the idea of tree-based is used in the IEEE standardization like IEEE 802.1D Bridging LAN standard [11]. This tree-based algorithm configures a simply connected active tree topology from the bridge ports of a Bridged LAN. One of the bridges is known as the root bridge in the Bridged LAN. On the other hand, IEEE 802.11 working group confirmed a baseline draft for wireless mesh network (WMN), designated as IEEE 802.11s "Wireless LAN medium access control (MAC) and physical layer (PHY) specifications: Mesh Networking" [2]. In the current draft, a hybrid wireless mesh protocol (HWMP) is a combination of on-demand and proactive routing protocols. In the proactive routing, the TBR protocol is used to cope with the most expected inter-mesh traffic that will occur between the nodes and the root (as gateway to further access the wired infrastructure).

Although a plethora of research has been produced in relation to tree-based approaches for efficient and effective information distribution purposes, the TBR protocol in the Mesh WLAN deployment is still open issues among researchers today. To the best of our knowledge, there is no so much investigations on the performance optimization of TBR protocol under the network of Mesh WLANs.

3. THE TBR PROTOCOL

A tree-based routing (TBR) protocol that is a kind of proactive routing protocols builds a tree-topology network when a root in the Mesh WLAN is configured. The root is a portal or shared edge node with high computation, which acts like a server for other nodes. An example of root is a gateway of campus network topology. In this paper, we intend to focus our research work mainly dealing with only one root. Before a node could send its traffic to another node inside the mesh network, the topology tree is constructed in order to link all the participating nodes. This topology tree formation begins when the root starts to periodically broadcast a root announcement (RANN) message by increasing the sequence number in every announcement, which is set to default value of 3 seconds. The RANN message format is shown in Fig. 2(a). A node receiving the RANN caches the originated node address of the corresponding RANN as a potential parent, and rebroadcasts the RANN with an updated cumulative metric. After waiting for a pre-defined period of one second for other arriving RANNs from all possible parents, the node selects a parent node with the best-metric for its path to the root from all the possible parents, and updates its route table in which, for instance, the latest message sequence number. Then, the node that has the known path to the root also registers itself by sending a route reply (RREP) message with the root as the destination address in the RREP message field. Figure 2(b) shows the RREP message format. Each intermediate node that received the RREP forwards the RREP to its selected parent and updates the node it was received from as the next-hop child to reach the source node in its route table. After receiving all the RREPs, the root learns all participating nodes and builds a tree topology to reach any node in the mesh network. If a node does not hear the RANN for a pre-defined period, the node does not participate in tree-building until hearing a valid RANN again. Each node in the tree-topology network maintains its own route table, which has entries for recent route towards the destination node. In the route table of each node, the contents are destination (DST), next hop (NH), link metric (LM), sequence number (SN), time stamp (TS), and node flag (NF). The field of link metric represents that the metric that is associated with the hop count, airtime cost, etc. For the sake of simplicity, the metric of hop count is hereinafter used for the TBR protocol as well as our proposed protocol in the simulation studies of this paper. The field of sequence number represents the most recent information of an entry. The field of time stamp represents that the time for an entry is stored and it is used to monitor the expiration of an entry. Each time the tree

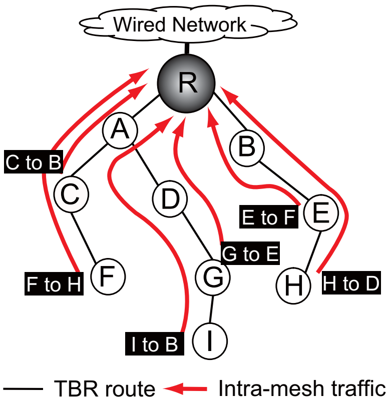


Figure 4: The inefficiency of the TBR protocol when dealing with intra-mesh traffic in the mesh network.

1	1	1	1	4	4	4	4	4
Type	Length	Flag	TTL	Lifetime	Source Address	Source Sequence Number	Destination Address	Destination Sequence Number

(a) RREQ message format

1	1	1	4	4	4		4
Type = RSET	Length	Flag	Lifetime	Source Sequence Number	Node Address #1 (Source)	...	Node Address #n (Destination)

n denotes number of notifying nodes

(b) RSET message format

1	1	1	4	4	4		4
Type = RNTF	Length	Flag	Lifetime	Source Sequence Number	Node Address #1 (Source)	...	Node Address #n (Destination)

(c) RNTF message format

Note: all the figures denote in Octets

Figure 5: RREQ, RSET, and RNTF message formats used in the proposed protocol.

route is used, its associated time stamp is updated. If the route is not used within the specified time, route table timeout must be at least the maximum of three times of *RANN announcement interval*, it is deleted. The field of node flag represents that the destination of entry is either a root (R) or a node (N). Figure 3 shows a root and all the participating nodes form a tree-topology network using the TBR protocol. With the tree-topology and table-driven routing, any node can participate and communicate with each other in the network. For instance, when a node wants to send traffic to another node, and if it has no route to its destination node, it sends the traffic to the root. Upon receiving the traffic from the source node, the root checks if the source traffic is intended for a node within the mesh or outside. The root forwards the source traffic to the destination node if it finds an entry in the route table, otherwise it sends to the destination node of the wired networks.

4. PROBLEM DESCRIPTION

There are three types of traffic requiring routing via a mesh gateway, which is usually configured as a root in the Mesh WLAN; upstream from inside mesh, downstream from outside mesh, and intra-mesh between nodes within mesh. For both downstream and upstream traffic, the root can provide the available proactive TBR protocol itself. For the traffic of intra-mesh between nodes within mesh, when a source node wants to send traffic to a destination node, which is inside the mesh network, the source node forwards the traffic toward the root if no active path exists and the destination node receives the traffic forwarded by the root. There is one serious drawback in the TBR protocol when other participating nodes always forward their intra-mesh traffic flow without using the best-metric route through the root. The root is noticeably overloaded with forwarding traffic as shown in Fig. 4. Moreover, when the network size grows and becomes significantly huge, the intra-mesh traffic around the root becomes so heavy that the overall network performance can be degraded sharply and the entire network can slow down or even stall. Routing the intra-mesh traffic through the root not only worsen the performance of TBR protocol, but also waste of network resources due to non-uniform spatial usage of shared wireless bandwidth. As a result, TBR protocol faces many problems like the increased end-to-end packet loss, the decreased network lifetime, root of the tree is unique point of failure, and poor load balancing whereby nodes near the root carry more traffic, which lead to traffic congestion around the root. To solve the aforementioned problems, we propose a hybrid routing protocol, which is a novelty protocol for the handling the increment of intra-mesh traffic despite the inter-mesh traffic in the Mesh WLANs.

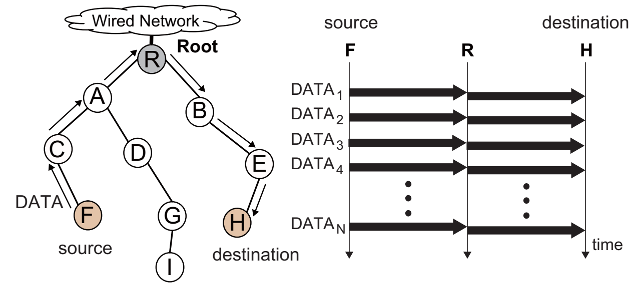
5. PROPOSED PROTOCOL

In this section, we introduce a proposed root driven routing protocol, which incorporates with the TBR routing so that it forms a hybrid routing protocol for the handling the increment of intra-mesh traffic despite the inter-mesh traffic in the Mesh WLANs. We first present how to build the whole network topology at the root beside having the tree topology and then present the proposed protocol description and procedure. We discuss the computation and algorithm of choosing the optimum route for any source-destination pair. We also discuss how to improve the proposed protocol and its protocol procedures when dealing with link breaks.

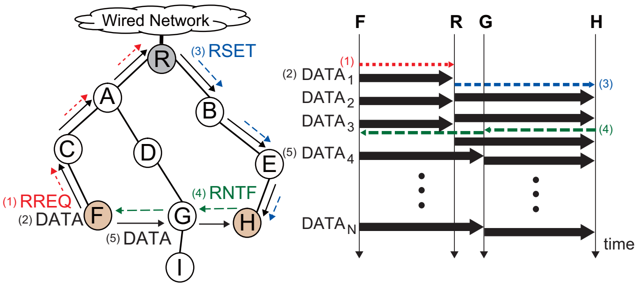
5.1 Protocol Description and Procedure

The core idea of our proposed protocol is to inaugurate a root driven routing protocol for handling the intra-mesh traffic within the mesh network. First, to enable a root to provide the best-metric route for any intra-mesh traffic, it needs to build a whole network topology in addition to the tree topology. To do so, upon receiving the RANN message, each node piggybacks the neighbor information that consist of neighbor addresses and the corresponding metric into the RREP message (see Fig. 2(c)).

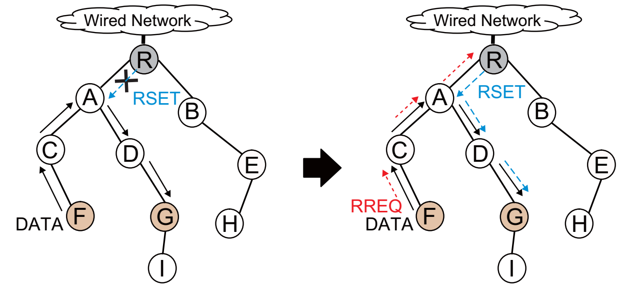
Second, we need two additional messages; route set (RSET) and route notification (RNTF) in order to notify nodes within the network for their intra-mesh traffic. These two message formats are shown in Fig. 5(b) and (c). Basically, the proposed protocol is very simple and efficient to provide an on-demand routes for any source to its corresponding destination in the mesh network. Simply to say, when a source node wants to send traffic to a destination node, the root can recommend the optimum on-demand route by notifying the route information using a RSET message via unicasting to the destination node or to the source node. Then, the destination node (or the source node) notifies the interme-



(a) The TBR protocol for intra-mesh traffic

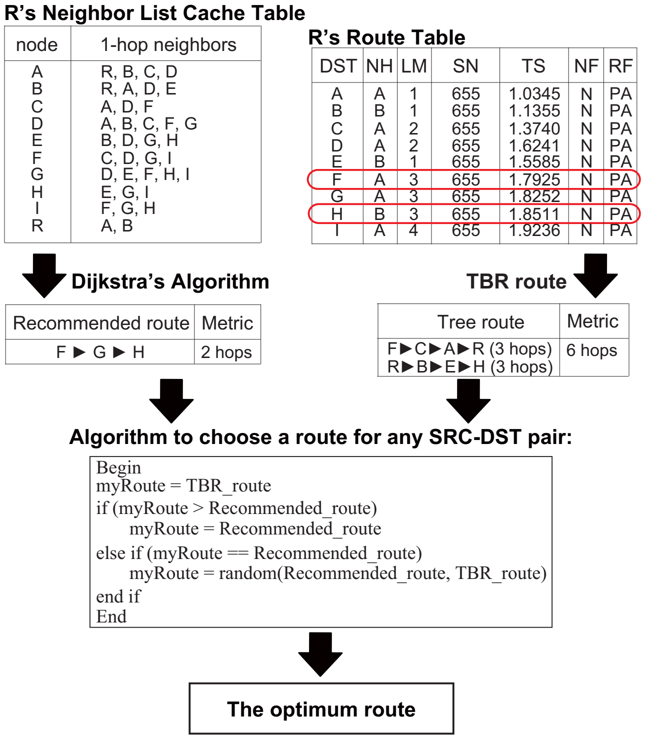


(b) The proposed root driven routing protocol for intra-mesh traffic



(c) The function of RREQ in the proposed protocol

Figure 6: (a) The TBR protocol operation for intra-mesh traffic. (b) The proposed root driven routing protocol operation for intra-mesh traffic. (c) The function of RREQ in the proposed protocol.



R's Neighbor List Cache Table

node	1-hop neighbors
A	R, B, C, D
B	R, A, D, E
C	A, D, F
D	A, B, C, F, G
E	B, D, G, H
F	C, D, G, I
G	D, E, F, H, I
H	E, G, I
I	F, G, H
R	A, B

R's Route Table

DST	NH	LM	SN	TS	NF	RF
A	A	1	655	1.0345	N	PA
B	B	1	655	1.1355	N	PA
C	A	2	655	1.3740	N	PA
D	A	2	655	1.6241	N	PA
E	B	1	655	1.5585	N	PA
F	A	3	655	1.7925	N	PA
G	A	3	655	1.8252	N	PA
H	B	3	655	1.8511	N	PA
I	A	4	655	1.9236	N	PA

Dijkstra's Algorithm

Recommended route	Metric
F ▶ G ▶ H	2 hops

TBR route

Tree route	Metric
F▶C▶A▶R (3 hops) R▶B▶E▶H (3 hops)	6 hops

Algorithm to choose a route for any SRC-DST pair:

```
Begin
myRoute = TBR_route
if (myRoute > Recommended_route)
      myRoute = Recommended_route
else if (myRoute == Recommended_route)
      myRoute = random(Recommended_route, TBR_route)
end if
End
```

The optimum route

Figure 7: Computation and algorithm of choosing the optimum route for any source-destination pair in the mesh network.

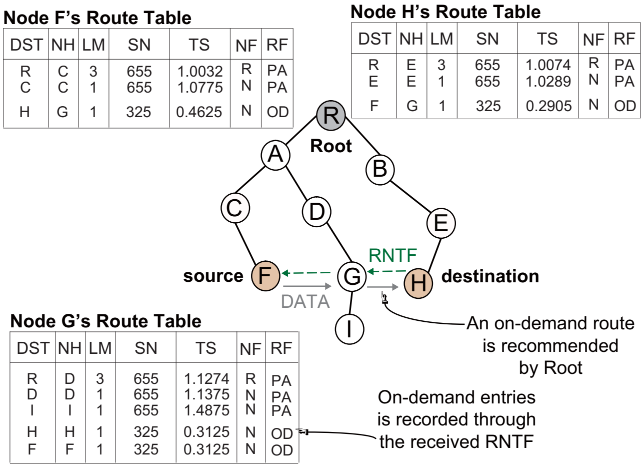
diate nodes along the recommended optimum route with a RNTF message via unicasting. For the sake of consistency in term of protocol implementation, we only specify the case where the root sends the RSET message to the destination node rather than to the source node. Figure 6 illustrates an example of how the root uses a root driven routing protocol to provide a pair of source-destination to deliver its intra-mesh traffic. When a source node (F) wants to send traffic to a destination node (H), F has no route to its H, it sends a route request (RREQ) message to the root and followed by sending the DATA messages to the root. Upon receiving the RREQ message, the root refers to the topology information of the whole network, and then it selects the optimum route from F to H. To notify the selected route, the root generates a RSET message via unicasting to H, whereby the RSET message contains the complete path information from F to H. Meanwhile, the root also forwards the DATA messages to H. Upon receiving the RSET message, H generates a RNTF message, which contains the path information from F to H, and then forwards it to F via G according to the path information. When F receives the RNTF message, F switches and unicasts its DATA messages destined to H along the recommended optimum route by the root.

5.2 RREQ Function

According to the example of network topology in Fig. 6(c), when a source node (F) wants to send traffic to a destination node, e.g., G, F sends the traffic to the root if F has no route to G. Upon receiving the traffic with the destination address field is set to G from F, node A realize that it has to forward the source traffic to G via node D. This is because A checked its route table and found out that there is an entry of destination G with two-hop away through D. Thus, A rationally sends all the source traffic to D rather to the root. In order to avoid the RREQ message is being forwarded by A to D, the destination address field in the RREQ message is set to root address. By doing that, the RREQ message is directly to the root. Upon receiving the RREQ message, the root generates a RSET message. In other words, the function of RREQ message is to trigger the generation of RSET message when the proposed protocol is applied. Before the RSET message is generated, the root computes the optimum route for the source node that sent the RREQ message and the information of the optimum route put into the node address fields of RSET message as shown in Fig. 5(b).

5.3 Optimum Route Computation

In the proposed protocol, the root builds a whole network topology upon receiving the RREP message that contains the neighbor information of the nodes. According to the topology information of the entire network, the root com-



Node F's Route Table

DST	NH	LM	SN	TS	NF	RF
R	C	3	655	1.0032	R	PA
C	C	1	655	1.0775	N	PA
H	G	1	325	0.4625	N	OD

Node H's Route Table

DST	NH	LM	SN	TS	NF	RF
R	E	3	655	1.0074	R	PA
E	E	1	655	1.0289	N	PA
F	G	1	325	0.2905	N	OD

Node G's Route Table

DST	NH	LM	SN	TS	NF	RF
R	D	3	655	1.1274	R	PA
D	D	1	655	1.1375	N	PA
I	I	1	655	1.4875	N	PA
H	H	1	325	0.3125	N	OD
F	F	1	325	0.3125	N	OD

Figure 8: On-demand route construction for an intra-mesh traffic transmission using one common route table.

putes the optimum route for all source-destination pairs using the Dijkstra's algorithm. Upon receiving the RREQ message, the root first selects all the possible valid paths for a source-destination pair. Then, the root chooses the best-metric route among the possible valid paths. After the Dijkstra's algorithm is carried out, the root compare the computation results with the existing TBR route information in its route table in order to make sure that the recommended route is an optimum route. Figure 7 shows a computation and algorithm of choosing the optimum route for a source-destination pair in the mesh network when the proposed protocol is applied. In other words, the root can adapt to the network demands by necessarily recommending the optimum route for a source-destination pair besides the tree-type route. If the computation result of best-metric route has the same metric with the TBR route, the algorithm chooses either one randomly as an optimum route. In order to avoid high computation in the root, the computation is conducted one based on the latest piggybacked neighbor information of participating nodes when a RREQ message is received. It is intuitively clear that the computation process is relatively simple and consumes less computation power for the root.

5.4 On-demand Active Route

In this section, we explain how to construct and maintain the on-demand active route for any source-destination pair when the proposed protocol is applied. Upon receiving the RSET message, a destination node generates a RNTF message with an information of on-demand (optimum) route that is recommended by root. An intermediate node that received the RNTF message has to update its route table with the on-demand entries and forwards it toward the source node after processing the RNTF message. To ensure the entries for on-demand and proactive can share in one common route table, new column of route flag (RF) field is added into the route table. The field of RF represents that the destination of entry is handled either by the proactive (PA) mode or for the on-demand (OD) mode. Figure 8 illustrates an example of how to implement both proactive and on-demand entries in one common route table when the proposed protocol is applied. Upon receiving the RNTF message, the source node switches its traffic transmission to the corresponding destination node via the recommended optimum route by the root. In the proposed protocol, the route between each source and destination pair is expected to be symmetric. Thus, the forward path to destination and the reverse path back to source are constructed when one RNTF message is received. As a result, it indirectly can reduce the overall control overhead of proposed protocol despite using the second RNTF message to build the reverse path back to source. In summary, one RNTF message is used to build a directtional path of source-destination pair when the route is assumed to be symmetric.

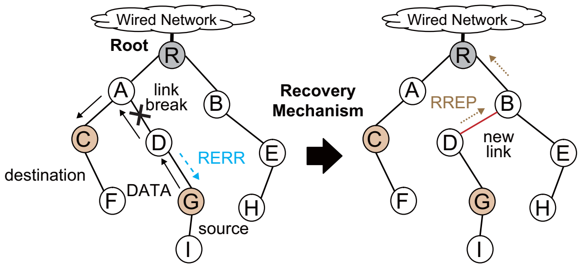
Each time an on-demand route is used to forward a data packet, the source, the destination, and the intermediate nodes along the route are updated their time stamp field of route table to be no less than the current time plus *active route timeout*. Since the on-demand route is assumed to be symmetric, the time stamp field of route table along the reverse path back to the source, is also updated to be no less than the current time plus *active route timeout*. Since the mesh network is nearly a static network, the *active route timeout* is set to default value of 3 seconds. In other words, on-demand routes if not used for 3 seconds will be invalidated. After 3 seconds, the source, the destination, and the intermediate nodes along the on-demand route will be deleted their corresponding entry of the route table. For simplicity, there is no RERR message is generated to trigger the on-demand route in the proposed protocol.

5.5 Optimization and Maintenance

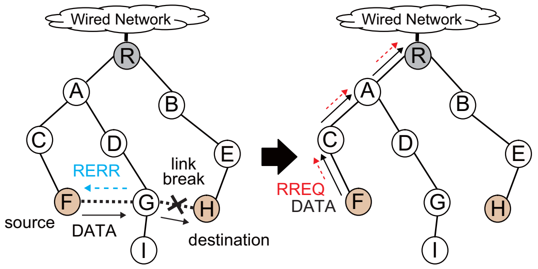
In the proposed protocol, the root can provide the optimum route information for all source-destination pairs, but it requires additional control overhead to piggyback the neighbor information of the nodes. Moreover, the root periodically needed to update the neighbor information that was piggybacked by the nodes in order to cope with the dynamic network changes. To reduce the control overhead, after the first piggybacked neighbor information, we recommend that upon receiving each consecutive broadcasted RANN message from the root, every node replies the RREP message without piggybacking the neighbor information when the topology is unchanged. We restrict piggybacking the neighbor information in the RREP message only when the changes of the metric between a node and its neighbor nodes occurs. A part of the route optimization and maintenance for the proposed protocol is quite similar to the TBR protocol.

5.6 Link Breaks

A link between two nodes is not stable due to node movement and other restrictions. Since the network topology is dynamically changed with respect to time, the root needs to maintain its topology table by sending the RANN with every maintenance interval. For the TBR protocol, it can provide good reliability and low latency through frequent dissemination of routing information, but it entails high control overhead and scales poorly with the increasing number of nodes. If the parent node is lost, the child node checks its cached route table and selects a new parent node (if any) by unicasting a RREP destined to the root via the selected parent node. Figure 9(a) shows the link of a child node (D) and a parent node (A) broken and a new link is built. For the proposed protocol, there is no additional mechanism is



(a) A new proactive link is built using RREP



(b) F initiates new RREQ and sends it to ROOT

Figure 9: (a) Repair of a broken tree link. (b) Heal of a broken on-demand link.

needed to re-establish the optimum route for an ongoing traffic transmission of a source-destination pair when an active link of the optimum route is broken. Once the intermediate node detected an active link is broken for the next hop of an on-demand active route in its route table while transmitting data, it sends a RERR message to the source node along the optimum route. For any intermediate node that receiving the RERR message, it deletes the corresponding entry of the on-demand route in its own route table. However, the source node stop sending its traffic transmission along the optimum route and generates new RREQ for hopping to look for another recommended route information from the root. Figure 9(a) and 9(b) show a repair of a broken tree link and a heal of a broken on-demand link, respectively.

6. SIMULATION STUDIES

In this section, we investigate the performance of the proposed protocol over the TBR protocol with the OPNET 11.5 simulator [12] assuming in the Mesh WLAN environment. In our simulation, all the nodes that included one root are confined to a 100 × 100 m^2 area. The root is located in the top-left corner of the simulation area whereas other nodes are placed randomly and distributedly. Other parameters are summarized in Table 1. We model our traffic based on voice over internet protocol (VoIP). In the simulations a bidirectional VoIP traffic is sent, one flow from source node to destination node and another flow vice versa. All source nodes are pre-selected and all corresponding destination nodes are chosen randomly in the network. The VoIP traffic consists of 160-byte frame size, which sends at the rate of 50 packets per second. A G.711 encoder/decoder is applied to the VoIP flows. When the mobility is taken into account in the network, only the root is static and the entire node is moving based on random waypoint model, where the node's direction is random, and the node speed is similar to human walking speed (1 m/s) with the pause time is 0 s. For comparison purposes, the simulation time is 120 seconds and ten scenarios with different tree-path are averaged.

Table 1: Simulation Parameters

Network simulator	OPNET 11.5
Physical characteristic	IEEE 802.11a OFDM
MAC protocol	CSMA/CA
Network coverage area	100 m × 100 m
Simulation time	100 s
Transmission range	50 m
Transmission bit rate	54 Mbps
RANN broadcast interval	3 s
RREP pre-defined time	1 s
Mobility model	Random waypoint
Pause time	0 s
Queue size	50 packets
Codec scheme for VoIP	G.711
Voice offered rate	64 kbps (50 pkts/s)
Voice frame size	160 bytes

6.1 Comparison of Packet Delivery Ratio

Figure 10 and 11 show how packet delivery ratio varies with number of traffic flows and the number of nodes, respectively. Packet delivery ratio is the ratio of total number of packets received at the destinations over the total number of packets transmitted by the sources. As both number of traffic flows and number of nodes increase, the superiority of the proposed protocol over the TBR protocol becomes very obvious. This is shown that traffic around the root of the tree-topology becomes significantly less when the proposed protocol is used. This leads to the fact that the number of packet drops due to packet collision and buffer overflow reduces largely as well as a decrement of packet processing and forwarding at the root. In the static network, only the proposed protocol always manages to deliver the packets with a reliability greater than 98%. When nodes are moving, both protocols experienced the packet delivery drops below 55%. The reason is that a large number of packet drops due to many broken links occurred in the network.

6.2 Comparison of Average End-to-end Delay

Average end-to-end delay is the average elapsed time to deliver a packet from the source to the destination, and it includes all possible delays before data packets arrive at their destinations. Figure 12 and 13 show how average end-to-end varies with number of traffic flows and the number of nodes, respectively. As both number of traffic flows and number of nodes increase, the average end-to-end delay of the proposed protocol is about three to four times smaller than the TBR protocol when nodes are static. This is because the proposed protocol yields smaller delays in routing the data messages with the best-metric route that recommended by the root, resulting in an decrement packet contention and number of transmissions, which leads to low end-to-end delay. When nodes are moving, both protocols experienced the average end-to-end delay more than 400 ms.

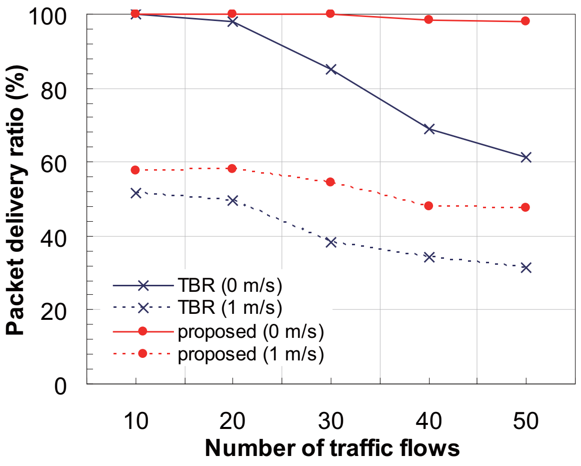


Figure 10: Packet delivery ratio as a function of number of traffic flows (50 nodes).

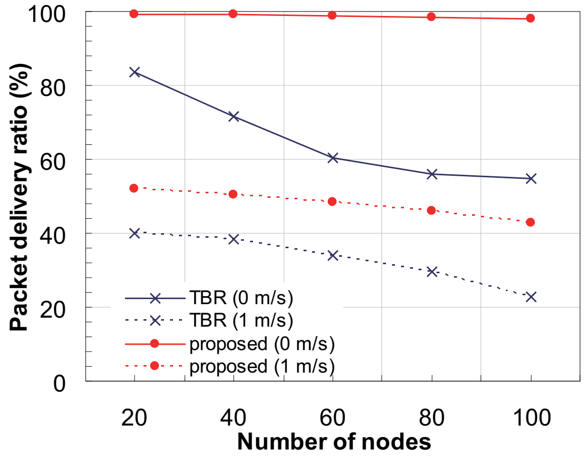


Figure 11: Packet delivery ratio as a function of number of nodes (40 flows with 50 packets/second).

6.3 Comparison of Routing Overhead

The routing overhead describes how many routing messages for route discovery and route maintenance need to be sent in order to propagate the data messages. In this paper, the routing overhead is obtained as follows:

$$Overhead = \frac{Control_{inBytes}}{Control_{inBytes} + Data_{inBytes}} \quad (1)$$

where $Control_{inBytes}$ is the total number of control bytes transmitted and $Data_{inBytes}$ is the total number of data bytes received. In the proposed protocol, the additional of control bytes accounts for RSET and RNTF messages as well as the piggybacked neighbor information of the nodes in the RREP message. However, the routing overhead remains fair when the number of traffic flows increases, because the number of control bytes transmitted is almost constant without change with the increasing traffic flow. We can see from Fig. 14 and 15 that the routing overheads of TBR protocol and proposed protocol become very close with each others as the number of traffic flows becomes large or as the number of nodes becomes less. However, simulation results show that when nodes are moving, the routing overhead for both protocols is about twice as large as that of the routing overhead when the network is static.

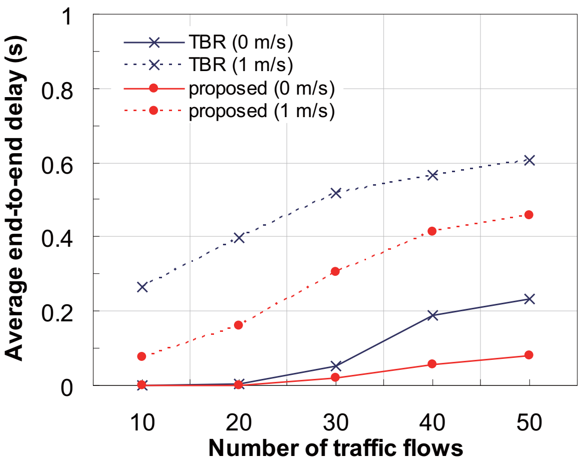


Figure 12: Average end-to-end delay as a function of number of traffic flows (50 nodes).

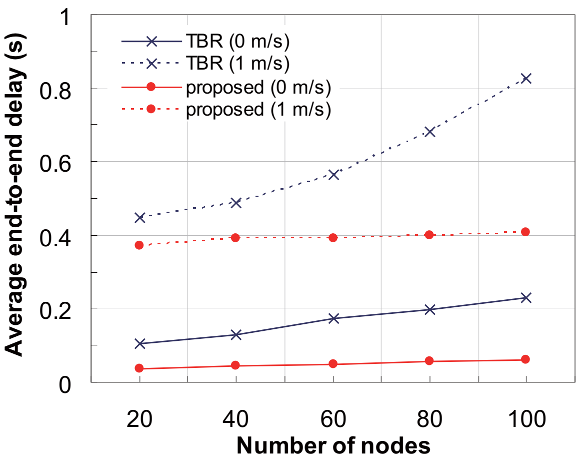


Figure 13: Average end-to-end delay as a function of number of nodes (40 flows with 50 packets/second).

6.4 Discussion on Voice Quality of VoIP

In the previous section, we adopt the VoIP traffic model and evaluate the average end-to-end delay and the packet delivery ratio of the WMN environment by using the TBR protocol and our proposed protocol. In order to justify the transmission quality of the VoIP traffic in our simulations, we use the requirements that is proposed by [13]. In [13], they determine that class A requires less than 100 ms of average end-to-end delay and more than 97% of packet delivery ratio, defining the speech quality for the fixed phone services. However, class B requires less than 150 ms of average end-to-end delay and more than 94% of packet delivery ratio, defining the speech quality for mobile phones services.

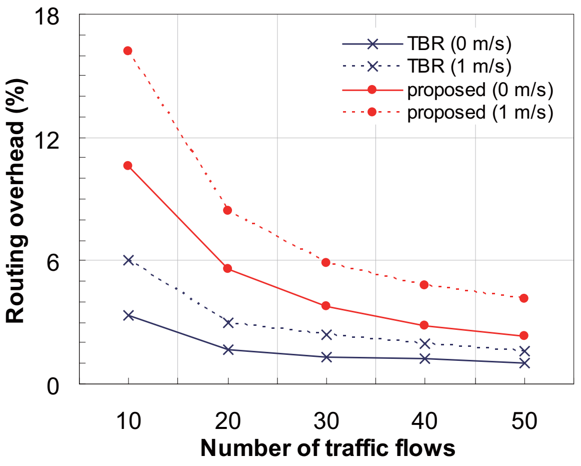


Figure 14: Routing overhead as a function of number of traffic flows (50 nodes).

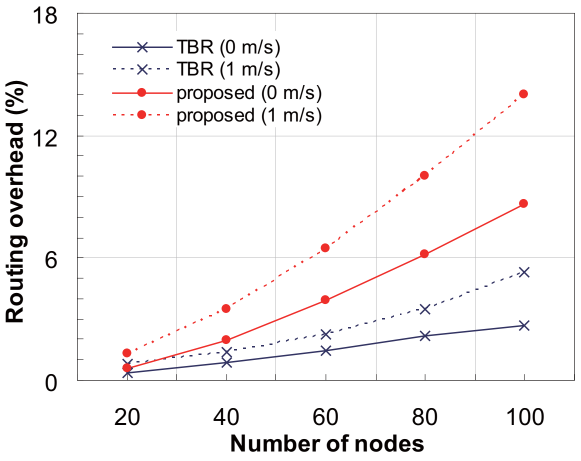


Figure 15: Routing overhead as a function of number of nodes (40 flows with 50 packets/second).

Based on the Fig. 10 and 12, we conclude that when all nodes are static the TBR protocol can support only 22 flows, and 24 flows when the number of nodes is 50 for class A and class B voice quality, respectively. On the other hand, under the same conditions the proposed protocol can support more than 50 flows for both class A and class B voice quality. The proposed protocol, therefore, is efficient and effective for practical voice applications such as VoIP service.

6.5 Discussion on Intra-mesh Traffic

In our previous results, all the traffic between nodes in the WMN are assumed to be intra-mesh traffic. Besides the intra-mesh traffic, the traffic between a node in the WMN and a node on the wired networks is dominated in most situations. Therefore, in this section, we examine the performance of the proposed protocol over the TBR protocol when the intra-mesh traffic ratio is increased from 0% to 100%. The intra-mesh traffic ratio is calculated as the number of intra-mesh traffic flows over the total number of user traffic flows. For fair evaluation, the rest of the parameters is the same except the number of nodes is 50 and 10 simulation scenarios with different random seeds are averaged. Figure 16 shows the throughput as a function of intra-mesh traffic ratio. The throughput is the average total number of data bytes received at the destinations over the total simulation time. Our evaluation reveals that when the intra-mesh traffic ratio is below 20%, the proposed protocol obtains approximately the same packet delivery ratio compared to the TBR protocol. We can see that the proposed protocol outperforms the TBR protocol when the intra-mesh traffic ratio is more than 20%. We conclude that in order to assure the best network performance, the TBR protocol can be used for inter-mesh traffic whereas the proposed protocol can be used for intra-mesh traffic.

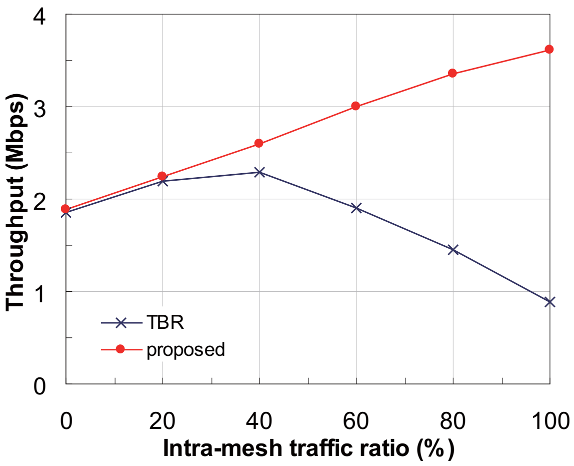


Figure 16: Throughput as a function of intra-mesh traffic ratio.

7. CONCLUDING REMARKS

In this paper, we proposed a root driven routing protocol to solve the traffic concentration around the root when the TBR protocol is used for the intra-mesh traffic in the Mesh WLANs. The proposed protocol provides the optimum route by the root for any source-destination pair of intra-mesh traffic. The proposed protocol advantageously improves the network performance without incurring any severe impact on the operation of TBR protocol. In order to accomplish the best network performance, the TBR protocol can be used for inter-mesh traffic whereas the proposed protocol can be used for intra-mesh traffic.

Numerical simulations reveal that the proposed protocol is very beneficial and outperforms the TBR protocol with much lower average end-to-end delay and much higher packet delivery ratio for the intra-mesh traffic. Furthermore, our simulation results show that when all nodes are static the TBR protocol can support only 22 traffic flows when the number of nodes is 50 for class A voice quality, whereas the proposed attains more than 50 traffic flows. Our simulation results are very encouraging and we currently focus on examining the multiple root broadcast trees issue for the Mesh WLANs.

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