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SINR-Based Multipath Routing for Wireless Ad Hoc Networks

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ABSTRACT

This paper proposes a multipath routing protocol called cross-layer multipath AODV (CM-AODV) for wireless ad hoc networks, which selects multiple routes on demand based on the signal-to-interference plus noise ratio (SINR) measured at the physical layer. Note that AODV (Ad hoc On-demand Distance Vector) is one of the most popular routing protocols for mobile ad hoc networks. Each time a route request (RREQ) message is forwarded hop by hop, each forwarding node updates the route quality which is defined as the minimum SINR of serialized links in a route and is contained in the RREQ header. While achieving robust packet delivery, the proposed CM-AODV is amenable to immediate implementation using existing technology by neither defining additional packet types nor increasing packet length. Compared to the conventional multipath version of AODV (which is called AOMDV), CM-AODV assigns the construction of multiple paths to the destination node and makes it algorithmically simple, resulting in the improved performance of packet delivery and the less overhead incurred at intermediate nodes. Our performance study shows that CM-AODV significantly outperforms AOMDV in terms of packet delivery ratio and average end-to-end delay, and results in less routing overhead.

Key words: Wireless ad hoc network, routing protocol, multipath routing, cross-layer design, route quality, SINR.

1. INTRODUCTION

A *mobile ad hoc network* (*MANET*) [2-4] is a collection of distributed mobile nodes without any fixed infrastructure (such as access points and base stations) or any form of centralized administration. Such a network can be effectively used in military battlefields, emergency disaster relief, and other emerging applications including dynamic wireless sensor networks. One of its most distinguished characteristics is that each node plays a router for multi-hop routing as well. Due to limited energy and bandwidth, there exist many challenging issues in wireless communication in MANETs.

At the physical layer in MANETs, interference (due to other nodes) and noise (due to communication environment) are two major obstacles in realizing their full potential capability in delivering the information. In wireless links, the signal propagation is affected by path loss, shadowing and multi-path fading, and dynamic interferences generate additional noise from time to time. In this study, as an approach to the cross-layer design of a multipath routing protocol, the *signal-to-interference plus noise ratio* (*SINR*) measured at the

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physical layer is taken into consideration. Note that SINR is measurable with no additional support at the physical layer at the receiver [5, 6] and it is more realistic than the so-called received signal strength indicator (RSSI). Furthermore, as nodes are fast moving, poor links are unpredictably increased and thus SINR-based decision is very useful to make the discovered route more robust. It is addressed in [7] that the communication quality of MANETs is low and users can experience fluctuation in link quality in practical operation environments. As a result, it is highly desirable to include as many strong links as possible in a route.

The network topology in MANETs may keep changing dynamically due to node mobility and link unstability, and thus *routing protocols* to find a multihop path from a source to a destination are more complicated than those of wired and cellular networks. For robust delivery of packets, *multipath routing* [8] is very important because the routes in MANETs are easily fragile. The motivation of this study is to design a cross-layer multipath routing protocol based on AODV for more robust communication resulting in higher performance. The AODV (Ad hoc On-demand Distance Vector) protocol, which was issued as RFC (Request For Comments) [9] by the IETF MANET working group [4], is one of the most popular routing protocols for MANETs. Like other MANET routing protocols, AODV also has unstable routing paths which are dynamically changed and frequently broken due to mobile nodes and noisy environment. To incorporate multipath routing to AODV, the ad hoc on-demand multipath distance vector routing (AOMDV) protocol [10-12] was proposed, in which multiple paths are guaranteed to be link-disjoint. On the other hand, DSR (Dynamic Source Routing)-based multipath routing protocols [13-15] were studied, which explores the source routing information included in route request (RREQ) packets in DSR in order to find multiple paths. In recent years, cross-layer design for efficient routing has been an active research area as summarized in [16] and a cross-layer approach to multipath routing [17] was introduced by piggybacking end-to-end acknowledgements onto MAC layer control packets.

In this paper, a multipath routing protocol called *cross-layer multipath AODV* (*CM-AODV*), which selects multiple routes on demand based on the *SINR* measured at the physical layer. Each time a RREQ message is forwarded hop by hop, the *route quality*, which is defined as the minimum SINR of serialized links in a route and is contained in the RREQ header, is updated by each forwarding node. The major contributions of this paper are two-fold:

- First, CM-AODV enables *robust packet delivery* but it is amenable to immediate implementation using existing technology by neither defining additional packet types nor increasing packet length. The eight bits out of 11 reserved or unused bits in RREQ are used for informing of the route quality to the next downstream node. Data and other control packets in CM-AODV are the same as in the basic AODV.
- Second, thanks to more robust routes and less overhead, CM-AODV achieves *higher performance* compared to AOMDV as well as the basic AODV. Unlike AOMDV, CM-AODV makes the destination node determine the primary and alternative paths, reducing the overhead incurred at intermediate nodes and making the construction of multiple paths algorithmically simple.

According to the simulation results, the proposed CM-AODV significantly outperforms AOMDV as well as AODV in terms of packet delivery ratio and average end-to-end delay, while inducing less routing overhead compared to AOMDV. It is also shown that the performance improvement is much better in harsh operation environments such as high node mobility and heavy load.

The rest of the paper is organized as follows:

In the following section, the AODV and AOMDV protocols are briefly reviewed. In Section III, the proposed CM-AODV protocol is presented; *i.e.*, route quality, cross-layer design, route discovery, data transmission and route maintenance are discussed in detail. In Section IV, the packet reception model, simulation environment and results are discussed. Finally, the conclusions and future works are covered in Section V.

2. PRELIMINARIES

This section briefly classifies MANET routing protocols in a broadly accepted manner first, and then overviews the AODV and AOMDV protocols in terms of operational characteristics and inherent features. Multipath routing mechanism in AOMDV is summarized as well.

2.1 Brief Classification of Routing Protocols

The routing protocols in MANETs can be roughly classified into two categories: *table-driven* (also called *proactive*) protocols and *on-demand* (also called *reactive*) protocols. The table-driven protocols try to continuously keep up-to-date routes between any node pairs in the network [18, 19]. That is, a node may have available routes to any other nodes at any time even if it may never use the routes to some destinations. The destination sequenced distance vector routing (DSDV) [20] and the cluster-head gateway switch routing (CGSR) [21] are examples of the table-driven protocols. On the contrary, the on-demand protocols only maintain the currently used routes between node pairs [18, 19]. The route is created only when a source needs to send data packets to a destination. The control overhead of route updates in on-demand protocols is far less than that in table-driven protocols. The dynamic source routing (DSR) [22, 23] and the ad hoc on-demand distance vector routing (AODV) [9, 24-26] belong to the on-demand protocols. Hybrid routing protocols are a combination of table-driven and on-demand protocols [19]. The zone routing protocol (ZRP) [27] is an example of hybrid routing protocols.

2.2 AODV Protocol

The AODV protocol [9, 24-26] is an on-demand routing protocol based on the DSDV protocol [20]. The main characteristics of AODV is to use the periodic beaconing and sequence numbering procedure of DSDV and a flooding-based route discovery procedure as in DSR [22, 23]. As described in Introduction, AODV was issued as RFC [9] by the IETF MANET working group [4] and it is one of the most popular routing protocols for MANETs.

In AODV, route discovery works as follows. Whenever a source node needs a route to a destination, it initiates a route discovery by flooding an RREQ for the destination in the network and then waits for a route reply (RREP) message. When an intermediate node receives the first copy of an RREQ, it sets up a reverse path to the source using the previous hop of RREQ as the next hop on the reverse path. In addition, if there is a valid route available for the destination, it unicasts an RREP back to the source node via the reverse path; otherwise, it rebroadcasts RREQ. Duplicate copies of RREQ are immediately discarded upon reception at every node. The destination node on receiving the first copy of an RREQ forms a reverse path in the same way as intermediate nodes, and it also unicasts an RREP back to the source along the reverse path. As RREP proceeds towards the source, it establishes a forward path to the destination at each hop. Note here that the destination node generates RREPs only when its destination sequence number is grater than or equal to the destination sequence number of the RREQ received.

Route maintenance is done by means of route error (RERR) messages. When an intermediate node detects a link breakage (*e.g.*, via a link-layer feedback), it generates an RERR. RERR propagates towards all sources having a route via the failed link, and erases all broken routes on the way. A source upon receiving RERR initiates a new route discovery if it still needs the route. Apart from this route maintenance mechanism, AODV also has a timer-based mechanism to purge stale routes.

2.3 AOMDV Protocol

The AOMDV protocol [10-12] is a multipath routing protocol based on AODV. The protocol guarantees loop freedom and link-disjointness of alternate paths. Loop freedom is guaranteed by using a notion of advertised hop count. Link-disjointness of multiple paths is achieved by using the property of flooding. Note here that the link-disjointness means that there is no joint link of multiple paths. AOMDV makes use of AODV control packets with a few extra fields in the packet headers, resulting in additional overhead required for the computation of multiple paths.

As in AODV, when a source node needs a route to a destination, the source initiates a route discovery process by generating an RREQ. Some duplicate copies of RREQ can be gainfully used to form alternate reverse paths and, thus, all duplicate copies are examined in AOMDV for potential alternate reverse paths. Reverse paths are formed only using those copies that preserve loop-freedom and link-disjointness among the resulting set of paths to the source. When an intermediate node obtains a reverse path via an RREQ copy, it checks whether there are one or more valid forward paths to the destination. If so, the node generates an RREP and sends it back to the source along the reverse path; otherwise, the node re-broadcasts the RREQ copy if it has not previously forwarded any other copy for this RREQ. Note that a copy of RREQ arriving at a node may or may not form a new reverse path. When the destination node receives RREQ copies, it also forms reverse paths in the same way as intermediate nodes. The destination generates an RREP in response to every RREQ copy that arrives via a loop-free path to the source, even though it forms reverse paths using only RREQ copies that arrive via loop-free and link-disjoint alternate paths to the source. When an intermediate node receives an RREP, it follows route update rules in AOMDV routing to form a loop-free and link-disjoint forward path to the destination, if possible; otherwise, RREP is dropped. Supposing that the intermediate node forms the forward path and has one or more valid reverse paths to the source, it checks if any of those reverse paths was not previously used to send an RREP for this route discovery.

Route maintenance in AOMDV is a little different from that in AODV. When an intermediate node detects a link error, it re-forwards the packet along another path if any; otherwise, it generates an RERR. RERR propagates towards all sources having a route via the failed link, and erases all broken routes on the way. A source upon receiving RERR checks whether there are one or more valid forward paths to the destination. If so, the source uses one of them for data packet transmission; otherwise, the source initiates a new route discovery if it still needs the route. AOMDV also has a timer-based mechanism to purge stale routes.

3. CROSS-LAYER MULTIPATH AODV (CM-AODV)

In this section, a multipath routing protocol called *cross-layer multipath AODV* (*CM-AODV*), which selects multiple routes on demand based on the *SINR* measured at the physical layer, is presented. We first define the route quality and present the impact of the SINR measured at the physical layer on the serialized links in a route. Next, the cross-layer route discovery algorithm with SINR-based route selection in CM-AODV is presented. We then discuss the data packet transmission along with the discovered route and the route maintenance mechanism against link breakage. Note here that the link breakage is mainly due to node failure, node mobility, interference, and noise.

3.1 Route Quality

The *route request* (*RREQ*) packet transmitted during route discovery in MANETs is a broadcast packet. In most MAC protocols such as IEEE 802.11 MAC [28], *broadcast packets* are transmitted at the base data rate of 1 Mbps. Given radio hardware and transmit power, the transmission range is affected by the transmit rate. If a distant node receiving an RREQ rebroadcasts the RREQ, a long weak link with low data rate can be included in the discovered route. Intuitively, this helps the routing protocol to find out the *minimum hop-count route* from source to destination. However, such a long link is relatively weak and unreliable and increases the possibility that it is broken. Moreover, the minimum hop-count route does not mean the best route as measured in [29,30]. In addition, any link-disjoint route does not always mean a good route with respect to route lifetime and network performance because it may include long and weak links. This will be verified through performance evaluation in Section IV.

As described in Section I, SINR can be used as the effective link metric because it is more realistic than the so-called received signal strength indicator (RSSI) and it is measurable with no additional support at the physical layer at the receiver [5, 6]. A route consists of serialized or chained links and, as a result, the route is broken if any one of the links fails. Taking this effect into consideration, in this paper, we define *route quality* as follows:

Definition 1. Given an l-hop route $R = \langle n_0, n_1, \cdots, n_l \rangle$ in a MANET, the *route quality* of R is defined by $Q_R = \min_{0 \le i \le l-1} \mathrm{SINR}(n_i, n_{i+1})$, where n_i and n_{i+1} are adjacent nodes in R and $\mathrm{SINR}(n_i, n_{i+1})$ is SINR of a link $\langle n_i, n_{i+1} \rangle$ for $0 \le i \le l - 1$.

Fig. 1 shows two routes between source s and destination d, in which the SINR of each link is shown in dB. By Definition 1, the route $R_1 = \langle s, a, d \rangle$ has the route quality of 10 dB while the route $R_2 = \langle s, b, c, d \rangle$ has the route quality of 13 dB. As a result, R_2 is stronger than R_1 in terms of route quality and, thus, R_2 ensures more robust *end-to-end delivery* of packets than R_1. Therefore, the SINR-based route selection can significantly improve the reliability of routes resulting in robust communication.

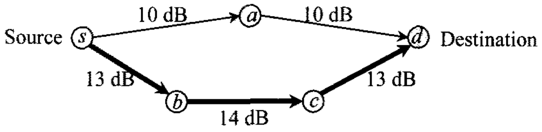

Fig. 1. Two routes with different route quality between source and destination.

3.2 Cross-Layer Discovery of Multiple Routes with SINR-Based Selection

In order to exploit multiple robust routes, CM-AODV newly defines an 8-bit field of route quality in the first four bytes of the RREQ header as shown in Fig. 2. Note that all the other fields except the 'Route Quality'field in Fig. 2 have the same convention and meaning as defined in the basic AODV [9]. The eight bits in the RREQ message are originally reserved or unused in AODV, but they are effectively utilized in CM-AODV to carry the route quality to the destination node that determines the primary and alternative paths from multiple RREQs received. In other words, out of 11 reserved or unused bits in the conventional RREQ format, the eight bits are newly defined as the 'Route Quality' field as in Fig. 2. When a node n_j receives an RREQ, it compares the measured link quality $\mathrm{SINR}(n_{j-1}, n_j)$ with the route quality $\min_{0 \le i \le j-2} \mathrm{SINR}(n_i, n_{i+1})$ contained in the received RREQ. If $\mathrm{SINR}(n_{j-1}, n_j)$ is lower than $\min_{0 \le i \le j-2} \mathrm{SINR}(n_i, n_{i+1})$, the link quality $\mathrm{SINR}(n_{j-1}, n_j)$ is forwarded as the route quality of $\min_{0 \le i \le j-1} \mathrm{SINR}(n_i, n_{i+1})$ in accordance with Definition 1. This update operation of the route quality in conjunction with RREQ forwarding

Bits: 8	1	1	1	1	1	3	8	8
Type	J	R	G	D	U	Reserved	Route Quality	Hop Count

Fig. 2. The first four bytes of RREQ in CM-AODV containing the newly defined 'Route Quality' field.

makes the destination node know the route quality of received RREQs.

The *route discovery process* in CM-AODV is similar to that in the basic AODV except for that the route quality field is defined and updated during RREQ forwarding and multiple RREQs are received by the destination node. When a source node needs a route to a destination node, the source node initiates a route discovery process by broadcasting an RREQ. Since RREQ is flooded network-wide, a node may receive several copies of the same RREQ. After receiving the first RREQ, an intermediate node receives and collects subsequent RREQ copies for the predetermined time period (*i.e.,* RREQ_WAIT_TIME_INT of 30 *msec*[1]). It then updates the route quality fields of the received RREQs and forwards the RREQ copy with the highest route quality by re- broadcasting it. Any RREQ copies arrived after the predetermined time period are discarded immediately. In the basic AODV, only the first copy of RREQ is used and the duplicate copies are simply discarded. In CM-AODV, however, the copy with the highest route quality is selected among the multiple RREQ copies received and it is then forwarded to find out more robust paths. As a result, the proposed *RREQ forwarding strategy* is algorithmically simple and helps the destination node select reliable routes with the highest route quality.

Fig. 3 shows an example of the SINR-based route discovery in CM-AODV. At node 5, two route <*s*, 1, 5> and <*s*, 7, 5> have the same route quality of 11 dB and thus tie break is necessary. In case of tie in the route quality, the first arrived RREQ (the traversed path of which can be regarded as the minimum hop-count route) is selected and forwarded. In Fig. 3, the path <*s*, 1, 5> is chosen. At node 9, the RREQ come from node 8 is selected and forwarded because its route quality is 10 dB while the route quality of the RREQ come from node 5 is 9 dB. The same *RREQ forwarding strategy* is used in other intermediate nodes: Node 3 selects the RREQ come from node 2 rather than from node 5 because the route quality of the former is 2 dB higher than that of the latter. Similarly, node 4 selects the RREQ come from node 3.

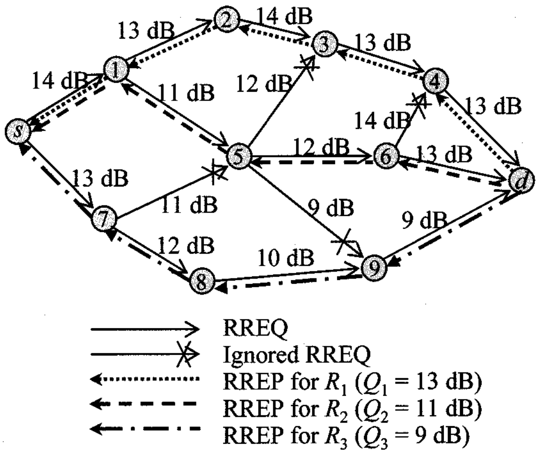

Fig. 3. Discovery of multiple routes with SINR-based selection in CM-AODV.

Similar to the intermediate nodes, the destination node receives and collects subsequent RREQ copies for the predetermined time period (*i.e.,* RREQ_WAIT_TIME_DST of 300 *msec*[2]) after receiving

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1) In the RFC of AODV [14], ACTIVE_ROUTE_TIMEOUT of 3,000 *msec* is typically used by default. Here, we set RREQ_WAIT_TIME_INT as one hundredth of ACTIVE_ROUTE_TIMEOUT, but it may be adjusted to reflect network size and dynamics.

2) RREQ_WAIT_TIME_DST is set as one tenth of ACTIVE_ROUTE_TIMEOUT, but it may be adjusted to reflect network size and dynamics as in

the first RREQ. Note here that each RREQ received by the destination node corresponds to a possible route. Let $S = \{R_1, R_2, \cdots, R_k\}$ be the set of k possible routes (corresponding to k RREQs received by the destination node d), where the i-th received route R_i contains its route quality Q_i. The destination node sorts S in the non-increasing order of route quality. In case of tie, the tied routes are automatically sorted in the order of arrival at d because they are initially ordered on the basis of first-come first-served. In Fig. 3, the destination node d receives three RREQ copies from nodes 4, 6 and 9, which are then labeled R_1, R_2 and R_3after sorted, respectively. That is, the three possible routes are R_1 = <s, 1, 2, 3, 4, d>, R_2 = <s, 1, 5, 6, d> and R_3 = <s, 7, 8, 9, d> and they have the route quality of Q_1 = 13 dB, Q_2 = 11 dB and Q_3 = 9 dB, respectively. The destination node sends RREPs back toward the source node in the sorted order as shown by different dotted lines in Fig. 3. The *multipath degree*[3] (or simply *degree*) can be controlled by limiting the number of RREPs according to the network environment and requirement. In practice, the multipath degree is usually set as 2 because the third and following routes can be easily failed if the first and second routes (which are stronger than the third and following ones) have been already failed. Loop freedom is guaranteed as in AOMDV [10-12].

3.3 Data Packet Transmission and Route Maintenance

Basically, the data packet transmission and route maintenance in the CM-AODV protocol are carried out in the same way as in the basic AODV protocol except for using multiple routes. As multiple RREPs travel back to the source node from the destination node along with their reverse paths, the source node updates its routing information for the multiple routes and it may begin data packet transmission. Normally, the primary path (R_1 in Section 3.2) is used for data packet transmission until it is unavailable due to link breakage. When the primary path is unavailable, the next one of the alternate paths (R_2 in Section 3.2) is immediately used for data packet transmission. If all the alternate paths are unavailable, the route discovery procedure is invoked again to find out new paths.

The link breakage may break routing paths in use. In particular, the network links are more likely to be broken due to node mobility in MANETs. When such a link breakage occurs, the upstream node of the broken link (*i.e.*, the next node forward the source node) invalidates all destinations that become unreachable due to the link breakage in its routing table. Then, it creates an RERR, in which it lists each of these lost destinations, and sends it back to the upstream node towards the source node. If there are multiple previous hops (so-called *precursors* in AODV) that were utilizing this link, the node broadcasts RERR. Once the source node receives RERR, it can re-initiate route discovery if it still requires a route.

Table 1 summarizes the step-by-step operations of the source, intermediate and destination nodes for the route discovery, packet transmission, and route maintenance in the proposed CM-AODV protocol.

4. PERFORMANCE EVALUATION

In this section, the performance of the proposed CM-AODV protocol is evaluated and compared with AOMDV as well as AODV. The packet reception model is presented first, and then the simulation environment is described and the simulation results are discussed with comparison.

4.1 Packet Reception Model

The packet reception model implemented in *ns*-2

RREQ_ WAIT_TIME_INT. It is ten times longer than RREQ_ WAIT_TIME_INT.

[3] In this paper, it is defined as the maximum number of routes for a source-destination pair.

Table 1. Routing operations at the three kinds of nodes in CM-AODV.

	Source node	**Intermediate node**	**Destination node**
Route Discovery (RREQ)	1. If there is no valid route to use for the destination, broadcast RREQ.	2. Receiving RREQs for the predetermined time period after the first RREQ, rebroadcast the RREQ with the highest route quality.	3. Receiving RREQs for the predetermined time period after the first RREQ, sort the routes in the non-increasing order of route quality.
Route Discovery (RREP)	6. Receiving RREPs, update the routing table.	5. Receiving an RREP, update the routing table and forward the RREP toward the source.	4. Send RREPs back toward the source in the sorted order.
Data packet transmission	1. Send data packets for the destination via the route retrieved in the routing table.	2. Receiving a data packet, forward it toward the destination according to the routing table.	3. Receive the data packets, and acknowledge back to the source (if required).
Route Maintenance (RERR)	2. Receiving an RERR, if there is an alternative path, use it; otherwise, broadcast RREQ for new route discovery.	1. Detecting any link error on a route or receiving an RERR, send the RERR toward the source.	N/A

[31,32] is based on three fixed thresholds, *i.e., carrier sense threshold* (CSThresh), *receive threshold* (RxThresh) and *capture threshold* (CPThresh). When a frame is received, each node in the proximity calculates the received signal power based on two-ray ground reflection model and compares it against CSThresh and RxThresh. If it is smaller than CSThresh, the receiver ignores the signal. If it is in between the two thresholds, the receiver considers the medium busy but do not attempt to decode the signal. If it is higher than RXThresh,the receiver attempts to receive the frame. However, when the node receives another signal during receiving the first signal, their ratio is compared against CPThresh. If one of them is much stronger, it captures the other; otherwise, both frames fail.

Here, we describe how SINR is calculated in *ns*-2 [31,32]. While the receiver receives one frame, other frames may arrive at the receiver resulting in interference. As a result, SINR of the receiving frame is calculated by $SINR = \frac{P_r}{\sum_{i \neq r} P_i + N}$, where P_r is the received power (signal strength) of the frame, P_i denotes the individual received power of other frames received by the receiver simultaneously, and N is the effective noise at the receiver. There are two components in the above equation - received power and noise plus interference.

The received power at the receiver (P_r) is calculated according to the propagation model. In the *two-ray ground reflection* model, it is represented by $P_r(d) = \frac{P_t G_t G_r h_h^2 h_r^2}{d^4 L}$ at distance d if $d \geq d_c$, where P_t is transmitted signal power, G_t and G_r are antenna gain of the transmitter and receiver, respectively, L is system loss, λ is wave length, h_t is the height of the transmitter, and h_r is the height of the receiver. Here, d_c is the cross-over distance calculated by $d_c = (4\pi h_t h_r)/\lambda$. If $d < d_c$, $P_r(d)$ is the same as in the *free space* model, which is given by $P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$. On the other hand, interference is the received signal power calculated as described above for other frames received by the receiver simultaneously.

Noise contains the noise generated by the receiver and the one come from environment. The effective noise level generated by the receiver can be obtained by adding up the noise figure of a network interface card (NIC) onto the thermal noise [33]. We first compute the thermal noise level within the channel bandwidth of 22 MHz in the

IEEE 802.11 standard [28]. This bandwidth is 73 dB above -174 dBm/Hz, or -101 dBm. Assuming a system noise figure of 6 dB as in [33], the effective noise level generated by the receiver is -95 dBm. For simplicity, the environment noise or channel noise is assumed to be fixed -88 dBm throughout the simulation.

4.2 Simulation Environment

In our simulation study, *ns*-2 [31, 32] is used. It is assumed that mobile nodes move over a square area of 600 ×800 m^2. A *two-ray ground reflection* channel with the radio transmission range of 250 *m* is assumed. With a data transmission rate of 2 Mbps, each run has been executed for 1000 *sec* of simulation time. The CBR source is assumed and the data payload of the packets is 512 bytes long. Mobile nodes are assumed to move randomly according to the *random waypoint model* [34], where two parameters of maximum node speed and pause time determine the mobility pattern of the mobile nodes. Each node starts its journey from a randomly selected location to a target location, which is also selected randomly in the simulation area, at a randomly chosen speed (uniformly distributed between 0 and maximum speed). The maximum speed is set from 5 to 60 *m/sec*. (The maximum speed of 60 m/sec corresponds to 216 km/hr which is taken into consideration for vehicular ad hoc networks.) When a node reaches the target location, it stays there during the pause time (30 *sec* in our simulation) and then repeats the mobility behavior. In the simulation environment, the link breakage is due to node mobility, interference, and noise.

In our simulation study, the following four performance metrics are extensively evaluated:

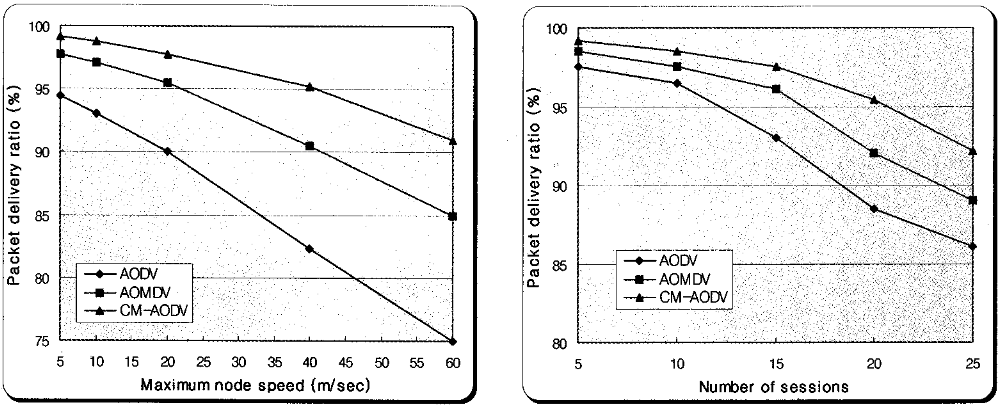
- *Packet delivery ratio* - the ratio of the number of data packets successfully delivered to the destination over the number of data packets sent by the source,
- *Average end-to-end delay* - the averaged end-to-end data packet delay including all possible delays caused by buffering during route discovery, queuing delay at the interface, retransmission delays at the MAC, propagation and transfer times, and the path change time (when the path is changed from the primary path to alternative one),
- *Routing overhead* - the total number of routing packets (*i.e.,* hello, RREQ, RREP and RERR) transmitted per second, where each hop-wise transmission of a routing packet is counted as one transmission, and
- *Path change frequency* - the aggregate number of path changes from the primary path to alternative one done by all sources per second.

Note here that the end-to-end delay is highly variable due to the randomness of source-destination distance and, thus, the average end-to-end delay is used. To measure the abovementioned performance metrics, four simulation factors of node speed, the number of sessions, packet rate and the number of nodes are varied; *i.e.,* the maximum node speed of 5~60 *m/sec*, the number of sessions from 5 to 25, the packet rate of 1~5 packets/sec, and the number of nodes from 10 to 100 are applied. While one simulation factor is varied during a simulation, the others are fixed: the maximum node speed of 20 *m/sec*, the number of sessions of 10, the packet rate of 4 packets/sec, and the number of nodes of 50. Note that the number of sessions is also called the number of connections and the number of nodes represents the node density for a given network area.

4.3 Simulation Results and Discussion

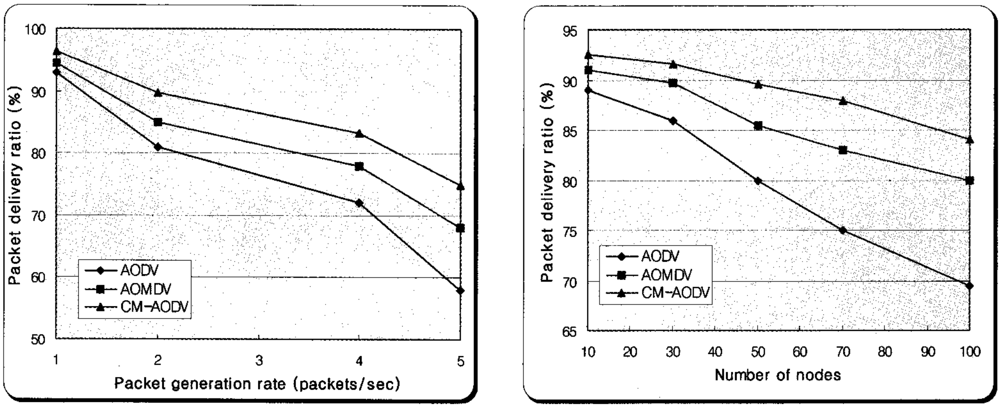
In this subsection, the simulation results of CM-AODV are discussed and compared with those of the conventional protocols with respect to the four performance metrics.

Fig. 4 shows the packet delivery ratio of AODV,



(a) Varying maximum node speed

(b) Varying the number of sessions



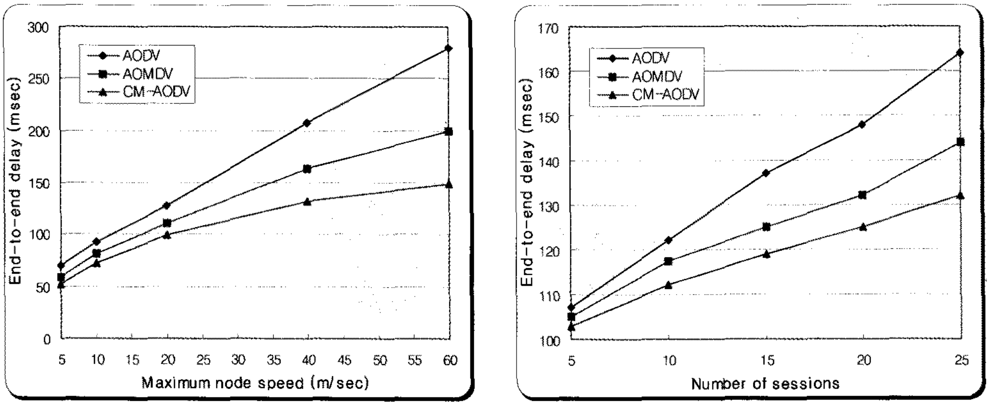
(c) Varying packet rate

(d) Varying the number of nodes

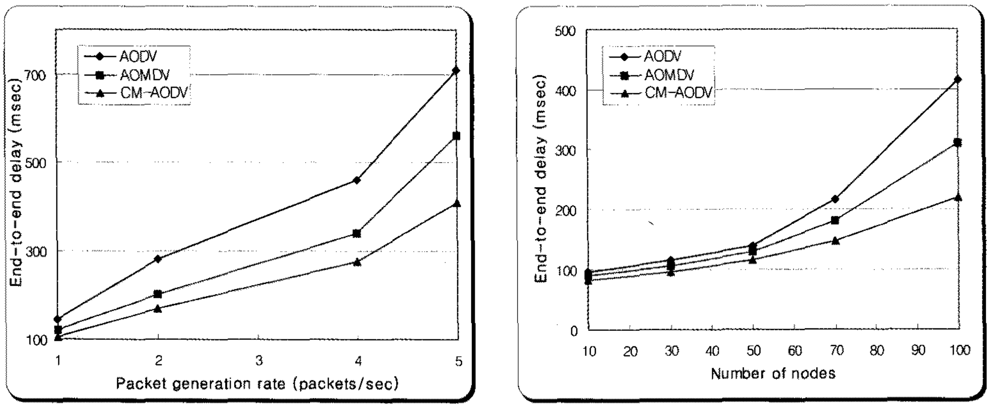
Fig. 4. Packet delivery ratio.

AOMDV and CM-AODV. Compared to AOMDV, the proposed CM-AODV represents higher packet delivery ratio by reducing packet loss by up to 70 percent. The significant reduction of packet loss in CM-AODV is thanks to more reliable routes and less overhead as explained in Introduction and Section 3.2. As expected, the multipath routing protocols(AOMDV and CM-AODV) always outperforms the unipath routing protocol (AODV) for all the four simulation factors. As the simulation factors increase, the packet delivery ratio is decreased for all the three protocols but the gap becomes larger and larger. It is mainly due to the fact that not only the higher node mobility induces more frequent link breakage (resulting in more packets dropped) but also the larger number of connections, heavier offered load and higher node density increase the probability of link breakage (causing more traffic and interference). That is, CM-AODV is much more robust than AOMDV in harsh operation environments.

Fig. 5 shows the average end-to-end packet delay of the three protocols under evaluation. CM-AODV represents shorter end-to-end delay than AOMDV by up to 30 percent. Furthermore, the improvement becomes much better as the four varying factors increase. As a matter of course, the multipath routing protocols (AOMDV and CM-AODV) have shorter delay than the basic AODV. Even though the waiting times of RREQ_WAIT_TIME_INT and RREQ_WAIT_TIME_DST are applied in CM-AODV as explained in Section 3.2, the



(a) Varying maximum node speed (b) Varying the number of sessions

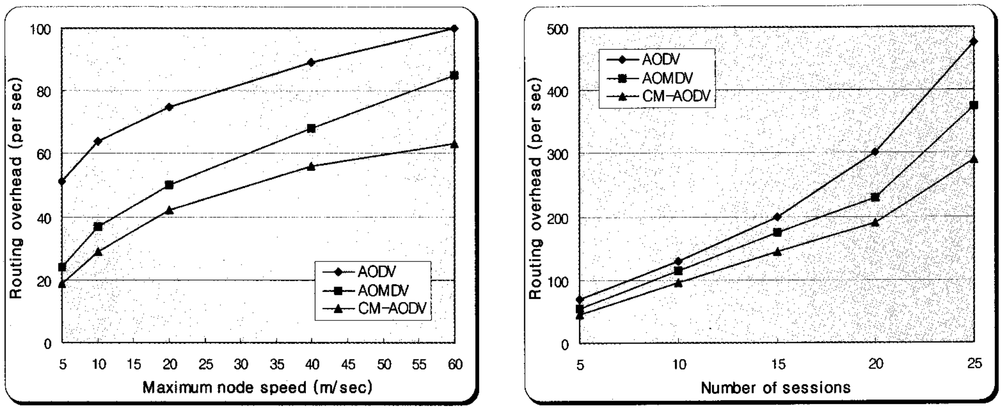


(c) Varying packet rate (d) Varying the number of nodes

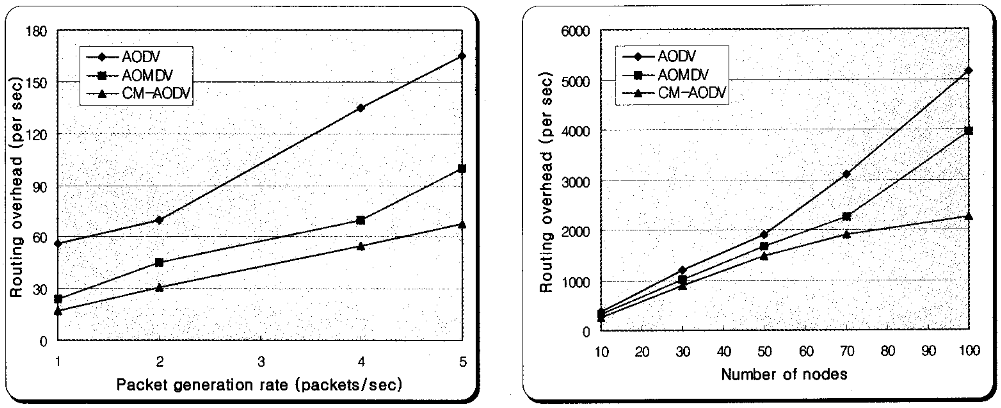
Fig. 5. Average end-to-end delay.

average end-to-end delay is improved compared to AOMDV. This is mainly due to more robust routes and less route discoveries, which minimize the potential possibility of link breakage. Note that the more reliable routes in CM-AODV significantly reduce the number of route discoveries and retransmissions. For all the three protocols, the average end-to-end packet delay is increased as the simulation factors increase.

Fig. 6 shows the routing overhead of the three protocols under evaluation. Note again that, in this paper, the routing overhead is defined as the total number of routing packets (*i.e.,* hello, RREQ, RREP and RERR) transmitted per second. Each hop-wise transmission of a routing packet is counted as one transmission. For all the four simulation factors, the multipath routing protocols (AOMDV and CM-AODV) have smaller routing overhead than the basic AODV. Compared to AOMDV, CM-AODV reduces the routing overhead by up to 45 percent. Furthermore, the gap becomes much larger as the four factors increase. In other words, it is easily inferred that CM-AODV has much smaller overhead than AOMDV in harsh operation environments. The improvement is mainly because the more reliable routes significantly reduce the possibility of route failure. As shown in Fig. 6(a) and 6(d), the routing overhead is very slowly increased as the node speed or the node density increases compared to the conventional protocols. That is, the reliable routes in CM-AODV are much more effective at high mobility and high node



(a) Varying maximum node speed (b) Varying the number of sessions



(c) Varying packet rate (d) Varying the number of nodes

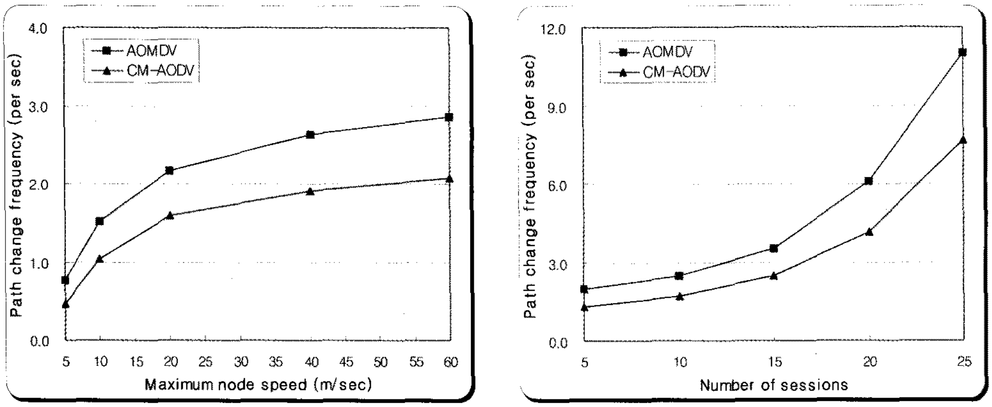
Fig. 6. Routing overhead.

density. As the two simulation factors increase, the routing overhead is also increased for all the three protocols since the operational environment is worse. In addition, it is observed in the given simulation setting that CM-AODV is robust and has a little less overhead even when the node mobility is relatively low.

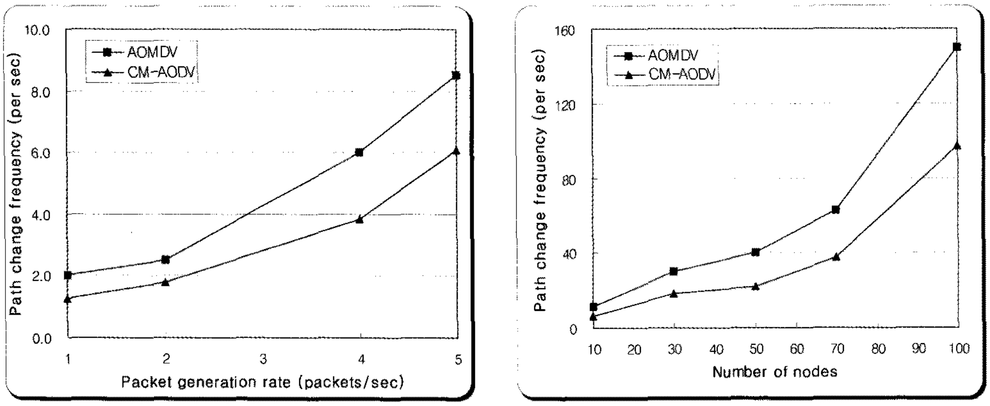
Fig. 7 shows the path change frequency of AOMDV and CM-AODV. Obviously, the path change is a negative effect in routing because it occurs when the path (or route) is broken. In all the simulated cases, the proposed CM-AODV outperforms AOMDV by reducing the path changes by up to 50 percent. The reduction of the negative effect is larger and larger as the simulation factors increase. As the four simulation factors increase, path change frequency is also increased for both protocols. Notice here that higher node mobility induces more frequent link breakages resulting in more route changes. Similarly, more sessions, heavier load and higher node density increase the possibility of link breakage requiring change of routing paths.

V. CONCLUSIONS

A multipath routing protocol called *cross-layer multipath AODV* (*CM-AODV*) has been proposed, which selects multiple routes on demand based on the *signal-to-interference plus noise* (*SINR*) measured at the physical layer. The construction of multiple reliable paths in CM-AODV is achieved



(a) Varying maximum node speed (b) Varying the number of sessions



(c) Varying packet rate (d) Varying the number of nodes

Fig. 7. Path change frequency.

by keeping track of the route quality of the paths that RREQ messages traverse. While achieving *robust packet delivery*, the proposed CM-AODV is amenable to immediate implementation using existing technology by neither defining additional packet types nor increasing packet length. Unlike the conventional approach, CM-AODV assigns the construction of multiple paths to the destination node and makes it algorithmically simple, resulting in the improved performance of packet delivery and the less overhead. According to the simulation results, CM-AODV significantly outperforms AOMDV in terms of packet delivery ratio and average end-to-end delay, but results in less routing overhead. It is also shown that the performance improvement is much better in harsh operation environments such as high node mobility and heavy load.

A limitation of the proposed scheme is that sort-term fluctuation in link quality in extremely dynamic environments makes the SINR-based selection less effective. This may be serious for a long route. Although it is not a common case, to find a solution is our future work. Another possible future work is to apply the proposed CM-AODV scheme to other routing protocols for MANETs in order to provide more robust and scalable routing paths. To extend the CM-AODV principle to the hierarchical routing protocols is another future work. Our future work includes the exploration of a new multipath routing protocol for MANETs with asymmetric links as well, which should be a very challenging work.

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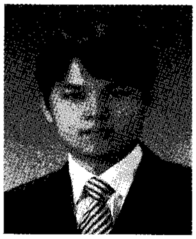

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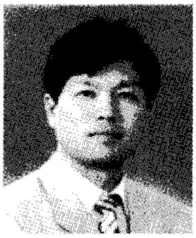

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