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A hybrid mode to enhance the downward route performance in routing protocol for low power and lossy networks

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Abstract

An IPv6 routing protocol for low power and lossy networks provides an IPv6 communication for a wide range of applications in multi-hop mesh networks. The routing protocol for low power and lossy networks defines the creation and management of downward routes with two modes of operations: storing and non-storing modes. The storing and non-storing modes have weaknesses for memory constraints and packet traffic overheads, respectively. The storing mode may cause routing failures due to constraints on memory in routers and the non-storing mode may cause packet fragmentation that can become a factor for packet delays or loss. Then the problems may degrade the downward route performance in routing protocol for low power and lossy networks. Therefore, in this article, we propose a hybrid mode that combines the advantages of the existing two modes to improve the performance of downward packet transmission in routing protocol for low power and lossy networks networks. The proposed hybrid mode uses a new routing header format. The routing information for packet delivery is distributed with the extended routing header. We implement the proposed hybrid mode in Contiki OS environment to compare with existing techniques. From the experiment, it was observed that the proposed hybrid mode can improve the performance of downward packet transmission. Therefore, with the proposed hybrid mode, it is possible to configure a network enable to be composed of many leaf nodes with constrained memory. We also discuss future works.

Keywords

Low power lossy network, routing protocol, routing protocol for low power and lossy networks, downward routing, performance

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Introduction

Low power and lossy networks (LLNs), also referred to as wireless sensor networks (WSNs), have been constantly studied over the past decade. The WSNs have enabled the development of wireless communications in academic and industrial fields as a key technology of machine to machine communication. As a result, WSNs have been deploying with a variety of applications in environments such as building management, home automation, smart grid, and industrial monitoring and control based on flexibility of low-power wireless network.[1–6]

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Several routing protocols have been proposed for LLNs which are often composed of devices with limited resources to meet requirements for LLN applications.[7] One of the most mature and commercially feasible solutions is a routing protocol for low power and lossy networks (RPL).[8] RPL is a gradient-based distance vector routing protocol for LLN supporting diverse link layers. RPL constructs a Destination-Oriented Directed Acyclic Graph (DODAG) initiated from a root node forming a tree-like routing topology. RPL nodes in a DODAG can be classified into two different types of nodes based on routing capability: routers and leaf nodes. The routers have the routing capability, while the leaf nodes do not. RPL supports bidirectional communication between nodes by providing routing paths in both directions along DODAG: upward routing from RPL nodes to DODAG root and downward routing from DODAG root to RPL nodes.

The routing for establishment of downward routes can be classified into two modes: storing and non-storing modes.[8] The storing mode stores routing information in routers, and the non-storing mode keeps all the routing information in a DODAG root. The two downward routing modes have their own disadvantages.[9] In the storing mode, RPL routers might suffer shortage of memory space due to the increase in entries in a routing table. The non-storing mode might, on the other hand, suffer high traffic overheads because it employs the source routing which piggybacks routing information in data packets, thereby increasing the possibility of fragmentation and reassembly of data packets. The disadvantages of the two modes might cause routing failure and increased overhead, thereby ultimately degrading network performance and scalability.

We assume a network where multiple mobile leaf nodes can travel between fixed routers which are preinstalled in buildings, such as a patient monitoring network in a hospital. We call these mobile leaf nodes as mobile nodes thereafter in this article. The mobile nodes do not have routing capabilities due to the low-power operation and memory constraints. In the storing mode, if a mobile node moves from a router to another router, the mobile node leaves stale routing information in the previous router. This stale routing information is not used anymore unless the mobile node comes back to the previous router. Large amounts of resources in an RPL network could be wasted for this outbreak of mobile nodes movements. On the other hand, the non-storing mode may cause traffic overheads such as the packet fragmentation by the source routing.

There have been several studies resolving the problems of the downward routing modes. MERPL[10] and D-RPL[11] are based on the storing mode and focus on the storage shortage problem for routing entries. The results of the studies show more scalable than the conventional storing mode of RPL. However, MERPL could incur packet processing overhead due to the exchange of additional routing information between nodes. D-RPL could increase network traffic due to the use of multicast.

In this article, we propose a hybrid downward routing mode. The pivotal point of the proposed mode is to segregate leaf nodes' routing information from routers' routing information in an RPL network. The routing information for leaf nodes is stored in a DODAG root like in the non-storing mode, while the routing information for routers is stored in RPL routers like in the storing mode. This segregation could relieve the shortage of storage space in routers because the routers store only the routing information for the routers themselves. For this proposed hybrid mode, a new extended IPv6 header is defined, and a packet delivery process is proposed using the extended header. Simulation results show that the proposed hybrid mode performs better than the two downward routing modes in RPL in terms of storage space and packet processing overhead.

The main contributions of this article are as follows:

(1) We discuss the routing failure of the two downward routing modes in RPL due to the limited resources of routers in the RPL network with numerous mobile nodes.
(2) We propose a novel hybrid downward routing mode which improves the existing downward routing modes to resolve the aforementioned problems. The proposed mode resolves the limitation of the capability to store the routing information in routers.
(3) We evaluate the performance of the proposed hybrid mode with simulations.

The rest of this article is organized as follows. In section "Preliminaries," we explain the two downward routing modes in RPL. Section "Problems of two modes of RPL downward routing" describes the problems that the two downward routing modes have. To solve these problems, a hybrid mode in RPL is proposed in section "Proposed hybrid operation mode." Section "Simulation environment" presents a simulation environment for the proposed hybrid mode. Simulation results are presented in section "Performance evaluations." Finally, the article is concluded with future research directions in section "Conclusion."

Preliminaries

In this section, we describe both storing and non-storing downward routing modes of RPL in more detail. RPL employs a DODAG which is a tree-like

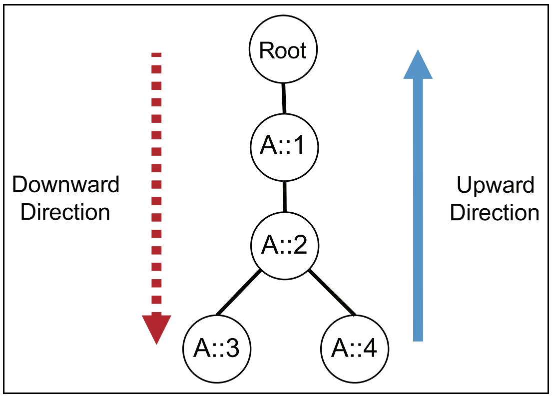

Figure 1. An example of DODAG topology.

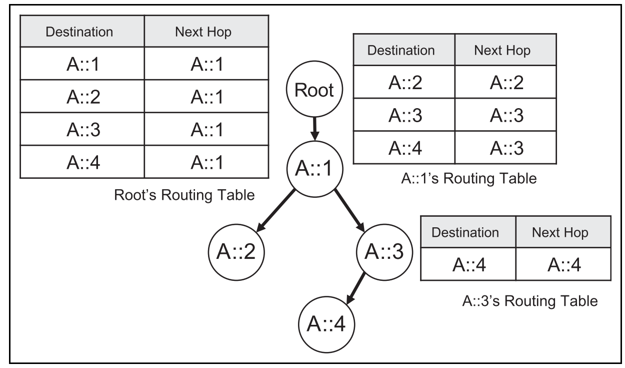

Figure 2. An example of routing tables in a storing mode.

routing topology where all the links are oriented in such a way that no cycle exists. Figure 1 shows an example of DODAG topology.

The DODAG is constructed and maintained using DODAG information object (DIO) messages. The DIO messages have configuration attributes that all RPL nodes should have in DODAG. RPL nodes in the DODAG periodically advertise DIO messages to all other nodes. When RPL nodes receive a DIO message, they decide whether to join in a new DODAG or to maintain the configurations of the DODAG in which they have already joined. After receiving the DIO message, the RPL nodes create a parent set using attributes of the DIO messages and choose a preferred parent from the parent set.

RPL supports two types of routings, upward routing (i.e. from leaf nodes toward DODAG root; solid arrow in Figure 1) and downward routing (i.e. from DODAG root toward leaf nodes; dotted arrow in Figure 1). The upward routing requires only minimal storage space for routing information because all nodes associated with DODAG have to convey packets toward their preferred parent until the packets arrive at a DODAG root. In the downward routing, in contrast, more information and storage space are required than the upward routing because the downward routing requires reverse path information of DODAG.

A downward routing path is generated using Destination Advertisement Object (DAO) messages after the generation of a DODAG. The DAO consists of destination information. RPL nodes transmit a DAO upward to propagate a destination information along DODAG after participating in DODAG. The RPL nodes use the destination information of the DAO to create a routing table for the downward routing.

The downward routing of RPL has two modes. One of the two modes is a storing mode and the other is a non-storing mode. In the storing mode, RPL nodes use routing information to select next-hop for packet forwarding. The routing information is stored separately in each router of an RPL network in the storing mode. When a packet arrives at a router, the router analyzes the routing information and selects a next-hop of the packet. In order to perform the selection of paths, every router in the storing mode should guarantee to keep routing information with a reference to entire sub-DODAGs. The sub-DODAG of a router is the set of nodes whose paths to a DODAG root pass through that router. In the non-storing mode, all the routing information is stored in a DODAG root, not routers. The DODAG root makes all decisions relevant to establish downward routing paths. The DODAG root uses a source routing when sending downward packets. In the source routing, the packets include a routing information from source to destination.

There are differences in DAO message transmission between the two modes for downward routing, so the method for storing routing information is also different. In case of storing mode, a node sends a DAO message to a preferred parent. The parent which receives the DAO message updates a routing table and then sends it again to a grandparent. RPL nodes repeat this procedure until the DAO message reaches a DODAG root. In the non-storing mode, a node sends a DAO message directly to a DODAG root, and routers do not process the DAO message. The DODAG root manages a routing table including entire downward routing paths and generates routing information for the source routing.

Figure 2 shows an example of the routing tables managed by RPL routers in a storing mode. Nodes A::1 and A::3 are working as routers, and nodes A::2 and A::4 are working as leaf nodes. The packet from a DODAG root toward node A::4 is transmitted via nodes A::1 and A::3 referenced by routing information stored in routers. In order to accomplish the packet transmission in this storing mode, every router node must possess a routing table that contains a route information toward all nodes of their sub-DODAG.

Figure 3 illustrates an example of downward packet transmission in a non-storing mode. When a downward

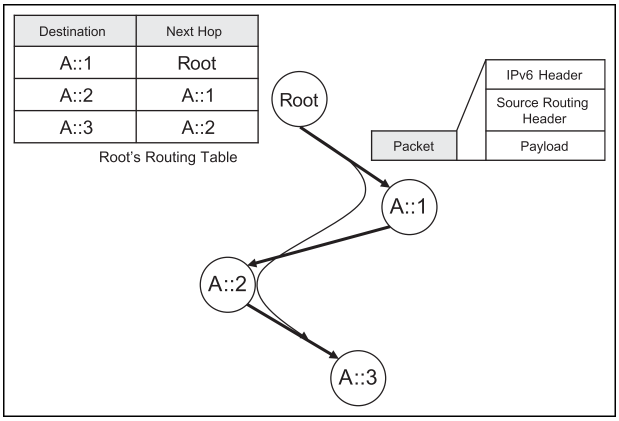

Figure 3. An example of downward packet transmission in a non-storing mode.

packet is generated from the DODAG root, the DODAG root creates a routing header for performing source routing referenced by a routing table recursively and attaches it to the packet. A packet toward node A::3 includes a routing header containing the addresses of the nodes A::1, A::2, and A::3. RPL nodes forward the packet to a destination referenced by addresses in the routing header.

Problems of two modes of RPL downward routing

RPL has two types of downward routing modes: storing and non-storing modes. The two modes have shortcomings to compete with each other. This section will discuss disadvantages of the two modes when mobile nodes join in DODAGs.

In the non-storing mode, a source routing is used for packet transmission, but the source routing may cause delays and packet loss.[9,10] In order to perform the source routing, the non-storing mode stores all routing path information in a DODAG root. The DODAG root generates additional parts of a routing header including information for source routing. Therefore, the non-storing mode would be advantageous to memory-constrained nodes.[12,13] However, the non-storing mode may cause packet fragmentation when the length of the route toward a destination becomes longer because all paths have to be stored in the routing header. The packet fragmentation leads to use of more packets for carrying the same amount of information. Thus, delays and packet loss are caused by the fragmentation.

The storing mode also has a weakness. In this mode, downward routing information is stored separately among routers, and the packet transmission is carried out using this stored information. A packet forwarding is possible without any additional information, but there is a drawback that routers closer to a DODAG root need more storage space because they have to guarantee to keep routing information with reference to entire sub-DODAGs.[12] This shortcoming suppresses scalability of the network with which limited memory nodes are configured.

The aforementioned innate defect of the storing mode may be exacerbated in the possible situation when mobile nodes come in a DODAG network. The mobile nodes are allowed to roam freely on the DODAG network without cleaning up existing trails of routing tables that have been kept in nodes which were previously participated in. For this reason, in the storing mode, routers may need extra storage space for storing routing information of mobile nodes.

Figure 4 shows an example for routing table state according to the movement of a mobile node. Figure 4(a) illustrates the appearance of a network before the mobile node moves, and Figure 4(b) shows subsequent changes. When a node A::3 moves from the range of a old parent A::1 to a new parent A::2, the routing information is stored redundantly in both the parent nodes. The shaded routing table entry of node A::2 in Figure 4(b) is the newly added routing information. It overlaps with the existing information that was used earlier (the shaded routing table entry of node A::1 in Figure 4(b)). If the movement of the mobile node happens frequently in the situation, a storage space shortage will be spread to the entire network, as well as near the root, and then can deteriorate a situation to a routing failure.

There are several studies solving the storage space shortage problem of the downward routing modes. The MERPL[10] limits the number of routing entries to solve the problem. If the number of routing entries exceeds a limited value, the routing information of the biggest sub-DODAG among child nodes is removed, and the information is stored at a DODAG root. After the moving of routing information, the DODAG root uses source routing for packet transmission to nodes where routing information is managed at the DODAG root. By applying the MERPL technique, nodes can configure a large-scale network with only the limited routing storage space.

The D-RPL[11] uses a multicast mechanism to solve the storage problem. All nodes might fail to advertise a DAO message because of the limited memory space of a parent node. The nodes that failed to advertise join a special multicast group to send data to a destination for which it does not have a route. For example, when the root wants to send a packet to a destination for which it does not have a route, it simply sends packets to all the member nodes of the special multicast group. This technique can be used to overcome the memory limitation of nodes, thereby improving the scalability of the storing mode.

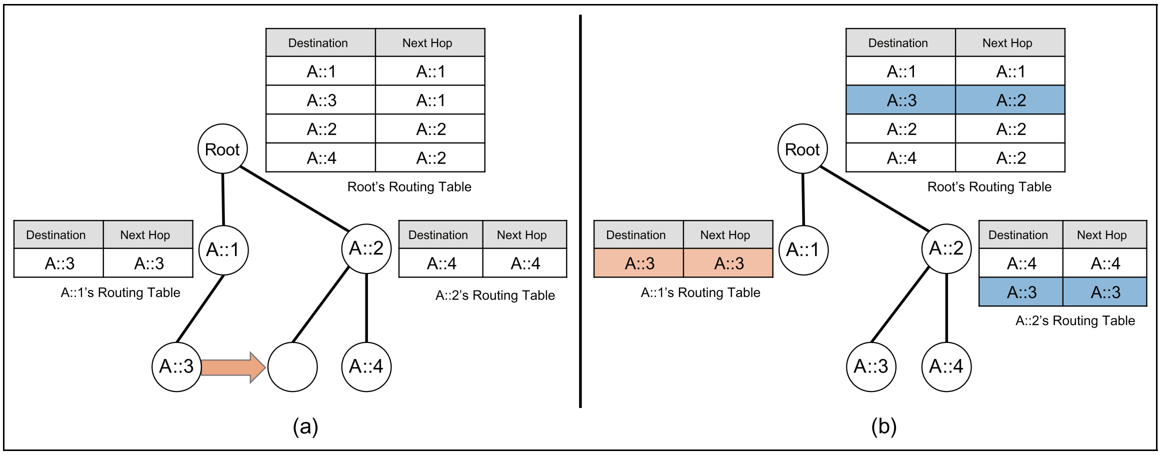

Figure 4. State of the routing table according to the movement of a mobile node in the storing mode: (a) the appearance of the network before the mobile node moves and (b) the appearance of the network and state of the routing table information after the mobile node moves.

The DualMOP-RPL[14] focuses on a interoperability problem between downward routing modes. It addresses a connectivity problem in a single network which consists of nodes operating as either the storing mode or the non-storing mode. To solve the connectivity problem, in DualMOP-RPL, the router stores the routing information and processes the source routing. Through this, all of nodes could operate in a single network regardless of the downward routing mode.

Carels et al.[15] analyzed the conditions during which packet loss can occur in the downward routing process for mobile nodes in an RPL network. Unlike the existing studies on the mobility in RPL that primarily covered the selection of a parent node of a mobile node, this study focused on the conversion of routing information according to the movement of the mobile node. When a DODAG root receives DAO after a parent node of a mobile node is changed, a new route cancellation technique is applied where No-path DAO is transmitted to the previous routes to delete the mobile node information. This could prevent packet loss resulting from inaccurate routing information.

Proposed hybrid operation mode

A novel hybrid mode for downward routing is proposed in this section. The hybrid mode could overcome limitations of downward routing methods in RPL by reducing routing information in router and using a fixed length routing header. The proposed hybrid mode modifies the two parts of RPL downward routing as follows:

(1) *Routing information management*. All the routing information for leaf nodes are stored in a DODAG root like the non-storing mode but the information except for leaf nodes is collected in RPL routers. For this purpose, we modify the DAO transmission mechanism to segregate routing information of leaf nodes from routers.

(2) *Downward packet transmission toward leaf nodes*. We modify the downward packet transmission toward leaf nodes using the segregated routing information. A new IPv6 extension header has been defined for the modified downward packet transmission in the proposed hybrid mode. We will call the new IPv6 extension header as hop extension header (HEH) in this article.

Routing information management

In RPL, a routing information should be managed only on either RPL routers or a DODAG root. However, the proposed hybrid mode distributes the routing information to RPL routers and a DODAG root. The routing information is located according to destination of DAO messages that are transmitted by RPL nodes. DAO messages are sent to the appropriate destination depending on the type of nodes (RPL router or DODAG root). If the type of node is RPL router, the destination of DAO message is the parent of its DODAG. On the other hand, DAO messages that are sent from leaf nodes are delivered to a DODAG root. A DODAG root receives DAO messages from two types of nodes (router and leaf). For distinguishing the type of source nodes in the received DAO message, the proposed hybrid mode uses transit information in RPL control message options. The transit information option in RFC6550 is mandatory for identifying the type of communication nodes.[8] Leaf nodes transfer

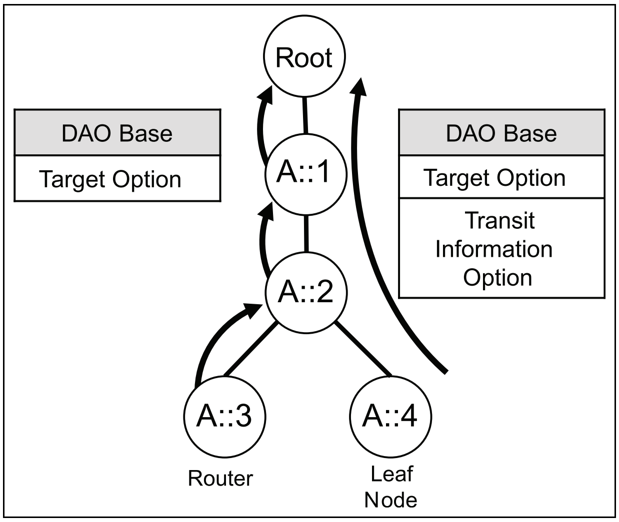

Figure 5. Difference in DAO transmission method between a leaf node and a router.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Next Header  |  Hdr Ext Len  | Routing Type  | Segments Left |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| CmprI | CmprE |  Pad  |               Reserved                |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
.                                                               .
.                        Addresses[1..n]                        .
.                                                               .
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 6. A format of source routing header (SRH).

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Next Header  |  Hdr Ext Len  | Routing Type  | Segments Left |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Cmpr  |  Pad  |                   Reserved                    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                            Address                            |
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 7. A format of hop extension header (HEH) derived from TYPE-0 Routing Header (RH0).

DAO messages adding the transit information option that has parent information to the DODAG root after joining an RPL network. The DODAG root creates a leaf–parent relation table using DAO messages of leaf nodes. The leaf–parent relation table includes relation information between leaf nodes and own parent node. According to this modified DAO transfer method, all the routing information of the leaf node that consist of its destination and parent address are stored in the DODAG root, and every router has routing information in terms of its own entire sub-DODAGs which do not have any leaf nodes.

The process for transferring DAO message is shown graphically in Figure 5. A node A::3 is a router and a node A::4 is a leaf node. These two nodes send DAO messages toward DODAG root using different methods depending on the type of nodes after a joining process. There are two routers (node A::1 and node A::2) between a DODAG root and new participant nodes (node A::3 and node A::4). These two nodes could relay DAO messages from leaf nodes to the DODAG root or make tables for its entire sub-DODAGs which include router nodes.

RPL HEH

In order to conduct routing process in the proposed hybrid mode for downward routing, a special-purpose field is required in IPv6 header fields. The new IPv6 header format is structured based on the TYPE-0 Routing Header (RH0) of RFC 2460 and the format is named RPL HEH.[16] It has a form similar to the source routing header (SRH) defined in RFC 6554.[13] A path of entire routes should fully be enclosed in SRH. On the other hand, HEH includes only one-hop path route from a parent to a child. Figures 6 and 7 present examples of an SRH and an HEH structure, respectively.

In the HEH, the *Cmpr* field is the number of prefix octets. The prefix could be elided from the address field because the nodes in a network use the same prefix. The *Pad* field is the number of octets that are used for padding after the address field at the end of the HEH. The *Address* field is a final destination address and the size of the field is $16 - Cmpr$. The length of SRH and HEH is calculated by equations (1) and (2), respectively. The SRH length is at least 16 bytes and increases correspondingly to the number of hops between an actual source and destination. The length of the HEH is at least 16 bytes ($Cmpr \geq 8$) and at most 24 bytes ($Cmpr < 8$). For this reason, HEH is always shorter than SRH

$$len_{SRH} = \left\lceil \frac{((16 - CmprI) \times (Num_{Hop} - 1) + (16 - CmprE))}{8} \right\rceil \times 8 + 8 \tag{1}$$

$$len_{HEH} = \left\lceil \frac{(16 - Cmpr)}{8} \right\rceil \times 8 + 8 \tag{2}$$

HEH is used in the downward packet transmission after a routing information has been formed using DAO messages. In the proposed hybrid mode, the HEH is used only for the downward packet transmission that has leaf node as destination. However, any additional routing headers are not used in the transmission of packet which has router as destination. To

Algorithm 1. Packet transmission process in a DODAG root.

---

d $\leftarrow$ *the destination of the packet*
p $\leftarrow$ *the payload of the packet*
parent $\leftarrow$ *lookup_leaf_relation*(d); {lookup destination address from the leaf-parent relation table}
if *parent* $\neq$ *NULL* **then**
  if parent is me **then**
  send_packet(d, p) {the destination is a leaf that is a child of DODAG root}
  else
  optHdr $\leftarrow$ *generate_hop_ext*(d)
  send_packet$(parent, optHdr, p)$ {the destination is a leaf that is a child of a router}
  end if
else
send_packet(d, p) {the destination is a router}
end if

---

deliver a downward packet to its destination, the DODAG root may need to generate an HEH and it is used in the last hop of the packet transmission phase.

The operation of downward packet transmission in proposed hybrid mode

In this section, we describe the operation of downward packet transmission in hybrid operation mode that uses the distributed routing information and the HEH. The downward packet transmission in the proposed hybrid mode is similar to the storing mode, except for packet generation at DODAG root and packet transmission from parent routers to leaf nodes.

An occurrence of downward packet transfer is initiated from a DODAG root. First, the DODAG root confirms the destination of a packet to transmit. The leaf–parent relation table of the DODAG root is used to determine whether the destination of the packet was a leaf node. If the destination is a leaf node, the DODAG root changes the packet destination to parent router address of the leaf node. Then, an HEH containing the leaf node address is added to the packet. The packet joined by the HEH is transmitted to the changed destination address. If the packet destination is not a leaf node, it is directly sent to the destination address without any process added. Algorithm 1 describes the packet transmission process at DODAG root as a pseudocode.

A packet generated from a DODAG root is sent to the parent router of the destination via intermediate routers. The intermediate routers use routing information stored at routers to send the packet to the destination as in storing mode. The HEH added to the packet by the DODAG root is used after the packet arrives at a destination router. As soon as the packet arrives at the destination router, the destination router checks for

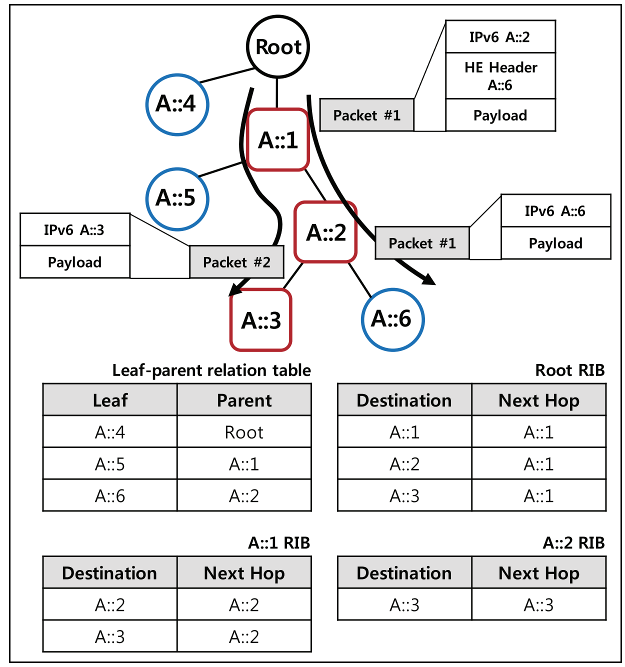

Figure 8. An example of downward packet transmission in the proposed hybrid mode.

the presence of HEH. The presence of HEH means transmission over one more hop to the packet's final destination. After confirming the HEH, the destination router modifies the packet destination to the address in the HEH before sending the packet to a final destination.

An example of the packet transmission in the proposed hybrid mode is shown in Figure 8 where the rectangles and circles represent router nodes and leaf nodes, respectively. A packet 1 is transmitted to node A::6 (leaf node) and a packet 2 does to node A::3 (router) as their respective destinations. The DODAG root refers to a leaf–parent relation table for routing of the packet 1. It places a node A::6 on the address field of HEH to transmit the packet to a node A::2. The packet 1 is delivered to node A::2 using the routing information of routers. As soon as the node A::2 receives packet 1, the node checks HEH information before sending the packet to a node A::6. In case of the packet 2, the DODAG root confirms that the packet destination address is not listed on the leaf–parent relation table and then the root transmits the packet to a node A::3. The packet 2 arrives at node A::3 using routing information of routers.

Comparison with the existing downward routing modes

In this section, we compare the proposed hybrid mode with the existing downward routing modes. Table 1 presents the comparison among those modes. In the

Table 1. Comparison between the proposed hybrid mode and existing downward routing modes.

	Required routing table size	Length of routing header	P2P communication
Storing	The number of nodes in the network	None	Through common ancestor
Non-storing	None	Variable (SRH)	Through DODAG root
MERPL	None (use only the number of entries configured)	Variable (SRH)	Through DODAG root
D-RPL	None (use only the number of entries configured)	Variable (multicast)	Through DODAG root
DualMOP-RPL	The number of nodes in the network	Variable (SRH)	Through common ancestor
Proposed hybrid	The number of routers in the network	Fixed (HEH)	Through DODAG root

DODAG: Destination-Oriented Directed Acyclic Graph; RPL: routing protocol for low power and lossy networks; SRH: source routing header; HEH: hop extension header.

Table 2. Simulation configuration.

Parameter	Value
Simulator/version	Cooja/Contiki OS 2.7
Simulation time	3000 s
Radio environment	Unit Disk Graph Medium (UDGM)
Area	130 m × 130 m
Simulated platform	Tmote Sky
Transmission range	50 m
Interference range	50 m
Tx success ratio	100%
Rx success ratio	100%, 80%
Mobility model	Random waypoint model
Speed	1 m/s

proposed hybrid mode, a router stores routing information (like the storing mode), and a packet includes an HEH (like the non-storing mode). However, a router using the proposed hybrid mode requires smaller storing capability for routing information than a router using the storing mode in same network size and a node using the proposed hybrid mode uses smaller routing header than a node using the non-storing mode. In the scenarios of downward packet transmission of RPL networks consisting of a fixed number of static routers and a large number of mobile nodes, the proposed hybrid mode uses a fixed length in the size of routing header and a limited storage for storing routing information.

Although MERPL and D-RPL provide scalability in the storing mode while limiting the number of routing entries in routers, these schemes may cause some disadvantages due to the nodes' mobility. If the mobility of the node increases the usage of the router's routing entry, MERPL may increase the routing overhead to the same level as the non-storing mode due to the SRH. D-RPL may increase network traffic due to use of multicasts which are sent as link-local broadcasts. In DualMOP-RPL, it has both disadvantages of the storing and non-storing modes because it uses both routing information storage and source routing in routers.

In the hybrid mode, communication between nodes is sent through the DODAG root in the same way as the non-storing mode. When a node sends a packet to another node, the packet is forwarded to the DODAG root using the default route, and then the DODAG root generates the route to the destination of the packet and forwards it. In addition, inter-router communication in hybrid mode is carried out using the first common ancestor of two routers in the same way as the storing mode.

Simulation environment

In previous section, we proposed a hybrid mode to enhance the downward route performance in RPL. The proposed hybrid mode has been implemented in Contiki OS[17] environment in order to compare with the two existing downward routing modes in RPL for performance evaluation. The simulation environment was set up in Cooja network simulator[18] with the configuration parameters of Table 2. Regarding the radio environment, we use a Unit Disk Graph Medium (UDGM) radio model. We use a mobility plugin for Cooja[19] for applying mobility to mobile nodes in each simulation. Waypoints of mobile nodes have been created based on a random waypoint model.[20]

We compared the performance of the proposed hybrid mode with the conventional storing and non-storing modes through three simulations. In the first simulation, we compare the storage space usage of the routing table for each mode according to the number of mobile nodes. In this simulation, we use a grid topology which is composed of 16 static routers and a DODAG root as shown in Figure 9. We measure the number of routing entries used by each router by changing the number of mobile nodes for three routing modes. We also performed the same experiment using static leaf nodes. Through this, we compare the number of routing entries of routers with respect to leaf node mobility. In evaluation, we represent static leaf nodes as leaf nodes.

In the second simulation, we compare the packet delivery ratio of the upward and downward routing cases according to the number of mobile nodes. Every mobile node sends a packet to the DODAG root and

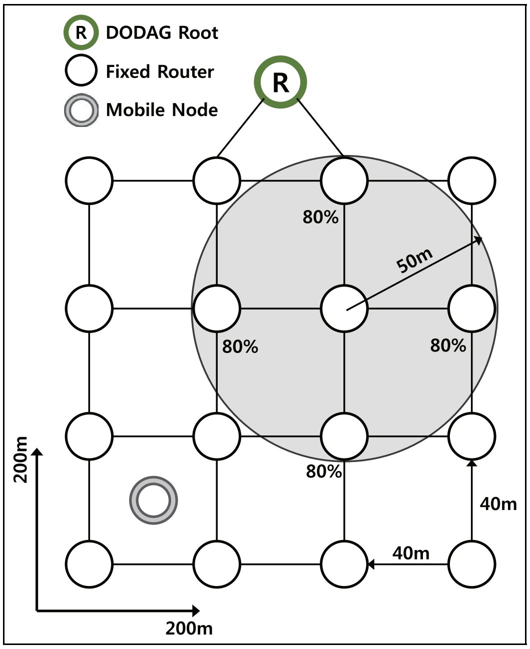

Figure 9. A grid network topology with 16 static routers.

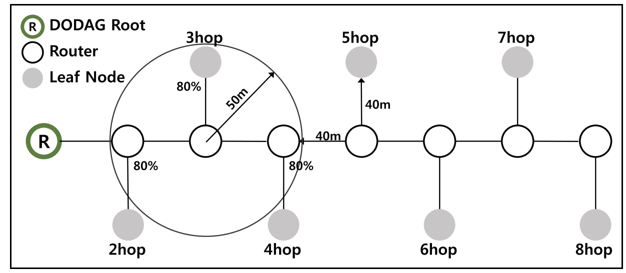

Figure 10. A linear network topology with seven static routers.

the DODAG root sends a reply packet to the node. We measure the upward and downward packet delivery ratio for each mode with the grid topology shown in Figure 9 with 10–20 mobile nodes deployed. In addition, we measure the upward and downward packet delivery ratio in each mode with the grid topology with 10–36 leaf nodes deployed. Also we set the receiving (Rx) success ratio to 100% and 80%, respectively. In this simulation, we set up the maximum routing table size to 20 which is the default value of Tmote Sky platform in Contiki OS.

In the last simulation, we compare the end-to-end delay variation for each mode according to the number of hops. In this simulation, we use a linear topology which is composed of seven static routers and a DODAG root as shown in Figure 10. We then deploy the same number of leaf nodes as the number of routers. Each leaf node is placed in a location where it can communicate only with one router. We measured the end-to-end delay per the number of hops by measuring the time taken to transmit a packet to the DODAG root for each leaf node. Also we set the Rx success ratio to 100% and 80%, respectively. In the experiments, leaf nodes and mobile nodes transmit 20-byte packets every 60 s after generating the DODAG topology.

Performance evaluations

Routing table size

Figure 11(a) presents the average number of routing entries in a router according to the increasing number of leaf nodes in the proposed hybrid, storing, and non-storing modes. In case of non-storing mode, as the routing information is not stored in a router, the number of the routing entries is always zero regardless of the increasing number of leaf nodes. In case of storing mode, since all routing information is managed in a router, the number of routing entries increases in proportion to the number of leaf nodes. In case of the proposed hybrid mode, however, the router does not store routing information for leaf nodes, thus showing a certain size of routing entries despite the increase in the number of leaf nodes.

Figure 11(b) illustrates the distribution of routers according to the number of routing entries on each operation mode as cumulative distribution function (CDF). In proposed hybrid and non-storing modes, the number of routing entries for all nodes is 20 or less regardless of the increase in the number of leaf nodes. The ratio of routers using 20 or more routing entries is 5% for 25 leaf nodes and 12.5% for 35 leaf nodes in the storing mode. As a router came closer to a DODAG root at RPL, the size of sub-DODAG became bigger and more routing information storage was required. As the number of leaf nodes increases, the number of routers that use more than 20 routing entries increases from the periphery of the DODAG root.

Figure 11(c) and (d) shows the average number of routing entries in a router and the distribution of routers according to the number of routing entries with the increase in mobile nodes in number. In proposed hybrid and non-storing modes, the required size of routing table is constant regardless of the increase in mobile nodes in number. In the simulation, the storing mode shows that the required size of routing table increases faster than the experiment with the previous leaf node. Thus, the hybrid mode used fewer routing entries than the storing mode, and the number of routing entries in a router was fixed despite the varying number of leaf and mobile nodes.

Packet delivery ratio

Figure 12 exhibits the end-to-end delivery ratio of upward packet from a leaf node and that of the

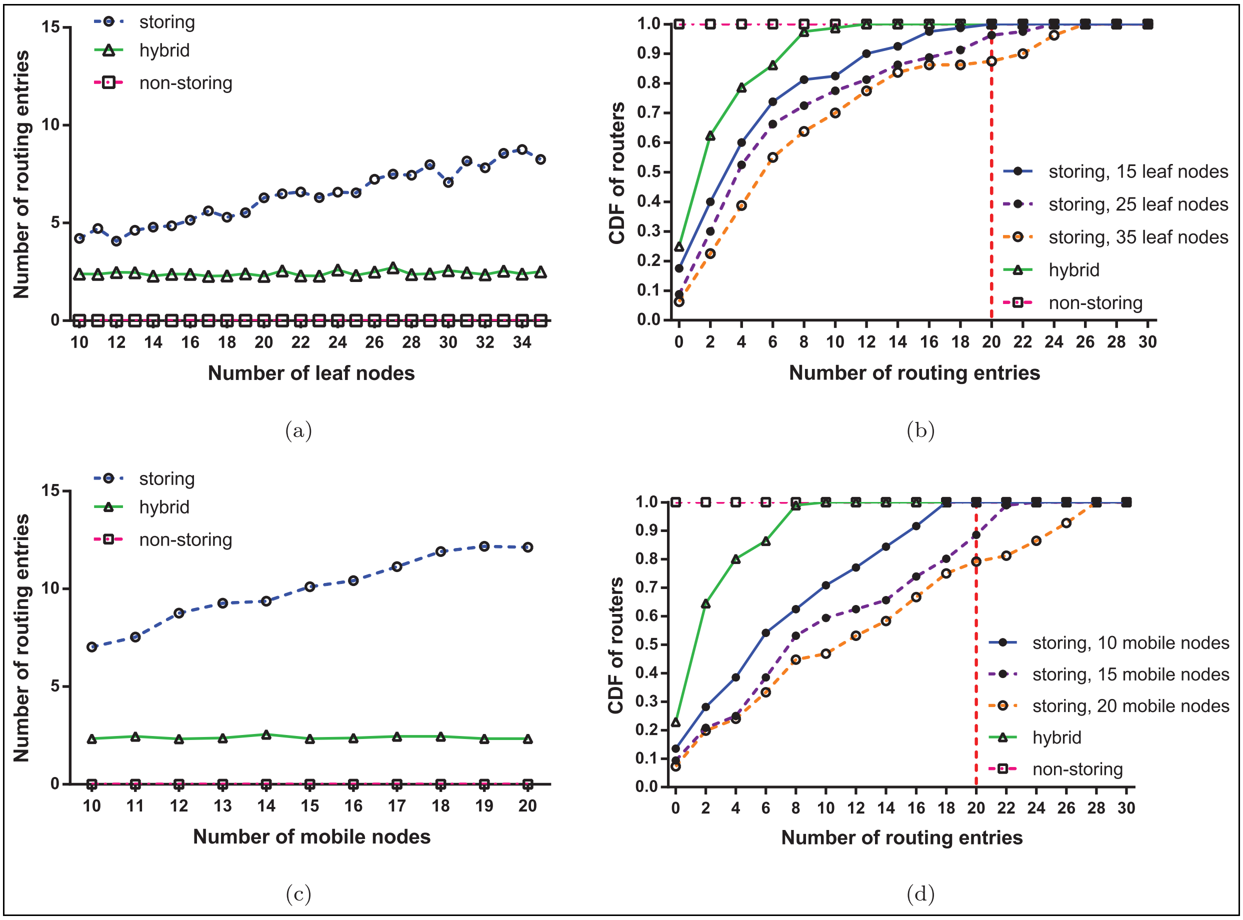

Figure 11. A routing table size of a router required according to the number of leaf nodes: (a) average number of routing entry for the number of static leaf nodes, (b) CDF of routers for the number of routing entries in case of static leaf nodes, (c) average number of routing entry for the number of mobile nodes, and (d) CDF of routers for the number of routing entries in case of mobile nodes.

downward packet for a leaf node in each mode. The upward end-to-end packet delivery ratio from a leaf node to a DODAG root was 100% without the number of leaf nodes in each mode. However, the downward end-to-end packet delivery ratio transmitted from the DODAG root showed much difference depending on the applied modes. It is found from Figure 12(b) and (d) that the downward end-to-end packet delivery ratio sharply dropped down when the number of leaf nodes becomes 24 or more in the storing mode. The routers lose their routing information when the routing storage space needed for 25 or more mobile nodes becomes greater than the routing storage space (20 at Tmote Sky) of the node. The loss of routing information can result in the drop of the packet delivery ratio. Figure 13 exhibits the end-to-end delivery ratio of an upward packet from a mobile node and that of the downward packet for the mobile node in each mode. In Figure 13, the end-to-end delivery ratio of downward packet in non-storing mode is reduced more rapidly than non-mobility environment because the router requires a larger size of routing table for node movement.

In Figures 12 and 13, the end-to-end delivery ratio of downward packet in the non-storing mode is about 10% lower than the proposed hybrid mode as the Rx success ratio is 80%. As the length of HEH is shorter than that of SRH, the proposed hybrid mode produced better performance than the non-storing mode.

End-to-end delay

Figure 14 shows the average end-to-end delay of the three modes according to the increase in hops in number where each node's Rx success ratios are 100% and 80% in packet transmission. If the Rx success ratio is 100%, the three modes generated almost the same delay value regardless of hops of packet transmission. When the Rx success ratio is 80%, the storing mode produces the lowest delay, with increasing delay in the hybrid and non-storing modes.

This experiment showed that the additional routing header does not affect the performance of packet transmission in a stable network. However, it showed that the packet size increased by additional routing headers

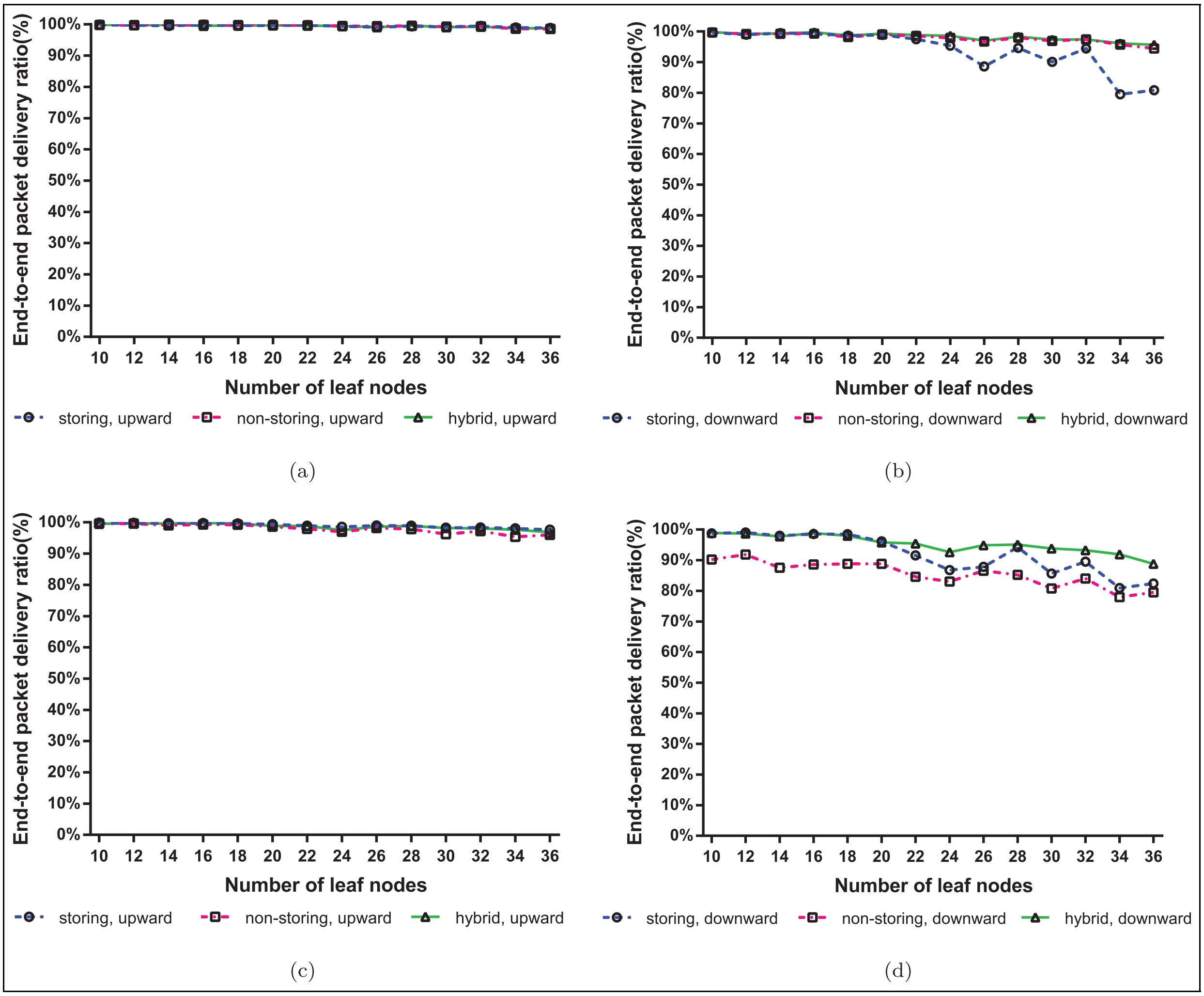

Figure 12. An end-to-end packet delivery ratio according to the number of static leaf nodes: (a) upward, receiving ratio of 100%; (b) downward, receiving ratio of 100%; (c) upward, receiving ratio of 80%; and (d) downward, receiving ratio of 80%.

had a significant influence on the transmission performance because of packet fragmentation and re-transmission occurred as the network communication became unstable. As the proposed hybrid mode used the routing header of a fixed size, it generated higher end-to-end delay than the storing mode that did not employ an additional routing header. However, it demonstrated better performance than the non-storing mode, under which the length of the header was proportional to the increase in hops.

Conclusion

In this article, we proposed a hybrid mode to address the problems in the two existing downward routing modes in RPL. The proposed hybrid mode stores a routing information by distributing the information to a DODAG root and routers. Then, the proposed hybrid mode provided a solution for the scalability issue occurred from resource limitation of routers in the storing mode as well as the increase in the fragmentation stemming from routing overhead in the non-storing mode.

We implemented the proposed hybrid mode with Contiki OS. Also we compared its performance with that of the two existing modes through a simulation. Simulation results show that the proposed hybrid mode use less routing entries than the storing mode and has a lower end-to-end delay than the non-storing mode. As a result of these two positive effects, the hybrid mode shows a better packet delivery ratio than the storing and non-storing modes. The proposed hybrid mode is suitable for networks where a fixed number of routers must accommodate a large number of leaf nodes.

During the experiments, we encountered the performance degradation of packet transmission incurred

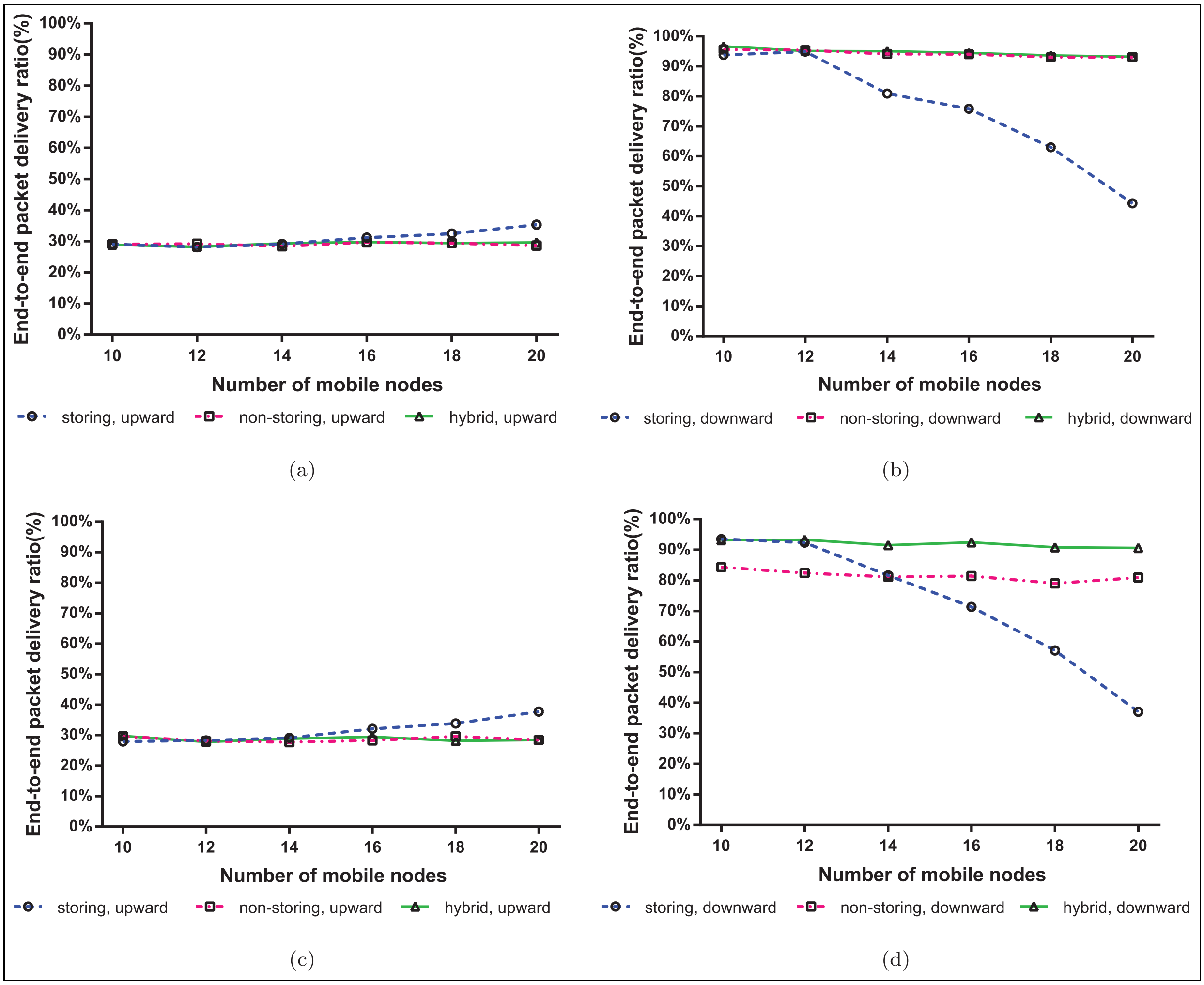

Figure 13. An end-to-end packet delivery ratio according to the number of mobile nodes: (a) upward, receiving ratio of 100%; (b) downward, receiving ratio of 100%; (c) upward, receiving ratio of 80%; and (d) downward, receiving ratio of 80%.

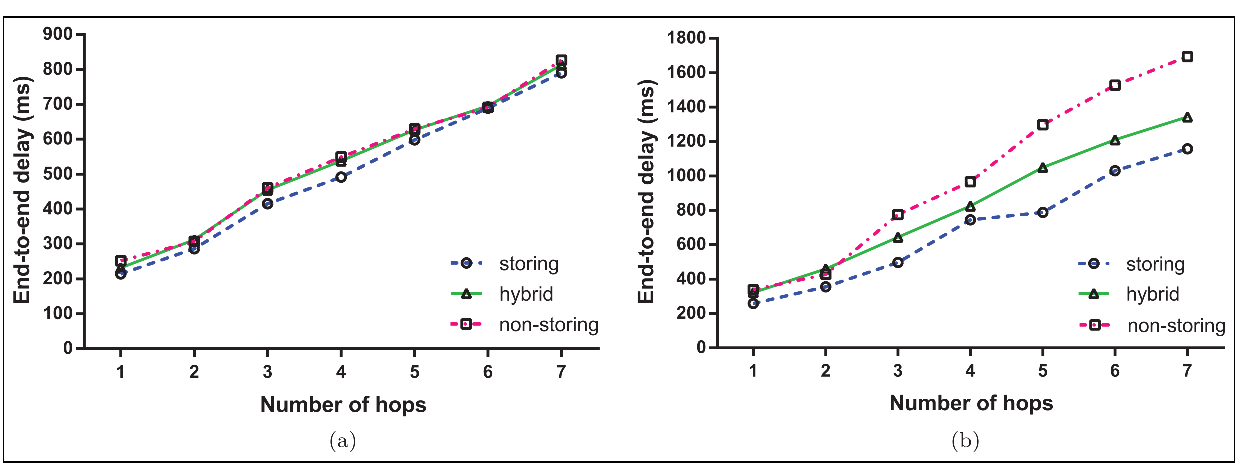

Figure 14. An end-to-end delay of downward packet according to the number of hops: receiving ratio of (a) 100% and (b) 80%.

from node mobility in RPL. The mobility support in LLNs is an important issue for extension to various application environments. In future work, we will conduct additional research on mobility support to enhance the packet transmission performance in a large-scale network.

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