An Efficient On-Demand Routing Approach with Directional Flooding for Wireless Mesh Networks

Dong-Won Kum, Anh-Ngoc Le, You-Ze Cho, Chai Keong Toh, and In-Soo Lee

Abstract: **Current on-demand ad-hoc routing protocols are not appropriate for wireless mesh networks (WMNs), because flooding-based route discovery is both redundant and expensive in terms of control message overhead. In this paper, we propose an efficient on-demand routing approach with directional flooding (DF), which is suitable for the WMNs with limited mobility. In the route discovery process to reach a gateway, our DF scheme can reduce the number of route request (RREQ) packets broadcast by using a restricted directional flooding technique. Simulation results show that ad hoc on-demand distance vector (AODV) with DF (AODV-DF) can significantly reduce routing overhead by RREQ packets and enhance overall performance compared with the original AODV.**

Index Terms: **Ad hoc on-demand distance vector (AODV), ad hoc routing, directional flooding (DF), wireless mesh network (WMN).**

I. INTRODUCTION

Wireless mesh networks (WMNs) are popular due to their low cost and rapid deployment. The application scenarios for WMNs include wireless broadband Internet access, intelligent transportation systems, and transient networks in convention centers or disaster recovery. A WMN comprises mesh routers and mesh clients. Mesh routers form the backbone of the infrastructure, and mesh routers or clients can either be stationary or semi-mobile. Compared with other ad hoc networks, one of distinguished characteristics in WMNs is that most traffic is destined towards a gateway [1].

Ad-hoc routing protocols are usually classified into: (a) On demand, (b) proactive, and (c) hybrid [2]. On demand routing is more suitable for mobile networks that have power and bandwidth constraints. Some of currently deployed WMNs consider to use on-demand routing protocols. The Microsoft mesh testbed [3] uses a modified version of the dynamic source routing (DSR) protocol, and the Kiyon network [4] uses the ad hoc on-demand distance vector (AODV) [5] as a basis for its routing protocol. On-demand routing protocols such as AODV and DSR, however, are designed to support ad hoc networks that have high mobility and user-to-user traffic pattern. Since links in WMNs tend to be long lived and the traffic patterns have user-to-gateway traffic, such traditional on-demand routing protocols are no longer suitable for WMNs due to high overhead and delay in route discovery. A routing protocol for WMNs should take advantage of such mobility characteristics and traffic pattern.

In current on-demand routing, the source will invoke a route discovery where route request (RREQ) packets will be flooded throughout the whole network. Once the destination node receives the RREQ, it will send back a route reply (RREP) to confirm the path. This is inefficient and many researchers have named this deficiency as broadcast storm [6].

In this paper, we present an efficient on-demand routing approach with directional flooding (DF), which is suitable for wireless mesh networks with limited mobility. It uses a hop-count check to restrict the propagation of RREQ packets destined towards a gateway. The DF uses hop count, which is the number of hops from a gateway, to limit the retransmissions of RREQ packets. Each node learns of its number of hops from a gateway through gateway and hop count discovery. On receiving RREQ packets, a node compares the hop count value on the RREQ packet with its own hop count value. It then relays RREQ packets only if the received RREQ has a higher hop count value than itself. Thus, RREQ packets will be directionally propagated towards the gateway. The proposed DF scheme can be applied to existing on-demand routing protocols such as AODV or DSR. This paper introduces AODV with DF (AODV-DF) routing protocol and evaluates its performance using the NS-2 simulator, compared with AODV.

The rest of the paper is organized as follows: In Section II, we describe the related work. In Section III, we explain the proposed AODV-DF protocol in detail. In Section IV, we compare the performance of AODV-DF with AODV by simulation. Finally, we make conclusions in Section V.

II. RELATED WORK

In on demand routing protocols, such as AODV and DSR, when the source node wants to establish the route to the destination, it will invoke a route discovery based on flooding mechanism. As mentioned above, the flooding mechanism produces the broadcast storm problem, which results in heavily contention, collisions, and many redundant rebroadcasts in the network. Therefore, many researchers have introduced schemes to alleviate the reduction of network performance caused by the broadcast storm problem [7]–[15].

In [10]–[12], the authors proposed the directional flooding schemes to mitigate the broadcast storm problem for the data delivery. In distance routing effect algorithm for mobility (DREAM) [10], each node maintains a position database that

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D.-W. Kum, Y.-Z. Cho, and A.-N. Le are with the School of Electrical Engineering and Computer Science, Kyungpook National University, Korea, email: {80kumsy,yzcho}@ee.knu.ac.kr, anhngoc.knu@gmail.com.

C. K. Toh is with the Department of Electrical and Electronic Engineering, University of Hong Kong, China, email: ck_away@hotmail.com.

I.-S. Lee is with the Deputy Director in the Department of Network & service Quality Research at the Network R&D Laboratory of KT, Korea, email: gazette@kt.co.kr.

Y.-Z. Cho is a corresponding author.

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Table 1. Comparison of directional flooding schemes for wireless ad hoc networks.

Schemes Criteria	DREAM [10]	V-GEDIR/ CH-MFR[11]	Ko's [12]	LAR [13]	LGF [14]	ARP [15]	AODV-DF
Flooding approach	Position-based	Position-based	Position-based	Position-based	Position-based	Position-based	Topology-based
Flooding target	Data delivery	Data delivery	Data delivery	Route discovery	Route discovery	Route discovery	Route discovery
Requirement of physical location information	Yes (with GPS)	Yes (with GPS)	Yes (with GPS)	Yes (with GPS)	Yes (with RSSI-based location tracking)	Yes (with GPS)	No
Main factor for expecting the direction	Expected zone	Voronoi diagram-based expected region	Estimated minimum hop count †	Expected zone/ request zone	Shortest distance	Expected region	Minimum hop count
Candidate ad hoc networks	MANETs	MANETs	WSNs	MANETs	MANETs	MANETs	WMNs
Considering traffic pattern	Peer-to-peer	Peer-to-peer	Sensors to sink	Peer-to-peer	Peer-to-peer	Peer-to-peer	Users to/from gateway

† Estimated minimum hop count is based on the knowledge about the two location information (sensor node and sink) and a sensor node's transmission range

MANET: Mobile ad hoc network
WSN: Wireless sensor network
WMN: Wireless mesh network

stores position information about each other node through the use of global positioning system (GPS). In this scheme, a sender broadcasts the packet to all one-hop neighbor nodes that lie in the direction toward the destination node. In order to determine this direction, a node calculates the region that is likely to contain the destination node, called the expected region which is a circle around the position of destination node.

V-GEDIR and CH-MFR [11] use Voronoi-diagram-based routing to reduce the flooding overhead in the mobile ad hoc network (MANET). They assume that all nodes have the position information about each other node. A Voronoi diagram partitions the network in n Voronoi regions, where n is the number of neighbor nodes. Each neighbor node is associated with one Voronoi region. The packet is forwarded through neighbors determined by the Voronoi diagram.

Ko *et al.* [12] suggested a directional flooding scheme using the directionality information towards a sink node in the wireless sensor network (WSN). This scheme assumes that all sensor nodes know their own location and the sink node's location information through a location service like GPS. At the setup time, the sink node announces its own location information to all sensor nodes in the network. A sensor node has a lower minimum hop-count value compared with that in the receiving packet just rebroadcasts the receiving packet. As a result, this approach can reduce the routing overhead.

On the other hand, in [13]–[15], the authors suggested the directional flooding scheme to reduce the overhead of the route discovery in the on-demand routing protocol. In location-aided routing (LAR) [13], the authors use location information to decrease the overhead of route discovery in the MANET. Thus, this scheme has the assumption that nodes have information about other nodes' positions through GPS. When the source node wants to establish a route to the destination node, the source node computes an expected zone for the destination node based on available position information. From the expected zone, this algorithm identifies a request zone which typically includes the expected zone. This scheme floods the route request packets only inside the request zone. Similarly, in location-based geocasting and forwarding (LGF) routing protocol [14], the authors use location information to decrease the overhead of route discovery in the MANET. Thus, this scheme also has the assumption that nodes have information about itself and its neighbor nodes' position. The node has a sending data packet makes an angle Q with respect to the direction. Among all nodes in the region, the node selects only two nodes to forward the packet in the route discovery.

In angle routing protocol (ARP) [15], the authors use a location-tracking mechanism based on received signal strength indication (RSSI) to get the location information. When a node wants to send the packet, it broadcasts the RREQ to all neighbors with the IP address of the destination node and distance from the source to the destination. All receiving nodes compare this distance to the distance between the node itself and the destination. The node has the lesser distance than the distance from the source to destination only forwards the receiving RREQ packet. Otherwise, it ignores and drops the RREQ packet.

Table 1 compares characteristics of directional flooding schemes which are proposed to reduce the broadcast storm in various wireless ad hoc networks. As mentioned above, most of the existing schemes are the position-based approaches using the physical location information. Therefore, they assume that each node in the network know its own location, as well as the location of the neighbor nodes and the destination node using GPS like system. In contrast, our proposed AODV-DF is a topology-based scheme, so it does not require such location information, but each node needs only number of hops away from the gateway in wireless mesh networks. Therefore, AODV-DF can be easily implemented in the real environment.

III. OPERATION OF AODV-DF

In this section, we introduce AODV-DF routing protocol. AODV-DF is basically based on AODV and it uses a hop count to directionally flood RREQ packets for the traffic destined to a gateway. But, it operates in the same way with AODV for peer-to-peer traffic between two nodes inside a WMN. We describe the operation of AODV-DF focusing on the route discovery to a gateway.

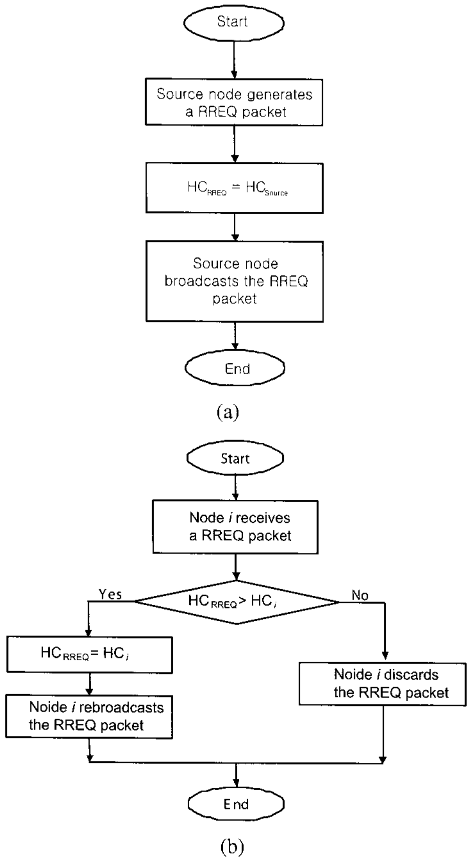


Fig. 1. The flowchart of RREQ packet processing at source and intermediate nodes in AODV-DF: (a) Source node and (b) intermediate nodes.

A. Gateway and Hop-Count Discovery

To support DF in AODV, a gateway must periodically broadcast its identity and presence to nodes in the WMN. AODV-DF embeds the gateway's address and hop-count information into the HELLO packets. There is no additional overhead here since original AODV routing protocol periodically exchanges HELLO packets.

The HELLO packet is radiated outwards from the gateway. Each node maintains a hop count (HC) variable to indicate the number of hops to a gateway, which is initially set to be infinite. Only a gateway's HC value is set to 0.

In the first step, a gateway broadcasts modified HELLO packets and sets a flag (named I-flag according to [16]) to indicate that these packets were originated by a gateway and contain the gateway's address and the hop count to the gateway.

When the nodes within a one-hop away from the gateway receive a HELLO packet with an I-flag set, they set their HC values with the HC value in the HELLO packet plus 1. These nodes later broadcast their HELLO packets with an I-flag set and their HC values. Thereafter, the two-hop away nodes receive these HELLO packets, thus they learn that they are a two-hop away from the gateway. In this manner, every node discovers the gateway's address and learns their hop count to the gateway. AODV-DF uses sequence number in HELLO packet to determine the timeliness of each packet. AODV-DF supports node mobility because the hop count to a gateway is constantly updated with every HELLO packet originated by the gateway.

B. Route Discovery

The route discovery of AODV-DF is basically based on AODV. AODV-DF uses a modified RREQ packet with an HC field to indicate the number of hops to a gateway. When a source node desires a route to a destination node for which it does not have a route, it broadcasts a RREQ packet to all its neighbors. If the destination resides within WMN, RREQ packets are flooded in the same way as AODV. Otherwise, RREQ packets are directionally propagated toward the gateway.

When a source node wants to send data to a destination node, the source should be able to determine whether the destination locates within WMN or not. One IP address assignment scheme for WMN was proposed in [16], which can distinguish the location of the destination node using the destination IP address. It is assumed that source nodes can determine whether their destinations locate within WMN or not. In the following, we describe the route discovery focusing on the traffic destined to a gateway.

When a source node wants to send data to a destination node outside the WMN, if it does not have a route to the gateway, it broadcasts the RREQ with an HC set to its HC value as shown in Fig. 1(a). Each node may know its minimum number of hops to the gateway through gateway and hop count discovery.

On receiving RREQ packets, a node compares the HC value on the RREQ with its HC. If the HC value on the RREQ is equal to or less than the node's HC, the intermediate node discards RREQ packets. Otherwise, it replaces the HC value on the RREQ with its own HC value and then re-broadcasts the RREQ to all neighbors as shown in Fig. 1(b). If an intermediate node does not know its hop count to the gateway (i.e., HC is infinite) before gateway and hop count discovery, it broadcasts RREQ packet to all neighbors as the same way in AODV.

As illustrated above in AODV-DF, RREQ packets are directionally flooded toward the gateway. Fig. 2 further illustrates how AODV-DF works for directional flooding of RREQ packets towards a gateway. When compared to AODV, AODV-DF evidently incurs fewer rebroadcasts of RREQ packets than AODV. In this example, AODV-DF needs to rebroadcast RREQ packets only three times, while AODV rebroadcasts RREQ packets nine times in total.

When a node receives the RREQ, it establishes a reverse route to the RREQ source in its routing table, and it either replies to the RREQ if it has an entry for the gateway in the routing table or it forwards the RREQ. Eventually, the RREQ reaches the gateway and the gateway send back an RREP using unicast to confirm the path. The node receiving the RREP sets up a forward route to the gateway and desirable routes can be discovered.

Route maintenance is similar to that of AODV. An existing routing entry may be invalidated if it is not used within a specified time interval, or if the next hop node is no longer reachable. In these cases, an invalidation notice is propagated to the neighbors that have used this node as the next hop. Each time a route is used to forward a data packet, its route expiration time is updated. When a node detects that a route to a neighbor is no longer valid, it removes the invalid entry and sends a route error message to the neighbors that are using the route. Nodes that receive error messages will repeat this procedure. Finally, the

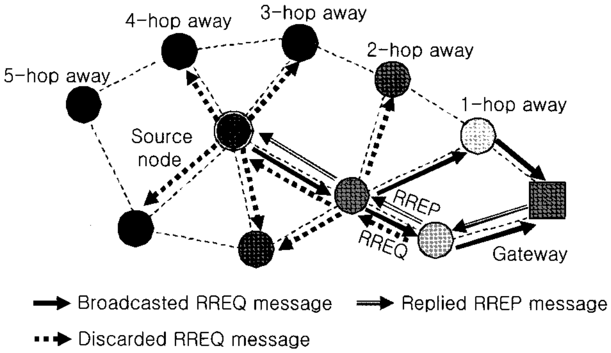


Fig. 2. Route discovery in AODV-DF.

source requests a new route if one is still needed to that destination. If the source does not receive RREP from the destination, then it broadcasts RREQ again as the same way with AODV.

IV. PERFORMANCE EVALUATION

In this section, we compare the performance of AODV-DF with AODV through packet-level simulations by using the NS-2 simulator. Simulations are run to estimate the efficiency and the overhead costs of the two routing protocols.

A. Simulation Model

We use a detailed simulation model based on the NS-2. The distributed coordination function (DCF) of IEEE 802.11 for wireless LAN is used as the medium access control (MAC) layer. The radio model uses characteristics similar to a commercial radio interface, Lucent's WaveLAN, which is modeled as a shared-media radio with a 2 Mbps nominal bit rate and a 250 m nominal radio range. Nodes in both protocols maintain a 64-packet buffer. All packets sent by the routing layer are queued at the interface queue until they can be transmitted by the MAC layer. Routing packets are given a higher priority than data packets in the interface queue.

We consider three simulation scenarios to evaluate the performance of the proposed scheme in an area of $1,500$ m $\times$ $1,500$ m area. In the first and second scenarios, we use a random network topology with 60 mesh routers. In the third scenario, we use a grid topology with 50 static mesh routers, in which 60 mobile mesh clients are randomly distributed.

In our simulation, we use constant bit-rate (CBR) traffic flows with user datagram protocol (UDP) as transport protocol. Since most of the traffic in mesh network will be directed towards the gateway, we assume that all traffic flows from mesh routers are destined to the Internet through a gateway. The sources of flows are randomly located in the mesh network. The common parameters for all the simulations are described in Table 2.

Table 2. Simulation parameters.

Parameters	Descriptions
Simulation time	250 seconds
Simulation area	1500 m × 1500 m
Mobility model	Random waypoint
Transmission range	250m
Traffic types	CBR (UDP)
Average packet rate	10 packets/second
Packet size	512 bytes
Data rate of IEEE 802.11	2 Mbps

B. Performance Metrics

The following metrics are used in the two scenarios to evaluate the performance of AODV-DF and AODV:

- *Throughput*: This is defined as the amount of data that is transmitted through the network per unit time, (i.e., data bytes delivered to their destinations per second).
- *Relative routing overhead*: The ratio of the number of routing control packets over the number of delivered data packet.
- *Average path length*: The path length which is averaged over all transmitted data packets is an indicator of a protocol's ability to maintain a multi-hop path.
- *End-to-end delay of data packets*: This is defined as the delay between the time at which the data packet originated at the source and the time it reaches the destination.

C. Simulation Results

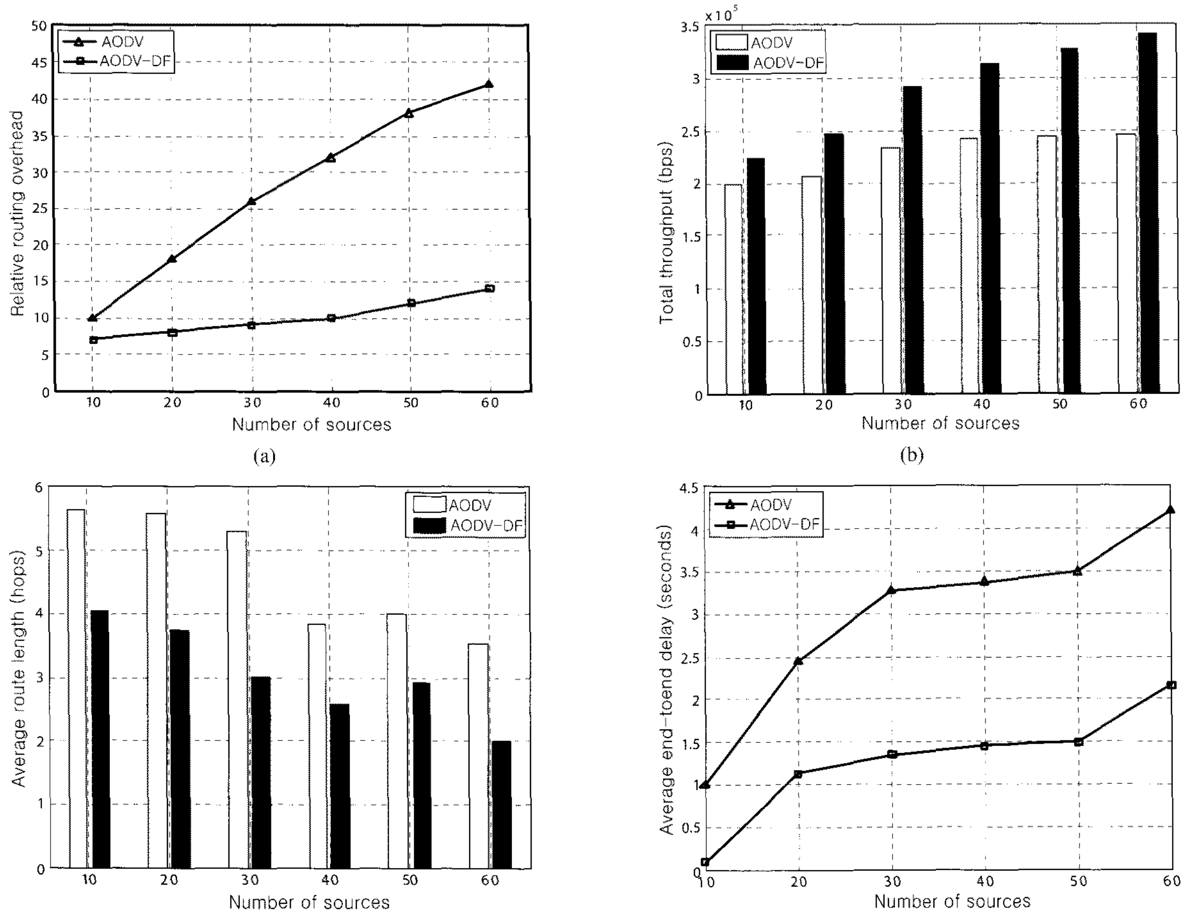
C.1 Scenario 1: Stationary Mesh Routers

In this scenario, we use a random network topology with 60 mesh routers and all mesh routers are stationary. We assume that the sources of flows are randomly selected among mesh routers in the mesh network. We have varied the traffic load from 10 sources to 60 sources (i.e., multiple sources to the gateway). As a default, HELLO packets are periodically sent at every second in AODV and AODV-DF. The simulation results are shown in Fig. 3.

Fig. 3(a) compares the relative routing overhead between AODV and AODV-DF by increasing the number of sources. This figure shows that the difference of the relative routing overhead between the two routing protocols becomes to be more distinct as the number of sources increases. Under heavy load, AODV-DF outperforms AODV. This is because AODV-DF uses directional flooding of RREQ packets unlike AODV. Therefore, AODV-DF can significantly reduce the routing overhead (by about 63 % at 60 sources) for traffic destined to the gateway.

Fig. 3(b) compares the throughput between AODV and AODV-DF. The routing overhead directly affects the total throughput of the network. This figure shows that at lower traffic load, observed throughput is similar, but as the number of sources increases, the total throughput of AODV-DF outperforms AODV significantly. Under heavy load (at 60 sources), compared with AODV, it is noted that AODV-DF can improve the throughput by 28%. This throughput enhancement of AODV-DF is due to the significant reduction of bandwidth wasted by RREQ packets in the route discovery.

Fig. 3(c) compares the average route length between AODV and AODV-DF. This figure shows that the average route length of AODV-DF is shorter than that of AODV. The reason is that the destination node in AODV and AODV-DF actually replies with RREP for the earliest arrived RREQ, not for the RREQ with the minimum hop. So, AODV tends to choose the least congested route in the whole network, thereby the chosen route in AODV



(a) (b)

(c) (d)

Fig. 3. Simulation results for the scenario 1: (a) Relative routing overhead, (b) total throughput, (c) average route length, and (d) average end-to-end delay.

may not be the minimum-hop path. But, AODV-DF has candidate paths to choose which are close to the minimum-hop path because AODV-DF floods RREQ packets directionally toward the gateway based on hop count.

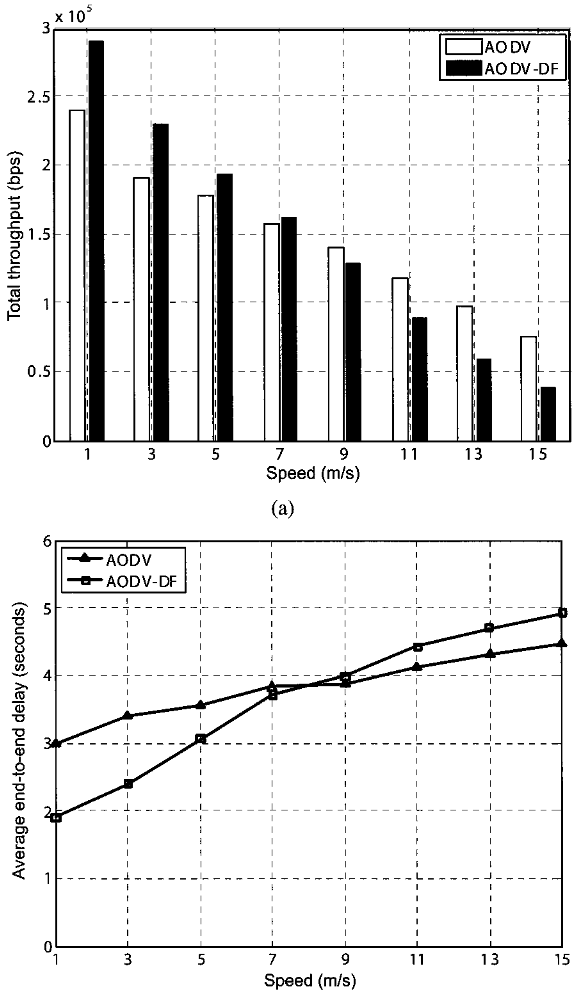
Fig. 3(d) compares the average end-to-end delay between AODV-DF and AODV-DF. As the number of sources increases, AODV-DF has better performance in the end-to-end delay than AODV due to the same reason in Fig. 3(c).

C.2 Scenario 2: Mesh Routers with Minimal Mobility

In this scenario, we investigate how mesh router's mobility affects the routing performance. We assume a random network topology with 60 mesh routers and that each mesh router has minimal mobility, in which the mesh routers move according to the random waypoint model. Maximum speeds of mesh routers are varied from 1 to 15 m/s. Mesh router starts its journey from a random location towards a randomly chosen destination. Upon arriving at the destination, the mesh router pauses again for 100 seconds, selects another destination, and repeats the previous procedure throughout the simulation. In this simulation, 50 sources randomly selected among 60 mesh routers generate traffic to a gateway.

In mobile environments, the interval of HELLO messages has a strong influence on the neighborhood management. A node detects a link to be broken if it does not receive HELLO messages from its neighbor node as its neighbor node moves away. In AODV-DF, the HELLO messages are also used to maintain the hop-count to the gateway. In our simulation, we assume that HELLO interval is 1 second both in AODV and AODV-DF.

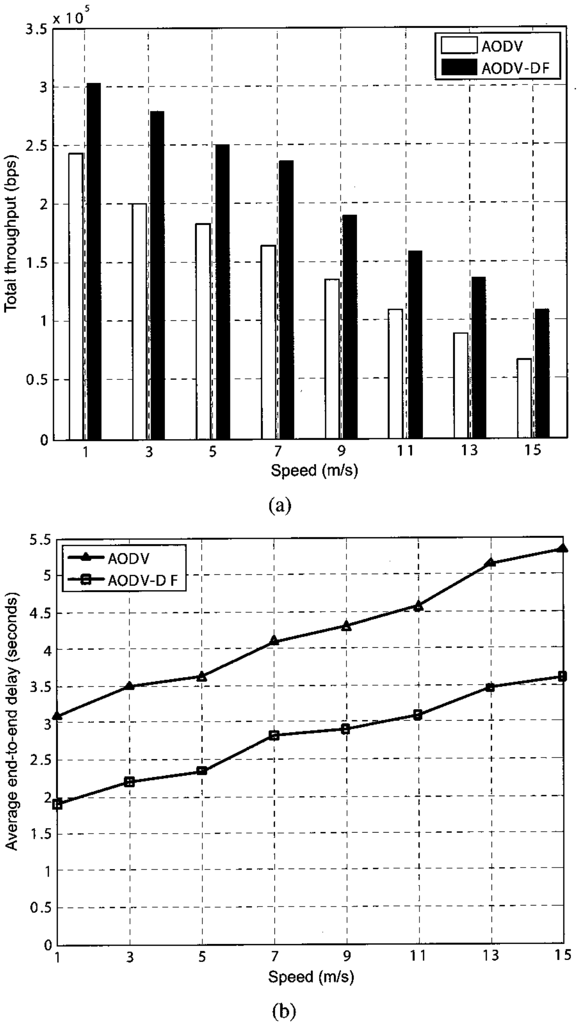
Fig. 4 shows the effect of node mobility on the routing performance by increasing the mobility of mesh routers. Fig. 4(a) compares the total throughput between AODV and AODV-DF and Fig. 4(b) shows how the node mobility affects the average end-to-end delay. These figures show that, as the moving speed of mesh routers increases, the throughput of the two routing protocols decreases, while their average end-to-end delay increases. As mesh routers move faster, route error occurs more often due to a link broken by topology changes, so it causes more routing control messages, resulting in more time in route discovery. This increased control messages waste more bandwidth, thereby the total throughput decreases. Also, the increased route discovery time directly affects the end-to-end packet delay. From these figures, we note that the routing performance of AODV-DF in the total throughput and the average end-to-end delay decreases more rapidly than AODV as the moving speed of mesh routers increases. The reason is that a wrong hop count value in AODV-DF due to topology changes by the movement of mesh routers can cause more routing overhead in route discovery than AODV.



(a)

(b)

Fig. 4. Simulation results for the scenario 2 (HELLO interval = 1 second): (a) Total throughput and (b) average end-to-end delay.



(a)

(b)

Fig. 5. Simulation results for the scenario 3: (a) Total throughput and (b) average end-to-end delay.

In AODV-DF, if a source does not receive RREP from the destination, then it broadcasts RREQ again as the same way with AODV.

But, from Fig. 4, we can see that the routing performance of AODV-DF is still better than that of AODV at a lower mobility such as pedestrian speeds (between 1 m/s and 3 m/s). However, at a higher mobility (moving speed > 9 m/s), AODV gives a better routing performance than AODV-DF. We note that the tradeoff of the routing performance between AODV and AODV-DF depends on node mobility and the interval of HELLO messages.

C.3 Scenario 3: Stationary Mesh Routers and Mesh Clients with Minimal Mobility

In this scenario, we investigate the effect of mesh client's mobility on the routing performance. We use a grid topology with 50 static mesh routers, in which 60 mesh clients are randomly distributed. We assume that mesh clients are mobile nodes, which move according to random waypoint model. Maximum speeds of mesh clients are varied from 1 to 15 m/s. The mesh client's mobility pattern is the same as the mesh router's mobility in the scenario 2. In this simulation, all 50 mesh clients generate traffic to a gateway.

Fig. 5 shows the effect of mesh client's mobility on the routing performance by increasing the mobility of mesh clients. Fig. 5(a) compares the total throughput between AODV and AODV-DF, and Fig. 5(b) shows how the client's mobility affects the average end-to-end delay. These figures show that, as the moving speed of mesh clients increases, the throughput of both routing protocols decrease, while their average end-to-end delay increase. The reason is that mesh routers more frequently discover the route again due to route errors caused by faster moving of mesh clients. However, we can see that AODV-DF outperforms AODV, even when mesh clients have some mobility.

V. CONCLUSION

In this paper, we proposed AODV-DF routing protocol for wireless mesh networks with limited mobility. The proposed AODV-DF uses the hop count to a gateway to limit the scope of rebroadcasts of route request packets during route discovery. Simulation results showed that AODV-DF could significantly reduce routing overhead by RREQ packets and enhance overall throughput compared with the original AODV. Even when mesh routers and clients have minimal mobility, we showed that AODV-DF could still enhance overall performance over AODV. Therefore, AODV-DF would be more suitable than original AODV for WMNs with most traffic destined to a gateway, in which mesh routers and clients are either stationary or semi-mobile. In our simulation, we considered a single gateway, but AODV-DF also can be applied for WMNs with multiple gateways.

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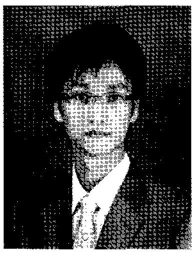
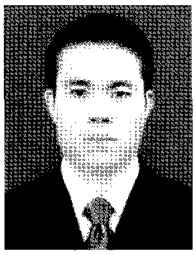
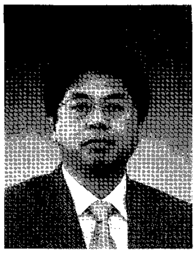


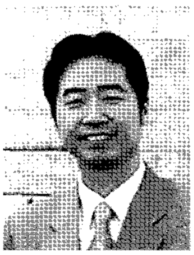
Dong-Won Kum received the B.S. degree from Woosong University in 2003, and the M.S. degree in School of Electrical Engineering and Computer Science, Kyungpook National University, Daegu, Korea. He is currently a Ph.D. student in School of Electrical Engineering and Computer Science, Kyungpook National University, Daegu, Korea. His current research interests include wireless mesh networks, vehicular ad hoc networks, and mobility management.



Anh-Ngoc Le received the B.S. degree in Mathematics from Vinh University in 1996, and the M.S. degree in Information Technology from Hanoi University of Technology, Vietnam, in 2001. He also received the Ph.D. degree in Information and Communication Engineering from Kyungpook National University, Korea, 2009. He is now a lecturer at Department of Technology Information, Vinh University, Vietnam. His current research interests include MAC protocols, routing protocols, mobility management for wireless, and mobile networks.



You-Ze Cho received the B.S. degree in electronics engineering from Seoul National University, Korea, in 1982, and the M.S. and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology, in 1985 and 1988, respectively. Since 1989, he has been with the Kyungpook National University, Korea, where he is currently a Professor of School of Electrical Engineering and Computer Science. From August 1992 to January 1994, he had been a visiting researcher at the University of Toronto, Canada. From March 2002 to February 2003, he had been a guest researcher at National Institute of Standards and Technology, USA. His research interests include mobility management and traffic engineering for wireless and mobile networks, broadband convergence networks, and the future Internet.



Chai-Keong Toh received his Ph.D. in Computer Science from Cambridge University (1996) and earlier EE degrees from Manchester University (1991) and Singapore Polytechnic (1986). He has been a visiting professor at Yale(USA), KTH(Sweden), KNU(Korea), and Osaka University (Japan). Since 2004, he has been an honorary full professor at the University of Hong Kong. Previously, he was a tenured Chair Professor at the University of London and Director of Research (Communication Systems) at TRW Tactical Systems Inc., United States. He has authored two books: "Ad Hoc Mobile Wireless Networks" (Prentice Hall, 2001) and "Wireless ATM Networks" (Kluwer, 1997). He is a Fellow of the British Computer Society (2002), New Zealand Computer Society (2003), Hong Kong Institution of Engineers (2004), and Institution of Electrical Engineers (2003). He is a recipient of the 2005 IEEE Institution Kiyo Tomiyasu Technical Field Award (for pioneering contributions to protocols in ad hoc mobile wireless networks). In 2009, he was named an IEEE Fellow.

In-Soo Lee received the B.S. and M.S. degrees from Kyungpook National University, Korea, in 1991 and in 1993, respectively. He is a Deputy Director in the Department of Network and service Quality Research at the Network R&D Laboratory of KT, Korea. Currently, his work focuses on measurement of QoS in IPTV and VoIP. He is currently studying for a Ph.D. degree at the School of Electrical Engineering and Computer Science, Kyungpook National University, Korea. His research interests include QoS routing and congestion control for wireless mesh networks.