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PAPER

3DMRP: 3-Directional Zone-Disjoint Multipath Routing Protocol

Dongseung SHIN[†a)], ***Nonmember and*** **Dongkyun KIM**[††b)], ***Member***

SUMMARY In static wireless ad hoc networks such as wireless mesh networks and wireless sensor networks, multipath routing techniques are very useful for improving end-to-end delay, throughput, and load balancing, as compared to single-path routing techniques. When determining multiple paths, however, multipath routing protocols should address the well-known route coupling problem that results from a geographic proximity of adjacent routes and that hampers performance gain. Although a lot of multipath routing protocols have been proposed, most of them focused on obtaining node or link-disjoint multipaths. In order to address the route coupling problem, some multipath routing protocols utilizing zone-disjointness property were proposed. However, they suffer from an overhead of control traffic or require additional equipment such as directional antenna. This paper therefore proposes a novel multipath routing protocol, based on geographical information with low overhead, called 3-directional zone-disjoint multipath routing protocol (3DMRP). 3DMRP searches up to three zone-disjoint paths by using two techniques: 1) greedy forwarding, and 2) RREP-overhearing. One primary and two secondary paths are obtained via greedy forwarding in order to reduce control overhead, and these secondary paths are found by avoiding the RREP overhearing zone created during the primary path acquisition. In particular, two versions of 3DMRP are introduced in order to avoid the RREQ-overhearing zone. Through ns-2 simulations, 3DMRP is evaluated to verify that it achieves performance improvements in terms of throughput and control overhead.
key words: *zone-disjoint, multipath routing, route coupling, 3DMRP*

1. Introduction

In static wireless ad hoc networks, which wireless mesh networks and wireless sensor networks belong to, nodes communicate wirelessly in a multi-hop manner and are positioned at fixed locations. In these networks, multipath routing techniques prove to be very useful to improve end-to-end delay, throughput, energy efficiency and load balancing, as compared to single-path routing techniques [1], [2]. The multiple paths acquired can be utilized in two different ways: (a) back-up paths and (b) load balancing. In order to utilize multiple paths as back-up paths, a source node acquires an alternative path in advance. Hence, nodes can conserve their energy since the source node does not need to perform an additional route recovery when its primary path is no longer available. On the other hand, if the source node distributes its traffic over these multiple paths, the end-to-end delay, throughput, and load balancing can be improved. The latter approach from the aspect of improving throughput is dealt with in this paper. When determining multiple paths, however, multipath routing protocols should address the well-known route coupling problem resulting from the geographic proximity of adjacent routes [2]. A route coupling occurs if the transmission of a node over one path interferes with that of any node over other node-disjoint paths. The route coupling therefore hampers the performance gain expected by means of multipath routing.

In general, three types of disjoint properties in multiple paths have been considered in order to minimize the route coupling problem, namely link-disjoint, node-disjoint, and zone-disjoint. In [3] and [4], each is defined as follows.

- link-disjoint: no communication link can be shared by several paths.
- node-disjoint: no single node can be part of several paths.
- zone-disjoint: data communication over one path will not interfere with any data communication over other paths.

Most proposed existing multipath routing protocols focused on node-disjoint or link-disjoint property. Although several zone-disjoint multipath routing techniques were proposed [4]–[7], they have significant control message overhead or rely on the accuracy of additional equipment, such as directional antenna.

It is believed that zone-disjointness among multiple paths can be guaranteed when taking advantage of the geographical location of nodes. In this paper, therefore, a novel multipath routing protocol, which can find up to three zone-disjoint paths with low overhead, is proposed. That exploits greedy forwarding techniques using location information. The location information can obtained by using GPS or localization techniques.

In our protocol, a source first acquires a primary path by greedy-forwarding an RREQ message and receiving its corresponding RREP message unicasted by the destination. During the primary path acquisition, a special zone (called an RREP-overhearing zone in this paper) consisting of nodes which received or overheard the RREP message is created. After creating the RREP-overhearing zone, two secondary paths are searched independently and simultaneously on both the left-side and right-side of the primary path via similar greedy forwarding techniques, while avoiding the RREP-overhearing zone. We also introduce two meth-

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[†]The author is with the Graduate School of Electrical Engineering and Computer Science, Kyungpook National University, Daegu, Korea.
[††]The author is with the Department of Computer Engineering, Kyungpook National University, Daegu, Korea.
a) E-mail: dsshin@monet.knu.ac.kr
b) E-mail: dongkyun@knu.ac.kr (corresponding author)
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ods for avoiding the created zone.

The remainder of this paper is organized as follows. In Sect. 2, several zone-disjoint multipath routing protocols are introduced and their drawbacks are discussed. In Sect. 3, the operations of the proposed protocol are described. The simulation results and their analysis are presented in Sect. 5. Finally, some concluding remarks with discussion regarding future works are given in Sect. 6.

2. Related Works

A lot of multipath routing protocols have been developed for wireless ad hoc networks [8]. Some of them try to find alternative routes which are used only as backup routes when a primary route is not available [9], [10]. In these cases, the route coupling may not occur because only one route is used for communication. Therefore, this paper deals with multipath routing protocols attempting to distribute source traffic over multiple paths.

A zone-disjoint multipath protocol, called NMPR (Novel Multiple Path Routing) [5], was proposed, based on AODV [11]. NMPR acquires two paths by flooding each RREQ message during two different cycles. In order to obtain a primary path, the source performs a network-wide flooding of RREQ messages and the destination node unicasts an RREP message. Meanwhile, all neighbors of the intermediate nodes over the primary path overhear the RREP message. The neighbors form an interference zone wherein a transmission over the primary path can be interfered with. Subsequently, nodes in the interference zone broadcast an indicate message in one-hop in order to create a special area along which a secondary RREQ message will be flooded in finding a secondary path with low control overhead. This technique enables the secondary path to consist of nodes which do not interfere with the primary path. Therefore, the two paths are considered to be zone-disjoint. However, the maximum number of paths that NMPR finds is limited to two. Further, it has a lot of control message overhead, because NMPR totally depends on a network-wide and scoped flooding of primary and secondary RREQ messages, respectively, in order to obtain the two paths. This flooding incurs network congestion and consumes a significant amount of energy.

A geographic zone-disjoint multipath routing technique, called GMP (Geographic Multipath Protocol) [6] was proposed, based on AOMDV. In order to guarantee a zone-disjoint property, GMP utilizes locations of neighbors of a source and destination. However, GMP does not achieve the perfect zone-disjoint property because it does not consider the interference between intermediate nodes.

In [4], a maximally zone-disjoint routing protocol using directional antenna was proposed in order to find zone-disjoint paths by reducing a transmission zone. However, it requires additional equipment (i.e. directional antenna), and its performance completely depends on the accuracy of the antenna.

In [7], a zone-disjoint multipath routing protocol, which also searches three paths, is proposed. However, it aims at finding zone-disjoint paths towards three proxy destinations which are connected to a final destination. A source searches a path to one proxy destination by flooding an RREQ message and an interference zone is created as in GMP. The final destination then selects two additional proxy destinations and each proxy destination floods its own RREQ message towards the source. Upon receiving RREQ messages, the source establishes paths towards those proxy destinations. In addition to the control message overhead, the protocol does not belong to a typical source-initiated multipath routing protocol.

3. 3-Directional Multipath Routing Protocol

We propose a novel zone-disjoint multipath routing protocol which finds up to three zone-disjoint paths with low overhead using geographical information. The maximum number of zone-disjoint nodes is known to be five (see Appendix). However, research studies have shown that too many paths do not contribute to performance improvements [12]–[14]. Furthermore, research indicates that more than three paths provide similar performance [14]. For these reasons, the number of paths searched was limited to three.

3.1 Basic Assumptions

Since our 3DMRP is based on a geographical greedy forwarding technique as in [15], four assumptions have been made. First, all nodes are aware of their own location, either based on GPS or through other location techniques [16], [17]. Second, a location service is available in order for a source to know the destination location [18]. Third, all nodes know their neighbors' location and maintain the neighbors' IDs and locations through a neighbor list. Fourth, we assume static networks, where all nodes are stationary.

In greedy forwarding, a node selects the one-hop neighbor that is the closest to the destination than itself, as its next-hop node towards the destination. However, the node may fail to perform the selection if there exists none of neighbor which are closer than itself. In order to handle this kind of failure (called void occurrence), recovery strategies, called void handling techniques have been proposed. Hence, 3DMRP utilizes a well-known right-hand rule (or left-hand rule) as its recovery strategy [22].

3.2 Path Discovery

This proposed protocol requires the acquisition of multiple paths by using a greedy forwarding technique before transmitting data packets. Since a per-packet greedy forwarding process invokes significant computational overhead at each hop, especially when a void is encountered during the forwarding process, it is recommended that paths should be established in advance.

When a source requires paths towards a destination, a

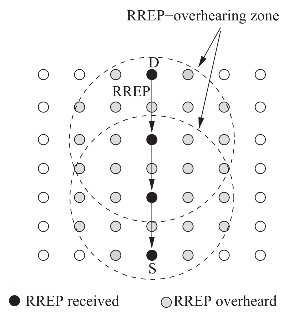


Fig. 1 RREP-overhearing zone.

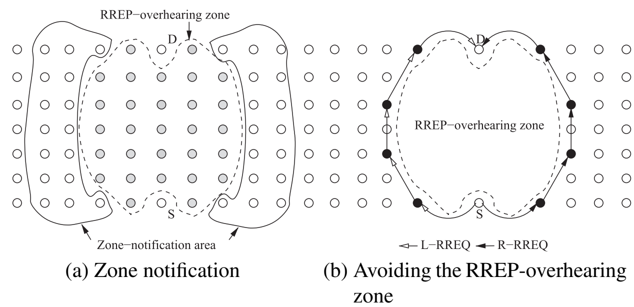


Fig. 2 An example of explicit zone notification method.

primary path between the source and destination nodes is acquired through the greedy forwarding of an RREQ message. During the primary path discovery, the right-hand rule is applied to handle a route discovery failure caused by local minima. When the RREQ message reaches the destination, the destination replies with an RREP message. While the RREP message is being propagated, there exist nodes which overhear the RREP message. These nodes consist of an RREP-overhearing zone (see Fig. 1).

Next, upon receiving the RREP message, the source node attempts to acquire two secondary paths by avoiding the RREP-overhearing zone; a left side path and a right side path of the primary path. Hence, two types of secondary RREQ messages, L-RREQ (left-side directed RREQ) and R-RREQ (right-side directed RREQ), are independently forwarded through a similar greedy forwarding technique. In order to preserve the zone-disjointness property among paths, L-RREQ and R-RREQ should both be forwarded by avoiding the RREP-overhearing zone.

In order to avoid the RREP-overhearing zone, two methods are proposed; (a) explicit zone notification method and (b) *N*-candidate selection method. In the explicit zone notification method, nodes located in an RREP-overhearing zone explicitly notify their one-hop neighbors that they are in the zone. During the process of obtaining secondary paths, an intermediate node will not select them as its next hop node towards the same destination. In the *N*-candidate selection method, each intermediate node selects *N* candidate nodes which are closer to the destination. A node receiving the secondary RREQ message will determine if it is located in the RREP-overhearing zone. If located, it will stop forwarding the secondary RREQ message. Otherwise, it will select its own *N* candidate nodes and forward the secondary RREQ message to them. Detailed descriptions of each method are described in Sects. 3.3 and 3.4.

Finally, when the destination receives the L-RREQ or R-RREQ message, it replies with L-RREP or R-RREP in order to complete its corresponding path set-up accordingly. Thereafter, the source can utilize three zone-disjoint paths: the primary path and two secondary paths.

3.3 3DMRP-EZN: Explicit Zone Notification Method

On overhearing an RREP message, nodes broadcast a zone notification message (denoted by ZN) which includes an RREP-overhearing zone ID (denoted by ZID). A ZID consists of a pair of sources ID and destinations ID. This message notifies the neighbor nodes of the transmitting node that it is located in the RREP-overhearing zone. In Fig. 2 (a), the nodes belonging to the zone-notification area will receive the ZN message.

A node receiving the ZN message updates its neighbor list in order to record its neighbor ID and its corresponding ZID, besides its neighbors' locations. However, it is unnecessary for the node to preserve the ZID information after finding all paths. Hence, when a given timer (called ZN expiring timer) expires from the time when the neighbor list is updated, the corresponding ZID is removed.

Upon receiving the RREP message, the source waits a given time (called ZN waiting time) in order to ensure that all nodes belonging to the RREP-overhearing zone have their opportunity to broadcast their ZN message. Then, the source greedily forwards a L-RREQ message into the left side area of the primary path, and a R-RREQ message into the right side area of the primary path. All nodes receiving the L-RREQ or R-RREQ message select their next hop node via the greedy forwarding technique, excluding neighbors which belong to the RREP-overhearing zone with the corresponding ZID (see Fig. 2 (b)). In 3DMRP-EZN, the right-hand and left-hand rules are utilized in order to handle a route discovery failure and to exclude the neighbors belonging to the RREP-overhearing zone when a source finds left side and right side paths, respectively, since the zone can be regarded as a void area. Alternatively, other void handling techniques as described in [19] can be applied.

3.4 3DMRP-NCS: *N*-Candidate Selection Method

Similar to 3DMRP-EZN, the source forwards L-RREQ and R-RREQ into the left side area and the right side area of the primary path, respectively. However, unlike the explicit zone notification method, each node receiving the secondary RREQ message is not aware of others in the RREP-overhearing zone. Hence, each node selects *N* candidate nodes which are closer to the destination, where *N* represents a system parameter. *N* is decided according to the size and density of the network topology. In Sect. 5.2, an appropriate value for *N* through various simulations is determined.

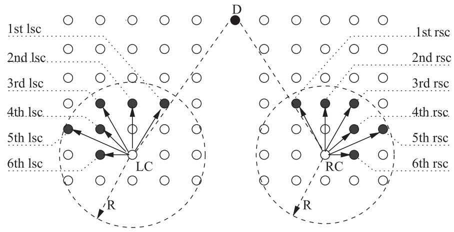


Fig. 3 Selecting N candidate nodes when $N = 6$.

Selection Rules 1 Left-hand Side Candidate Nodes

*n*th left-hand side candidate node (*n*th lsc) of node LC must accommodate following rules.

1: If n=1 then 1st lsc is the closest node towards D.
2: $\pi > \theta_{lsc\_n} > \theta_{lsc\_n-1} > \ldots > \theta_{lsc\_1}$,
   where $\theta_{lsc\_n} = \angle(nth\ lsc, LC, D)$
3: If $(\angle(n_i, LC, D) = \angle(n_j, LC, D))$
   and $d(n_i, D) < d(n_j, D)$
   then nth lsc = n_i
   where n_i and n_j are two neighbors of node LC.

Selection Rules 2 Right-hand Side Candidate Nodes

*n*th right-hand side candidate node (*n*th rsc) of node RC must accommodate following rules.

1: If n=1 then 1st rsc is the closest node towards D.
2: $\theta_1 > \ldots > \theta_{n-1} > \theta_n > -\pi$
   where $\theta_{rsc\_n} = \angle(nth\ rsc, RC, D)$
3: If $(\angle(n_i, RC, D) = \angle(n_j, RC, D))$
   and $d(n_i, D) < d(n_j, D)$
   then nth rsc = n_i
   where n_i and n_j are two neighbors of node RC.

These candidate nodes are selected according to the types of secondary RREQ messages as well as the selection rules. If a node receives a L-RREQ message, the node will select N left-hand side candidate nodes by using selection rules 1. With respect to a R-RREQ message, the node also selects N right-hand side candidate nodes by using selection rules 2. Figure 3 illustrates an example of selecting candidate nodes when $N = 6$.

After selecting N candidate nodes, their IDs are included in the secondary RREQ message, which is one-hop broadcasted then. Upon receiving the secondary RREQ message, each candidate node first checks to determine if its ID appears in the message. If present, it selects its N candidate nodes and forwards the received secondary RREQ message to them. Otherwise, it drops the message. This process is executed at each node until the corresponding message reaches the destination. 3DMRP-NCS also uses the right-hand and left-hand rules in order to handle a route discovery failure.

Figure 4 presents an illustrative example where L-RREQ and R-RREQ are forwarding by utilizing the 3 candidates selection method.

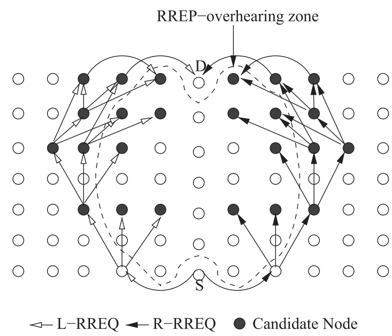


Fig. 4 An example of 3DMRP-NCS when $N = 3$.

Table 1 Fields of a routing table.

originator ID	target ID	sequence number	next hop node addresses of every paths	hop counts of every paths

3.5 Structure of Routing Table

As RREQ and RREP messages are delivered, a node sets up reverse and forward paths, and creates its routing table. Table 1 shows fields required for a routing table entry.

A reverse path is set up when a node receives an RREQ message, and the address of the neighbor, from which the RREQ message is received, is recorded in the routing entry. When an RREP message is propagated towards the source, a node records which one sent the RREP message over a link as its next hop node towards the destination and creates the forward path. In addition, a value in the hop count field, representing a hop distance to the destination, is recorded in the routing entry.

In the N-candidate selection method, multiple L-RREQ or R-RREQ messages can reach the destination. Whenever receiving a type of RREQ message with a smaller hop count, the destination replies with its corresponding RREP message. Therefore, multiple forward paths can exist. However, the source will use only three bidirectional paths with the smallest hop count, but the remaining paths will not be used. Hence, a node deletes an unused path where any data packet has been not transmitted over the path for ACTIVE_ROUTE_TIMEOUT.

3.6 Route Error Handling

A node may fail to operate due to the depletion of its energy. In this case, paths containing the node become unavailable. In 3DMRP, a node detects the failure of other nodes after all failure to transmit a packet for the given number of successive trials. When detecting such a failure, it removes the path from its routing table. Particularly, if it is an intermediate node, it sends an RERR message to the source. Other nodes on the reverse path to the source also remove the unavailable path from their routing table during their delivery of the RREP message. Finally, upon receiving the RERR message, the source removes the unavailable path from its routing table and distributes packets over other active paths. If the source has no route towards the destination and still has packets to send, the source initiates a new route discovery process.

4. Discussions

4.1 Overhead for the Location Information

In 3-DMRP, a node utilizes the locations of itself and its neighbors. Since it is applied to static networks, each node requires its neighbors' locations only once and thus has no need to update. Hence, each node broadcasts its HELLO message at bootstrap in order to inform of its location and it also acquires its neighbors' locations by receiving other HELLO messages.

In mobile environments, however, since nodes have their mobility, they should advertise their new locations and have to acquire their neighbors' new locations periodically. However, these periodical HELLO broadcastings generate a lot of control overheads in addition to routing overheads. In some cases, the control overheads might be larger than routing overheads. Hence, to extend our 3DMRP for mobile networks, such techniques to reduce the overhead to obtain locations are needed, which is our future work.

4.2 Decision of Simulation Parameters

4.2.1 ZN Waiting Time and ZN Expiring Timer

During a secondary path discovery, when intermediate nodes select their next-hop node, the nodes which sent a ZN message are excluded. However, when all the nodes in the RREP-overhearing zone broadcast their ZN messages at the same time, a broadcast storm can invoke collisions at intermediate nodes, so that ZN messages are lost. In order to avoid such collisions, we exploit the random back-off mechanism as in [21]. Each node selects a random time slot among a given period of time (i.e. ZN waiting time) and broadcasts its ZN message at the selected time slot. In this paper, we have a time slot of 1 ms and we empirically choose the ZN waiting time to be 500 ms (The same values are applied to NMPR for comparisons in our simulations.). The ZN waiting time should be determined by considering the scale of a network, the number of nodes, and etc. Furthermore, according to its selected value, there exists a tradeoff between the latency to acquire secondary paths and the number of paths found. However, in this paper, since the optimization of the time value is not our main concern, we need to investigate the best technique to avoid the broadcast storm in our future work.

In addition, a node which has received a ZN message has to preserve the ZID included in the ZN message until a source finishes its secondary path discovery. Therefore, the ZN expiring timer value should be large enough to allow an RREP message to be propagated to the source and also allow the secondary path discovery to be completed. The ZN expiring timer value is set by referring to NET_TRAVERSAL_TIME in AODV. In AODV, NET_TRAVERSAL_TIME is defined as the time that a source node has to wait after broadcasting an RREQ message until it receives an RREP message. Hence, we use a half of NET_TRAVERSAL_TIME as one-way propagation time of a message and should consider each propagation time of three messages, namely RREP, secondary RREQ, and secondary RREP messages. Also, we should consider the ZN waiting time that the source needs to wait before its secondary path discovery. Therefore, the ZN expiring timer is given by "3 × NET_TRAVERSAL_TIME/2 + ZN waiting time" and should be larger than 4.7 seconds. Hence, we decide the ZN expiring timer value to be 5 seconds.

4.2.2 ACTIVE_ROUTE_TIMEOUT

As mentioned before, ACTIVE_ROUTE_TIMEOUT, a system parameter, is needed to delete paths which were created during the acquisition of left-hand side and right-hand side paths, but have been unused for the time duration. In static networks that we assume, when a source initiates a new route discovery, the same paths will be acquired if nodes are still alive, resulting in routing overhead. Hence, a large value can help to reduce the routing overhead. However, if the value is too large, stale routing entries will exist in the network even if a path is unavailable due to a node failure. In this paper, we choose 1 minute as the ACTIVE_ROUTE_TIMEOUT value empirically by considering such a tradeoff. More judicious value should be determined by considering a network's goal, which is a common issue that most timer-based schemes to manage stale route entries should address and is also our future work.

5. Performance Evaluation

5.1 Simulation Environments

We evaluated the performance of 3DMRP, which belongs to a class of zone-disjoint multipath routing protocols through the ns-2 simulator [20]. First, we attempted to find an optimal value of N in 3DMRP-NCS by using a grid topology. Then, we compared the performance of 3DMRP with NMPR, which also belongs to zone-disjoint multipath routing protocols and relies on the overhearing mechanism. However, we did not compare them with GMP since it does not guarantee the zone-disjoint property as mentioned before. In addition, [4] and [7] were not compared because utilizing directional antenna and multiple destinations are out of consideration. NMPR was also implemented using ns-2, and IEEE 802.11 MAC [21] was modified in order to allow the RREP messages to be overheard.

All evaluations were performed by using two types of network topologies; (a) a grid topology and (b) random topologies. In our simulations, 10 random topologies where all nodes were connected in single or multi-hop manner

Table 2 Simulation parameters.

MAC	IEEE 802.11 DCF
Topology	21×21 grid, node distance = 100 m 2.5 km × 2.5 km random
Number of Nodes	441
Transmission Range	250 m
Link Bandwidth	2 Mbps
Traffic	CBR 5, 10, 15, 20, 25 connections
Packet Size	512 bytes
Packet Send Rate	20 packets per second
Transport protocol	UDP
Routing protocol	3DMRP-EZN, 3DMRP-NCS, NMPR
Simulation Duration	120 s
ACTIVE_ROUTE _TIMEOUT	60 s (1 minute)
ZN expiring timer	5 s
ZN waiting time	500 ms

were generated by using *setdest* utility in the ns-2 simulator. Other simulation parameters are summarized in Table 2.

Four performance metrics of interest are: 1) throughput (i.e. the average amount of bytes received by each destination during simulation), 2) overhead of control message incurred (i.e. the total number of control messages generated during simulation), 3) the average number of zone-disjoint paths found, and 4) the path setup delay (i.e. the time that a source takes to setup the last path). Results obtained were averaged over 10 simulation runs.

5.2 The Number of Candidate Nodes

As described in Sect. 3.4, 3DMRP-NCS selects the N number of candidate nodes. First, we attempted to find a value of N showing the best performance by using various grid topologies (7×7 to 21×21) where nodes were uniformly distributed, and various values of N (2 to 6). In this simulation, only one destination node was positioned at the center of the grid topology and all other nodes were setup as source nodes. The performance was measured in terms of two metrics: 1) the average number of paths found per source and 2) the average number of control messages per path.

As shown in Fig. 5, it is observed that the average number of paths found per source increases when the value of N is larger. A larger N value allows 3DMRP-NCS to have more paths because it has more opportunities to select next hop nodes, which are located out of an RREP-overhearing zone. In addition, a large scaled network also enables 3DMRP-NCS to find additional paths in comparison to a small scaled network, due to the existence of more detouring paths. However, as shown in Fig. 6, a larger value of N requires additional control messages. In addition, values large than 4 do not show significant performance improvement in terms of the average number of paths per source, but rather produce significantly more control message overhead. Hence, it was concluded that 3DRMP-NCS works appropriately when $N = 4$.

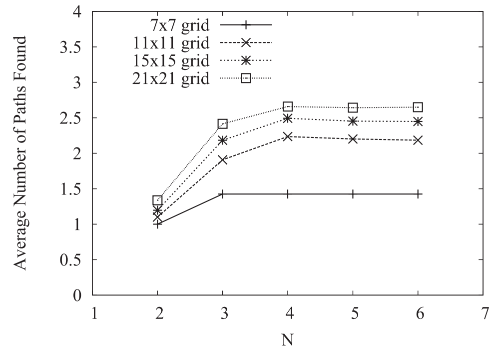


Fig. 5 Average number of paths found.

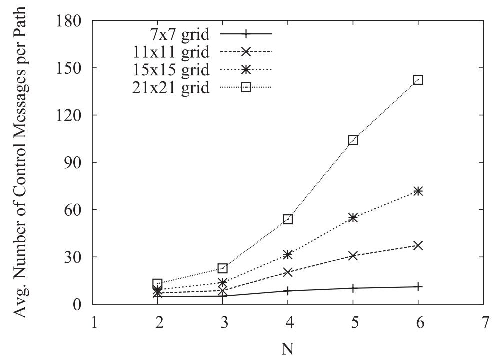


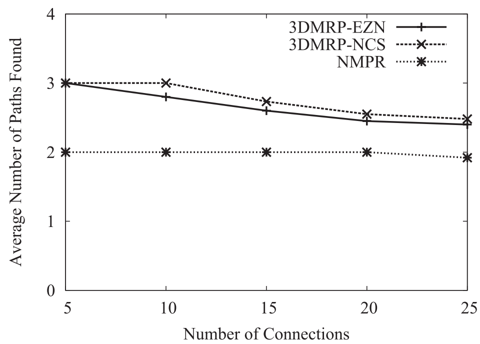
Fig. 6 Average number of control messages per path.

5.3 Comparisons in a Grid Topology

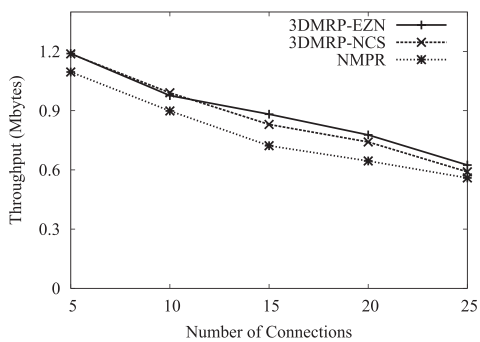
We compared 3DMRP-EZN and 3DMRP-NCS with NMPR in a 21×21 grid topology. Here, each N in 3DMRP-NCS was set to 4, according to the above-observed simulation results.

First, we investigated the average number of paths found successfully with various numbers of connections in the network. When creating connections, each pair of source and destination nodes was randomly selected. In all cases, as shown in Fig. 7 (a), 3DMRP-EZN and 3DMRP-NCS succeed in obtaining 2~3 paths, while NMPR utilizes only two paths. In cases where nodes are positioned at the edges of networks, 3DMRP-EZN and 3DMRP-NCS may fail to find secondary paths because there are an insufficient number of nodes in its left-hand or right-hand side. In addition, since 3DMRP-EZN broadcasts a ZN message, some nodes cannot receive the message due to the hidden terminal problem in 802.11 DCF which is used as a MAC layer in our simulation. In this case, when a source in 3DMRP-EZN attempts to acquire a secondary path, it fails to obtain the secondary path because an intermediate node can select its next hop node among those located in an RREP-overhearing zone. Hence, the number of paths found in 3DMRP-EZN is slightly less than 3DMRP-NCS.

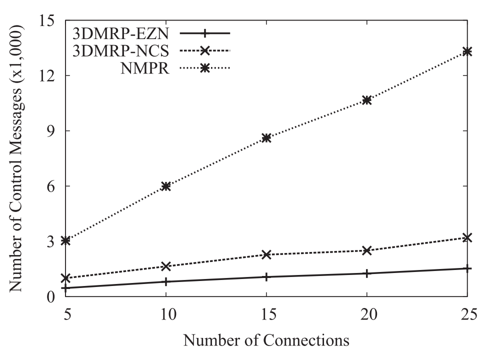
Next, we measured the average throughput of each connection by varying the number of connections in the network. Both 3DMRP-EZN and 3DMRP-NCS, taking ad-



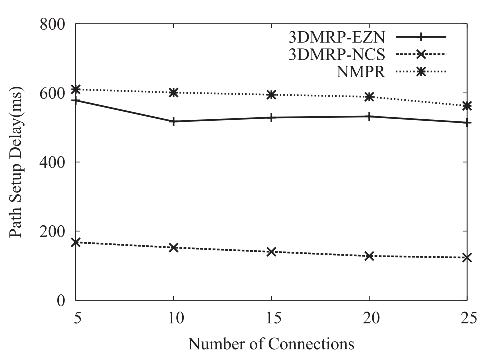
(a) Average number of paths found



(b) Average throughput for each connection



(c) The total number of control messages



(d) The average path setup delay

Fig. 7 Performances of the grid topology.

vantage of up to three paths, show better performance than NMPR (see Fig. 7 (b)). In addition, the throughput decreases as the number of connections increases in both 3DMRP and NMPR, because the existence of more connections incurs more interference among multiple paths from different connections. However, 3DMRP-EZN shows better performance than 3DMRP-NCS, despite a smaller number of paths. This is due to a failure of 3DMRP-EZN in finding a secondary path which reduces an interference from a secondary path. Most of multipath routing protocols, including our 3DMRP, only take into account interference among multipaths from a given source and destination pair, not the interference among multipaths from different source and destination pairs. This requires further investigation in future research studies.

Third, the control overheads in 3DMRP-EZN, 3DMRP-NCS and NMPR were measured. Unlike NMPR, which depends on the flooding of messages, 3DMRP utilizes geographic information. Hence, from Fig. 7 (c), we observe that 3DMRP shows a significant performance improvement with low overhead of control message. In addition, 3DMRP-EZN shows less overhead than 3DMRP-NCS because the former needs only additional overhead which requires a ZN message to be broadcasted by one hop neighbors over a primary path, while the latter produces additional overhead at each candidate node.

Finally, path setup delays were measured (see Fig. 7 (d)). We observe that 3DMRP-NCS has the lowest delay, since it initiates its secondary path discovery immediately when it receives an RREP message. However, since 3DMRP-EZN and NMPR have a waiting delay in order to broadcast ZN and indicate messages, respectively, they have longer delays than 3DMRP-NCS.

Table 3 summarizes improvements achieved in 3DMRP by using a grid topology, as compared to NMPR.

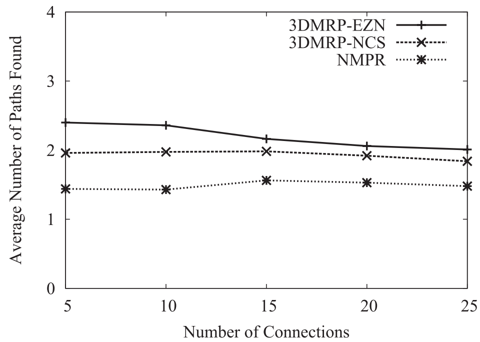
Table 3 The achieved improvements in the grid topology.

	3DMRP-EZN	3DMRP-NCS
Throughput	8%∼22%	8%∼15%
Control Overhead	75%∼89%	67%∼77%
Number of Paths Found	22%∼50%	27%∼50%
Path Setup Delay	5%∼14%	63%∼76%

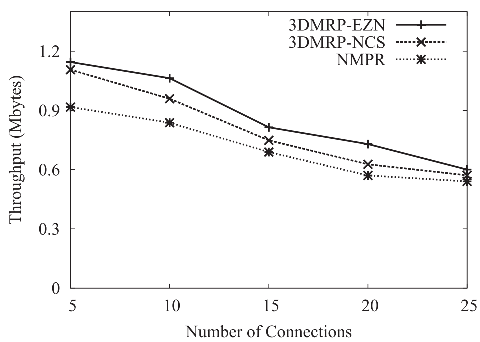
5.4 Comparisons in Random Topologies

In this section, we compared 3DMRP-EZN and 3DMRP-NCS with NMPR by using random network topologies. The N value in 3DMRP-NCS was also set to 4.

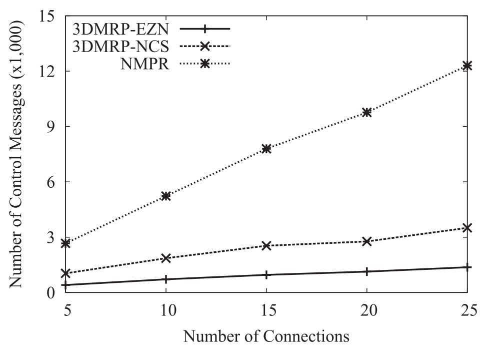
First, we measured the average number of paths found for each pair of source and destination nodes with various numbers of connections. These pairs were randomly selected. Unlike a grid topology, 3DMRP-NCS and NMPR obtain less than two paths, whereas 3DMRP-EZN succeeds in finding more than two paths (see Fig. 8 (a)), due to possible reasons, as listed below. First, it is possible that there are insufficient neighbors around an intermediate node over a primary path in order to forward a secondary RREQ message due to the random deployment of nodes. Hence, NMPR fails to find a secondary path because it cannot further forward a secondary RREQ message. Second, all next hop nodes of a node, including a source node while searching a secondary path, are located in an RREP-overhearing zone so that 3DMRP-NCS fails to forward its secondary



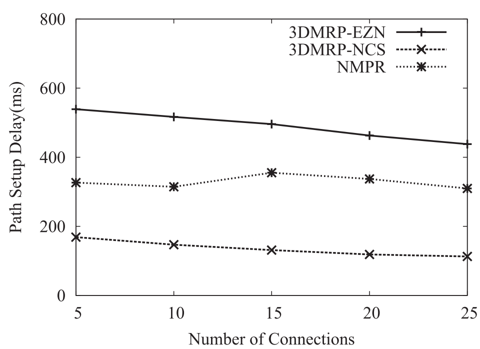
(a) Average number of paths found



(b) Average throughput for each connection



(c) The total number of control messages



(d) The average path setup delay

Fig. 8 Performances of random topologies.

RREQ message. Hence, the number of paths found is less than in a grid topology. However, since 3DMRP-EZN can handle an RREP-overhearing zone as a void, it obtains a secondary path by simply avoiding the zone through a void handling technique.

As shown in Fig. 8 (b), we observe that 3DMRP has a better throughput performance than NMPR as in the simulations using the grid topology. In addition, it is observed that the throughput in both 3DMRP and NMPR decreases as the number of connections increases, due to the same reasons mentioned in simulation results using the grid topology. However, the throughput in random topologies is less than that of the grid topology, due to a low availability of paths in random topologies.

Third, the control overhead was also measured. As in a grid topology, NMPR and 3DMRP-EZN show the largest overhead and the lowest overhead, respectively (see Fig. 8 (c)). In particular, there are marginal differences between the grid topology and random topologies in 3DMRP-NCS. In random topologies, the occurrence of voids cannot be avoided. As 3DMRP-NCS attempts to avoid a void by forwarding a secondary RREQ message to candidate nodes which detour the void, the overhead increases.

Finally, path setup delays were measured (see Fig. 8 (d)). According to the definition of the metric, the path setup delays are lower than those in the grid topology, because more time is spent in finding the larger number of paths. In particular, the delay in NMPR is nearly a half of that in the grid topology. However, since 3DMRP-EZN still consumes time to find its secondary path, it has longer delay than NMPR. In addition, the delay in 3DMRP-NCS is similar to that in the grid topology because 3DMRP-NCS does not rely on the ZN waiting time.

Table 4 summarizes the achieved improvements in 3DMRP by using random topologies, as compared to NMPR.

Table 4 The achieved improvements in random topologies.

	3DMRP-EZN	3DMRP-NCS
Throughput	11%∼28%	8%∼20%
Control Overhead	85%∼89%	61%∼72%
Number of Paths Found	37%∼67%	24%∼38%
Path Setup Delay	−37%∼−65%	48%∼65%

6. Conclusion

This paper proposed a novel zone-disjoint multipath routing protocol (3DMRP) based on geographical information in order to address the route coupling problem in static wireless ad hoc networks. 3DMRP searches up to three zone-disjoint paths with low control overhead through two mechanisms: 1) greedy forwarding, and 2) RREP-overhearing. In 3DMRP, one primary and two secondary paths are obtained via a greedy forwarding technique. Two secondary paths are found in the right-hand and left-hand sides of the primary path by avoiding the RREP-overhearing zone created during the primary path acquisition. In particular, two versions of 3DMRP, called 3DMRP-EZN and 3DMRP-NCS, were introduced in order to avoid the RREP-overhearing zone.

We evaluated two versions of 3DMRP and NMPR which are both representative zone-disjoint multipath routing protocols. Through extensive simulation study by using ns-2, it was observed that 3DMRP achieved a significant reduction in the control message overhead (61%~89%). This overhead reduction can assist nodes to conserve their energy and alleviate network congestion caused by much control traffic. In addition to the control overhead, 3DMRP also improved throughput performance (8%~28%). In particular, 3DMRP-EZN showed better performance over 3DMRP-NCS in terms of throughput and control overhead.

In this paper, we applied 3DMRP to static networks. The extension of 3DMRP to dynamic networks with node mobility is our future work. Optimizing system parameters and mitigating interference among multipaths from different source and destination pairs will also be investigated in future work.

Acknowledgement

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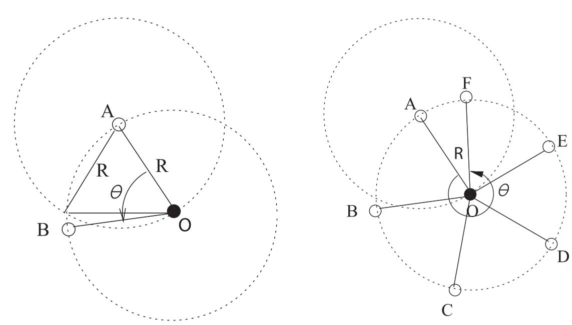
Appendix: Maximum Number of Zone-Disjoint Nodes

Ideally, the maximum number of zone-disjoint nodes within the transmission range of a node is limited to 5. In Fig. A· 1 (a), A and B are neighbors of node O. Let us denote the angle between lines (O, A) and (O, B) by θ. The condition which requires nodes A and B to be zone-disjoint is $\theta = \pi/3 + \epsilon$. Suppose that more than five nodes (e.g., six nodes) are zone-disjoint with each other within the transmission range of node O. Then, the sum of each θ is $\geq \frac{5}{3}\pi + \epsilon$, which means that nodes A and F are never zone-disjoint (see Fig. A· 1 (b)). Therefore, we conclude that the maximum number of zone-disjoint nodes is limited to five.



(a) Condition of zone-disjoint (b) Case of six nodes

Fig. A· 1 Zone-disjoint nodes.

Dongseung Shin received the B.S. and M.S. degrees in the School of Electronic Engineering, Kyungpook National University, Daegu, Korea, in 1996 and 1999, respectively. From 1999 to 2006, he engaged in software development. He is currently a Ph.D. student in the Graduate School of Electrical Engineering and Computer Science of Kyungpook National University. His current research interest is focused on wireless sensor networks and underwater sensor networks.

Dongkyun Kim is a professor with the Department of Computer Engineering, Kyungpook National University, Daegu, Korea. He received the BS degree at Kyungpook National University. He also obtained the MS and Ph.D degrees at Seoul National University, Korea. He was a visiting researcher at Georgia Institute of Technology. He also performed a post-doctorate program at University of California Santa Cruz. He has been a TPC member of several IEEE conferences. He received the best paper award from the Korean Federation of Science and Technology Societies, 2002. His research interests are ad-hoc network, sensor network and wireless LAN, etc.