DAG-based Multipath Routing for Mobile Sensor Networks

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Abstract—**We propose a new multipath routing protocol called DMR for mobile sensor networks, where any node can move anytime. DMR is based on the IETF RPL framework, which uses directed acyclic graph (DAG) to remove routing cycles. By broadcasting DAG construction messages including rank and link quality indication, DMR constructs DAG and provides path redundancy. This allows mobile sensors to find multiple alternative paths easily on local and global route failures. Our experimental results show that DMR successfully delivers more than 97% of messages while improving the energy efficiency for MSN by effectively reducing routing overheads by 65% and 56% on average compared to the existing MANET routing protocols AODV and AOMDV, respectively.**

***Keywords*— mobile sensor networks, routing, LLN, DAG, RPL.**

I. INTRODUCTION

With advances in MEMS and VLSI technologies, sensors are now sufficiently small and cheap, and everywhere due to the popularity of mobile sensing devices such as smart phones. By adding an ad hoc network interface to these devices, we can deploy the sensing devices in the area of interest to form a self-configured network to dynamically acquire information anywhere anytime. In such mobile sensor networks (MSN), the sensors attached to mobile objects, such as humans, pets, and automobiles, are suitable for detecting and tracking events on mobile objects without regard to time and place, which was not possible with traditional wireless sensor networks (WSN) with stationary sensors. Also, the mobile sensors can monitor events that occur sparsely in a vast region without increasing transmission power or bandwidth. Thus, the mobility of sensor nodes can enrich the application areas of existing WSN.

However, a mobile node may frequently lose link connectivity and the disconnection changes the network topology dynamically. Node mobility presents challenging issues for a networking protocol design since the protocol needs to adapt to frequent topology changes in a way that is transparent to the end user. In mobile ad-hoc networks (MANET) [1], a number of routing protocols [2] have been proposed to deal with topology changes flexibly, and to minimize the cost of route failures. But, these protocols are not optimized for MSN where traffic is concentrated into a few sink nodes. Unlike MANET, data and flooding control messages may collide with each other around the sink nodes in MSN when traffic is extremely heavy. So, the sink nodes become inevitably hot spots, and then frequency of route failures may increase rapidly. Such frequent topology changes eventually leads to the higher routing overhead, wasting energy and bandwidth due to wasteful collision and retransmission requests.

Similar to MSN, low-power and lossy networks (LLN) are characterized as networks consisting of a number of embedded devices with limited power, memory, and processing resources interconnected by a low-power low-bandwidth communication protocol, such as IEEE 802.15.4, Bluetooth, and low-power WIFI, which is irregular and unreliable by nature. The Routing Over Low-power and Lossy Networks Working Group (ROLL WG) [3] in Internet Engineering Task Force (IETF) designs a new IPv6 routing protocol for LLN, called RPL [4], which aims at providing support to reliable and low-latency routing using directed acyclic graphs (DAG). RPL specifies how to build a destination-oriented directed acyclic graph (DODAG) using objective function (OF) [5] that defines how to select parents and how to compute rank. Since the DAG differs from a tree mainly in that a child node can have more than one parent node, RPL can maintain multipath routing and react to frequent topology changes. Moreover, RPL can also support many-to-one communication flow appeared in MSN since each node in the DODAG has routing path to the DODAG root (e.g., a sink node).

In this paper we propose a DAG-based multipath routing protocol for MSN, called DMR, based on the RPL framework. Although the framework has been specified in [4], it still has various open issues, including behavior of objective functions and network topology repair. As with RPL, DMR is based on a reactive on-demand approach, maintaining information for active routes only. So, before sending data packets, each source node requests a sink to build DODAG in order to establish routes between them. DMR constructs DODAG by using two routing metrics, rank information and link quality indication (LQI) [6], which is a parameter offered by IEEE 802.15.4. In DMR, rank is determined by a hop count from the root, which is simple and easy to compute, and requires no additional measurements even in a situation where nodes are moving randomly. Since DMR can avoid creating routing loops by using a rank-based route selection process, the network topology can maintain acyclic nature of DAG. Moreover, DMR can select the route which has the best quality link among all the feasible routes in addition to the rank information to improve the reliability of data transfer.

After establishing routes between nodes, DMR can support reliable packet delivery against both temporary and permanent route failures through sibling nodes. Adding sibling nodes to routing table of each node provides fast local repair of network topology. Even if there are no more sibling nodes, the node detecting a broken link can initiate global repair by requesting its sink to rebuild a new DODAG. Thus, these local and global repairs are complementary techniques to each other and can improve network lifetime in MSN.

In our experimentation, we have compared DMR, AODV [7], and AOMDV [8] using NS-2.34 simulator in MSN environment. Our simulation results show DMR reduces routing overheads by 65% and 56% on average compared to AODV and AOMDV respectively. By reducing the routing overhead, DMR is able to reduce the per-node energy consumption by 22.5% compared to AODV and AOMDV, while maintaining more than 97% message delivery ratio although the end-to-end packet delay of DMR can be as large as 2.6 times of AODV's delay due to the usage of alternative routes on route failures. In conclusion, we argue that DMR can substantially improve routing performance for MSN in the presence of node mobility and link error.

The rest of this paper is organized as follows. Section II briefly summarizes the framework of RPL. Section III describes the operation of DMR in detail. Section IV presents our experimentation methodology and discusses the simulation results. Finally Section V concludes the paper.

II. The RPL Protocol

RPL [4] is a routing protocol designed for low-power and lossy networks (LLN). Since LLN routers typically operate with constraints on processing power, memory, and energy, the routing protocol must be robust and be prepared to intermittent loss of network connectivity. RPL organizes the network as a directed acyclic graph (DAG) that is partitioned into one or more destination-oriented DAGs (DODAG) according to the number of DODAG roots. Since a DAG is a directed graph with no directed cycle, all the edges have identical directions to the DODAG root.

In RPL, a DODAG can be considered as a logical routing topology over a physical network. An objective function (OF) [5] defines how routing metrics, optimization objectives, and related functions are used to compute rank. The rank of a node is the hop count from the DODAG root to the node in the DODAG. A node with a lower rank means that it is closer to the DODAG root. Each node computes its own rank according to objective code point (OCP) which identifies OF, and determines what metrics and functions should be used for a node to build routing solutions.

The RPL routing protocol specifies a set of new ICMPv6 control messages [9] in order to construct a DODAG and to support communication between a DODAG root and a source node. The three main ICMPv6 messages are the following:

1) DODAG Information Object (DIO): The DODAG root issues a DIO message to construct a DODAG. The DIO message conveys a DODAGID, which is used to identify the DODAG root, rank information, and OCP. Upon receiving a DIO message, a node has to determine whether or not the DIO message should be processed. So, the node computes its own rank according to the OCP, and selects a parent node which has a lower rank than itself, then joins the DODAG. After the process, the node advertises the DIO message until a leaf node receives it. If the node has already joined the DODAG, it can discard the DIO message, or process the DIO message in order to modify its rank. Therefore, each node in the network has a routing path through its parents to the DODAG root.

2) Destination Advertisement Object (DAO): A DAO message is aimed at supporting outward traffic from the DODAG root to a DODAG member node, called DODAG node. So, in order to establish the outward routes, the DODAG node issues a DAO message to its parent node when it joins the DODAG. If a node receives the DAO message, it records reverse route information, and sends the DAO message to its parent node again. When the DODAG root receives the DAO message, all the intermediate nodes record the reverse route information, and complete outward routes are established from the DODAG root to the DODAG nodes.

3) DODAG Information Solicitation (DIS): A DIS message is used to solicit a DIO message from its neighborhood as an initial probe for a nearby DODAG.

As we discussed above, although RPL is specified by [4], RPL still has various open issues since any specific OF for DODAG construction and rank computation, and optimizations of RPL are not fully defined yet.

III. DMR Design

In this section, we present the operation details of DMR. First, we introduce DODAG construction mechanism using rank information and link quality indication (LQI). Then, we show DODAG repair mechanism in terms of both local and global repairs.

A. DODAG Construction

DMR is based on a reactive on-demand approach similar to RPL. The advantage of this approach is that routes are adaptable to frequent topology changes of MSN, since each node can maintain its routing table freshness. So, before sending a data packet, a source node first broadcasts a DIS message to a sink node (i.e., a DODAG root) in order to request the DODAG construction. As with RPL, in DMR only the sink node participates in the DODAG construction and maintenance.

Fig. 1 shows the processes performed by a sink node and intermediate nodes when they receive a DIS message and a DIO message, respectively. Upon receiving a DIS message, the sink node increases DODAGID by one to represent a new DODAG, and initializes rank value to 0. Then, it

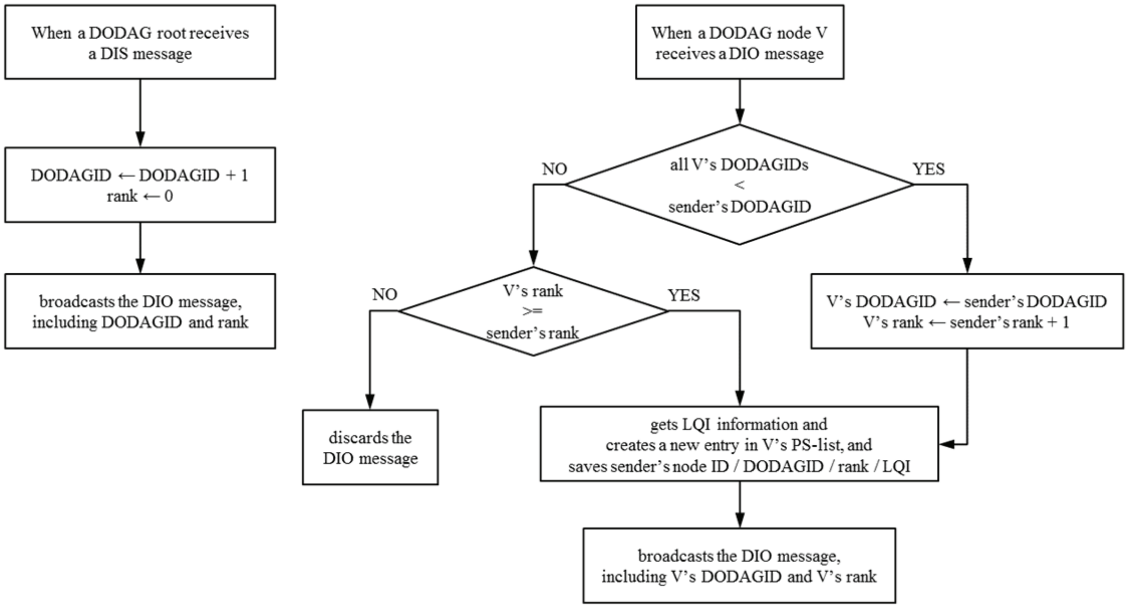


Figure 1. The processes performed by a sink node and by an intermediate node when they receive a DIS message and a DIO message, respectively.

broadcasts the DIO messages in order to construct a new DODAG in the network.

The DODAG construction procedure is as follows. When an intermediate node V in the DODAG receives the DIO message, the node V compares its DODAGIDs with the sender's DODAGID that is contained in the DIO message. If the sender's DODAGID is larger than all the DODAGIDs of the node V, the node V regards the DIO message as a new DODAG construction. So, the node V replaces its DODAGID by sender's DODAGID, and increases its rank by sender's rank + 1 in order to assign the sender for the parent of node V.

In DMR, the rank value is same as the hop count from a sink node. Although several metrics such as expected transmission count (ETX) [10], per-hop round trip time (RTT) [11], and per-hop packet pair delay (PktPair) [12] are popular metrics for evaluating link quality, the hop count metric outperforms all of the link-quality metrics in a scenario where any node can move anytime such as MSN [13]. Furthermore, the hop count is simple and easy to compute since it requires no additional measurements. The hop count can be easily assigned to a parent node and a sibling node even in MSN environment. In addition, DMR also uses link quality indication (LQI) [6] to determine priority among the nodes that have the same rank. An intermediate node can compute LQI information based on RSSI (received signal strength indicator) value received from its radio chip when it receives a DIO message.

After updating its DODAGID and rank, the node V creates a new entry in its parent-sibling list (PS-list), and saves sender's node ID, DODAGID, rank, and LQI information to the PS-list. Then, the node V broadcasts the DIO message, including its DODAGID and rank.

If the sender's DODAGID is equal to the node V's DODAGID, the sender can be regarded as another parent node or as a sibling node of the node V after comparing its rank with the node V's rank. However, if the sender's rank is larger than the node V's rank, the node V discards the DIO message since the sender can be its descendent node in order to avoid loop creation. Note that the node V's DODAGID cannot be larger than the sender's DODAGID since a sink always increment DODAGID before it broadcasts the DIO message. The constructed DODAG expires after a predetermined period time.

B. DODAG maintenance and repair

In a DAG, a node can have multiple parents. So, the DAG can provide data path redundancy since each node is able to forward the data packet to any of its parents. In DMR, after constructing a DODAG, an intermediate node receiving a data packet should search its PS-list to determine the next node to forward the data packet. Fig. 2 shows the procedure of data packet forwarding and route repair. A node with a lower rank than and the highest LQI value is chosen as the next node. The LQI value is used to estimate the distance between a sender and a receiver. According to IEEE 802.15.4, LQI is characterized by the strength and the quality of a received packet. Several recent researches within the ZigBee standard [14], the IETF 6LowPan Working Group [15], and the IETF ROLL Working Group [3] recommend the use of LQI [6].

Although there is no valid parent on a route failure, DMR can repair broken routes locally using sibling nodes. As we discussed, a DODAG node records the information of not only its parent nodes but also its sibling nodes in its routing table when the node receives DIO messages. The usage of sibling links enables nodes to make detour routes towards a sink node. Thus, even if parents of an intermediate node

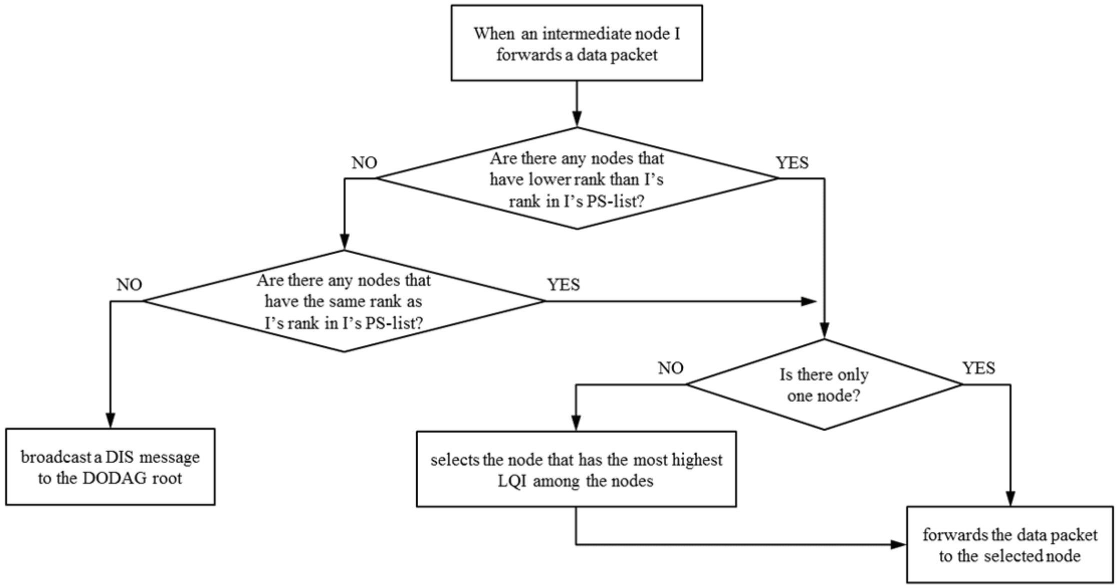


Figure 2. The procedures of data packet forwarding and route repair.

become invalid, the node can still maintain reliable data delivery by forwarding the data packet to one of its sibling nodes despite the fact that the intermediate node may not use the existing route anymore. However, if neither parent nor sibling nodes are available in the PS-list, the node can broadcast a DIS message in order to ensure the packet delivery by reconstructing a DODAG in the network. Therefore, a node can repair broken routes both locally and globally when network topology changes frequently under high mobility scenario.

IV. PERFORMANE EVALUATION

A. *Simulation environments*

We have modeled DMR along with AODV and AOMDV by using NS-2.34 simulator. AODV is known as one of the best MANET routing solutions and AOMDV is a multi-path routing protocol based on AODV and is more robust to route failures. 100 sensor nodes are randomly deployed in 500m x 500m network field. Each sensor follows the random waypoint model [16] and moves randomly with a pause time of 5 seconds during 200 seconds simulation time. Radio transmission range of each node is 50 meters. We use 1 Mbps IEEE 802.11b Distributed Coordination Function (DCF) as the MAC protocol, and the energy consumption values are determined according to the study results of Chipcon CC2420 [17]: transmit mode=31.32mW, receive mode=35.28mW, idle mode=712uW, and sleep mode=144nW.

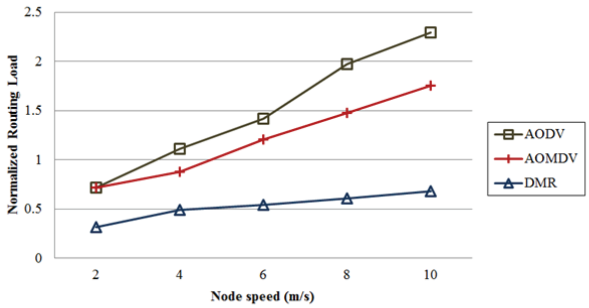
A traffic generator is developed to simulate constant bit rate (CBR) sources. For the simulation, the number of source node and sink nodes are fixed at 30 and 4, respectively. The mobile speed of each node varies from 2m/s to 10m/s. The size of data payload is 200 bytes.

B. *Simulation results*

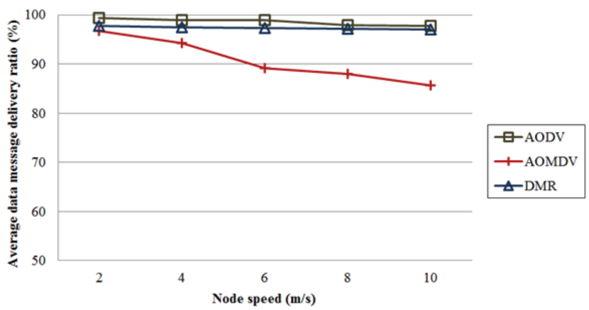
Fig. 3(a) shows the routing overhead of the three routing protocols in terms of the normalized routing load, which is the number of routing control packets transmitted per data packet delivered. The total number of routing control packets in AODV and AOMDV is the sum of the number of RREQ, RREP, and RERR messages. In DMR, the total number of routing control packets is the sum of the number of DIS and DIO messages. In this simulation, we do not count DAO messages since we only consider inward traffic in our traffic scenario. The normalized routing load is important as it is used to evaluate the efficiency of routing protocols. The normalized routing load in DMR is reduced, on average, by 65% and 56% compared to AODV and AOMDV, respectively. Since DODAG can be maintained as long as possible in DMR by using local and global repair schemes, control messages for route maintenance can be minimized when route failures occur. In contrast, packet collisions and data retransmissions occur frequently in AODV since several source nodes generate a number of control messages in order to discover routes individually, and intermediate nodes with broken links request source nodes to perform route discovery process repeatedly.

Fig. 3(b) shows the average data message delivery ratio with respect to node speed. Both DMR and AODV maintains more than 97% data delivery ratio whereas AOMDV delivers less than 89% of messages when the node speed exceeds 6m/s. The improvement of DMR is attributed to its responsiveness to frequent topology changes. Although AOMDV establishes multiple alternative routes to improve the robustness against route failures, it is possible that all the routes are broken simultaneously.

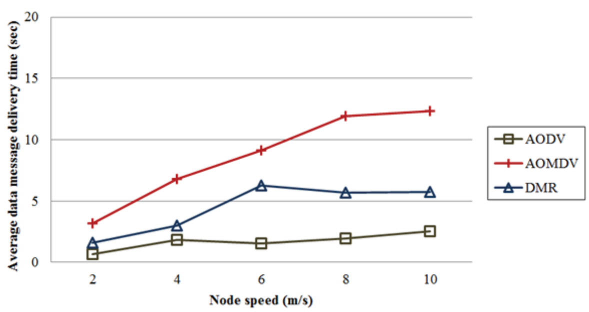
Fig. 3(c) shows the average message delivery time. Note that the message delay of DMR can be as large as 2.6 times



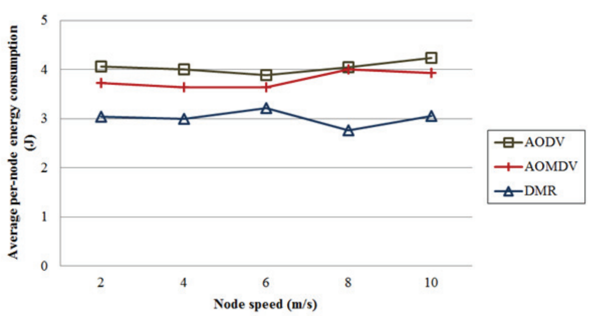
(a) normalized routing load



(b) average data message delivery ratio



(c) average data message delivery time



(d) average per-node energy consumption

Figure 3. Simulation results.

of AODV's delay. In DMR, local repair scheme can direct a data message through an alternative path using sibling nodes when a node detects a broken link. However, this local repair scheme does not guarantee the shortest path since the packet may detour. In contrast, AODV guarantees the shortest path. However, the average data delivery time of DMR is about twice faster than that of AOMDV. This is due to the fact that, although AOMDV provides multiple routes to a destination, AOMDV requires more control packet exchanges than DMR to maintain backup routes between a source node and a destination node.

As shown in Fig. 3(d), DMR is the most energy efficient routing scheme. DMR reduces the average per-node energy consumption by 25% and 20% compared to AODV and AOMDV, respectively. This is due to the fact that DMR can minimize control messages exchanges on route failures using local and global repair schemes. The energy efficiency of DMR can lead to longer network lifetime for MSN.

V. CONCLUSION

This paper presents a DAG-based multipath routing protocol for MSN, called DMR, based on the framework of RPL. By using rank and LQI information DMR can effectively build the DODAG and can provide path redundancy. On a route failure, our local repair scheme can quickly find alternative paths using sibling node information when all the parent nodes are no longer available. In addition, the proposed global repair scheme can ensure the recovery of the network even when neither sibling nor parent nodes are accessible by reconstructing DODAG. We compared the performance of DMR against AODV, and AOMDV by using NS-2.34 simulator. Experimental results show that DMR improves energy efficiency by 25% and 20% compared to AODV and AOMDV, respectively, by exploiting DAG structure while maintaining more than 97% data delivery ratio. These results indicate that DMR can provide robustness to mobility and can also enhance routing performance for MSN compared to existing MANET routing solutions.

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