Load Balancing Techniques for Extending Smart Metering System Lifetime

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***Abstract*—In smart metering systems, when the density of node is high or distance of communication range is large, the adjacent node number becomes large. If routing based on the number of hop from the sink node is used in such a network, the deviation of load will become large and it will shorten the network lifetime, also degrades other network performance. In this paper, we proposed the techniques solving the above-mentioned problem as routing technique and intermittent interval control technique. The sender node control reduces differences in load and throughput resulting from topology by bypassing to sideward nodes. In the receiver node control, data reception probability is controlled by adjusting the intermittent interval. Simulation results show that proposal technique prolonged the network lifetime by about 53%, and reduced the average delay time by about 21%, comparing with existing method.**

I. Introduction

In recent years there has been increased interest in wireless ad hoc networks in which nodes autonomously form a network. Wireless networks allow easy collection and management of sensing information without special infrastructure, making large-scale applications in wireless ad hoc networks attractive. One such application is smart metering systems, where each meter incorporates wireless communication functions. Meters are installed in each room of a home, creating a wireless ad hoc network. Each meter transmits data periodically to a central management node, called a sink node. Merits of such systems include automatic meter inspections and optimal supply planning.

Smart metering systems tend to have high node densities and low packet generation frequencies [1, 2]. A drawback, however, is that many such systems must function for several years without requiring battery exchanges. Reducing power consumption is therefore an important problem. Various approaches have been explored, most importantly duty-cycled MAC [3-7] and energy-efficient routing protocols [8-12].

This paper examines wireless networks with large adjacent node numbers and low packet generation frequencies. An example of such a network is a wireless multi-hop network used as a gas metering system in a large-scale apartment. If the communication range is wide and the node density is large, the number of nodes adjacent to each node increases. For such cases, we propose a scheme based on intermittent receiver-driven data transmission (IRDT), and show that energy consumption performance of the proposed scheme exceeds that of other techniques [13]. However, such networks result in increased load variation among nodes with the same number of hops to the sink node. For a given node, an adjacent node with a smaller number of hops to the sink node is called a forward node, and an adjacent node with a larger number of hops is called a backward node. Nodes with the same number of hops are called sideward nodes. Load variation is due to forward and backward nodes having different physical locations. Figure 1 shows an example of variation in load. Here we assume that all nodes are in the same communication range, and we divide the network into three domains by the number of hops to the sink. Nodes A and B are in a domain two hops from the sink. Since node A is located far from the sink node, it has many backward nodes in domain A_b, and few forward nodes in domain A_f. Node B is close to the sink, however, so it receives from few nodes in domain B_b, and transmits to many forward nodes in domain B_f. This topology results in a load deviation problem and increased energy consumption. Such variation in power consumption shortens the life of specific nodes, shortening the operational life of the entire network. Despite this being a problem in many such networks, most existing techniques use only the number of hops for routing. Then, this may happen to the network which performs routing based on the number of hops instead of the problem restricted to the network which adopted IRDT protocol which we are using as the target of

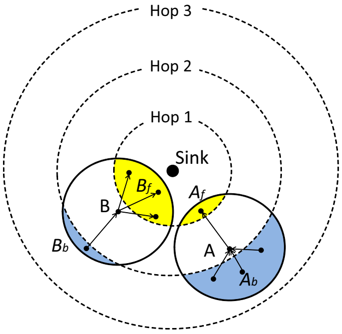


Fig. 1. Load variation originates in differing forward and backward node counts due to physical location.

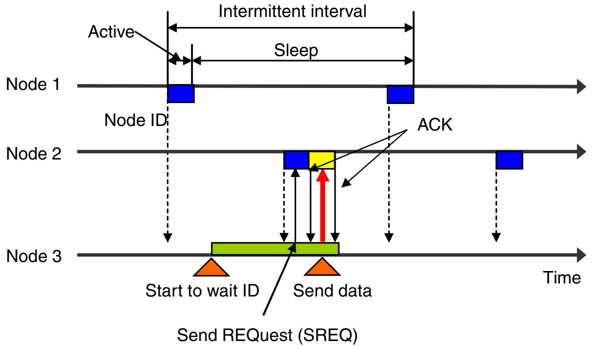
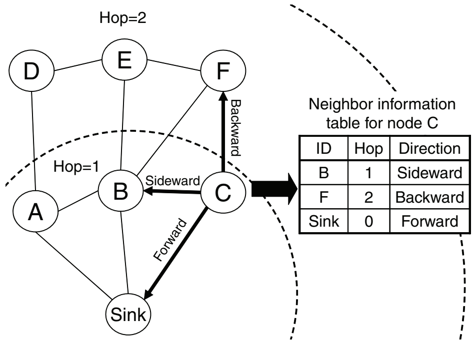


Fig. 2. Data transmission process in the MAC layer of the IRDT protocol.



ID	Hop	Direction
B	1	Sideward
F	2	Backward
Sink	0	Forward

Fig. 3. Example of neighbor information table for routing in IRDT

this research. The previous researches on the load balancing in sensor networks had many which aimed at dissolution of a hot spot [14], and equalization of the power consumption by clustering [15]. However, researches which paid their attention to the deviation of the load resulting from network topology like this research are scarcely carried out.

To solve the above-mentioned problem, this paper proposes a load balancing technique for smart metering systems with many adjacent nodes and high density. The technique controls load balancing in each send and receive node. The sender node control reduces differences in load and throughput resulting from topology by proactively bypassing to sideward nodes. In the receiver node control, data reception probability is controlled by adjusting the intermittent interval based on the node load and throughput. These techniques should balance loads across the network, prolonging life and improving packet delay time. We evaluated performance of the technique through computational simulations of a network topology in a real apartment. We compared our proposed technique with an existing IRDT system, using network lifetime, average delay, and packet collection ratio as comparison metrics, and the time until the first battery depletion as the network lifetime.

This paper is organized as follows. Section II outlines the basic operation of an IRDT system. Section III explains the proposed load balancing technique. Section IV evaluates the proposed technique. Finally, section V presents our conclusions and suggests directions for future work.

II. OVERVIEW OF IRDT

A. MAC Protocol

In the IRDT protocol, each node intermittently wakes and transmits its ID to adjacent nodes in a very short packet. After waiting for a reply from the node holding send data, if nothing is received after a short time, it sleeps again. Nodes holding transmission data wait for an ID packet from suitable destination nodes, and upon receiving one, respond with a send request (SREQ) packet. After receiving a relay acknowledgement (RACK) packet, the sender transmits its data packet and ends communication following receipt of a data acknowledgement (DACK) packet. Figure 2 shows this intermittent operation involving nodes labeled 1 and 2. Here, the sender node 3 accepts the ID of node 2 as an appropriate receiver. The routing protocol determines receiver appropriateness. Having many nodes suitable as the destination shortens the waiting time for ID packets, reduces power consumption, and improves communication reliability.

B. Routing Protocol

The IRDT routing algorithm is based on multi-hop routing, where each node is involved in relaying the packet. Although minimum-hop routing is preferable for achieving lower energy consumption, in some situations certain nodes cannot be used for minimum-hop routing, owing to poor conditions for radio wave transmission or node failure. Therefore, for higher flexibility, the IRDT routing algorithm considers alternative paths in addition to the minimum-hop route. All nodes update their own *neighbor information table* as topology information by periodically exchanging topology information packets, which they use to determine the number of hops to the sink node. Denoting the minimum number of hops from a node to the sink node as h, its adjacent nodes' number of hops is classified into $h-1$, h, and $h+1$, and we refer to these neighbors as forward nodes, sideward nodes, and backward nodes, respectively. For example, for node C in Figure 3, the sink node is a forward node, node B is a sideward node, and node F is a backward node. For minimum-hop routing, the sender node should select a forward node as a receiver. When a sender receives the ID of a forward node, it returns an SREQ packet. We define a *communication failure* as a situation where the sender cannot obtain RACK or DACK packets from the receiver. When communication with all forward nodes fails, the sender selects a sideward node for the receiver. Furthermore, if communication fails with all sideward nodes, backward nodes are selected as a receiver. All data packets contain a time-to-live (TTL) field to avoid heavy repetition of data relay. For each relay of a data packet, TTL is decremented by one, and when TTL becomes 0, the data packet is discarded.

C. The Problem with IRDT

This paper examines wireless networks where the communication range is long and node density is high, or wireless multi-hop networks where the adjacent node number is large. In such wireless networks, there is a deviation problem of load and throughput, even between nodes with the same number of

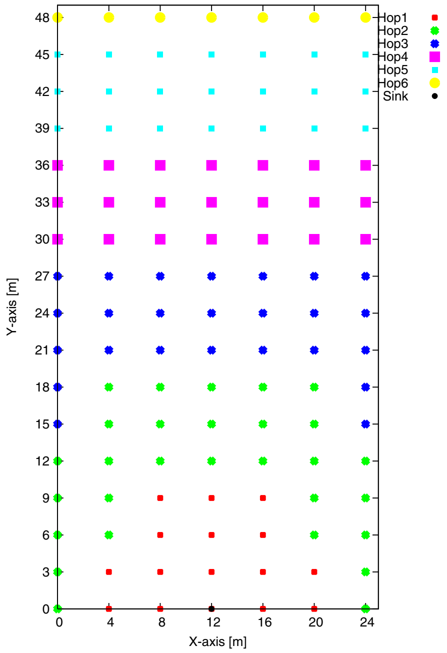


Fig. 4. Topology of a smart metering system in a 17-story apartment building. Node color expresses the number of hops to the sink.

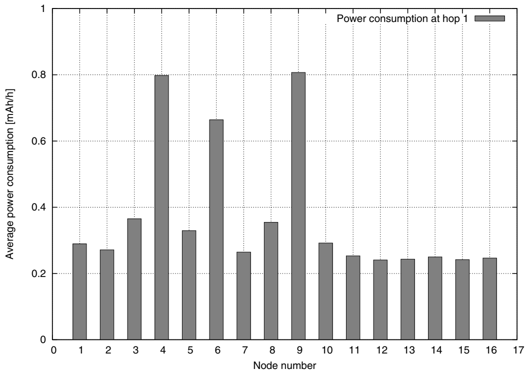


Fig. 5. Average power consumption at 1-hop nodes. The power consumption of nodes 4, 6, and 9 is large, which will result in early battery depletion.

hops to the sink, as physical location can affect the number of forward and backward nodes. The original IRDT routing technique used only the number of hops, regardless of such differences, resulting in varying power consumption among nodes and shortened network lifetimes. Figure 5 shows the average power consumption of all nodes one hop from the sink when the existing IRDT protocol is applied to the topology in Figure 4. Nodes 4, 6, and 9 are far from the sink and have high load, resulting in high power consumption as compared with other nodes.

III. PROPOSED LOAD BALANCING TECHNIQUE

A. *Sender Node Side Control*

Here, we describe sender node control. The number of forward and backward nodes can be considered as an index showing the operational status of a node. If there are many forward nodes, IDs are frequently received from those nodes, decreasing ID wait time before transmitting a packet. If there are many backward nodes sending SREQ packets, the data reception probability increases. Nodes with many backward and few forward nodes will receive many packets, but transmitting packets will take increased time as compared with the other nodes having the same number of hops, thus increasing the node's power consumption. Increasing the number of transmission nodes will improve throughput for such a heavily loaded node, thus performing load balancing.

The IRDT routing technique is a method for determining the probability of a sending node transmitting data when it receives an ID from a receiver node. The original IRDT routing technique determines this probability according to the hop number to the sink node. Our proposed technique uses not only hop number, but also network topology. In addition to the number of hops to the sink, each node also maintains a value indicating its operational status, called its *Relaying Ability* (RA). In the proposed technique, RA is added to the intermittently transmitted ID packet, allowing for easy sharing between adjacent nodes. The probability of data transmission to a certain node is determined according to both the hop number and RA. Each node determines its own RA value in two steps, based on the number of forward nodes N_f and backward nodes N_b.

Step 1:

First, each node calculates RA as the difference between the number of forward and backward nodes according to the following formula. This value expresses the operational status of that node.

$$RA \leftarrow (N_f - N_b) \tag{1}$$

Next, RA values are mutually exchanged by each pair of sideward nodes, each of which counts the number of nodes with higher and lower RA than its own. If the former number is larger the node is classified as a *light* node, and if the latter number is larger the node is classified as a *heavy* node. This heavy or light classification expresses the node's relative operational condition. Figure 6 shows an example of this classification.

Step 2:

Next, each node updates its RA value. Heavy nodes cannot afford increased data relay, and thus set their RA to 0. Each light node updates its RA value, and notifies each sideward node of the new value. The principal idea is that heavy nodes should proactively transmit data to light nodes, because doing so averages the power consumption of certain hop range nodes. When a heavy node transmits data to a light sideward node, it will use the light node's RA value as the probability of data transmission.

Each light node informs all heavy sideward nodes of their RA, and the probability of data transmission forwarding to a light sideward node is determined by this value. Each light

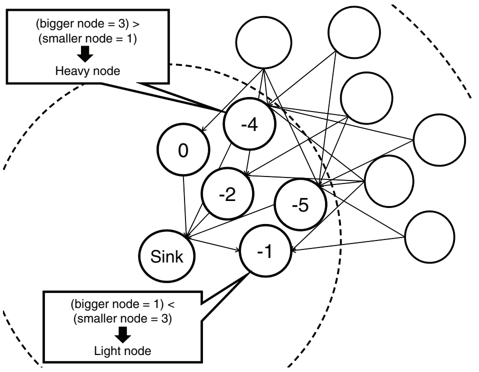


Fig. 6. *Light* and *heavy* nodes. Numbers represent the initial RA value (the difference between forward and backward node counts).

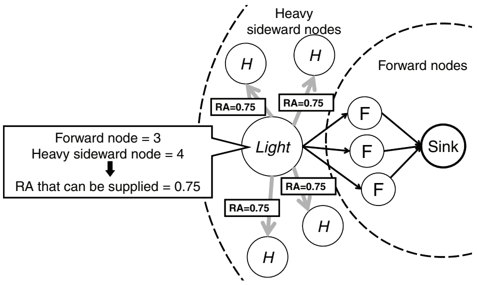


Fig. 7. Light nodes inform all heavy sideward nodes of their RA.

node updates its RA value according to Eq. (2):

$$RA \leftarrow \frac{N_f}{N_{Side}} \cdot \alpha \tag{2}$$

Here, N_f is the number of forward nodes, those nodes that can receive data transmissions. Data can be transmitted easily if there are many forward nodes, while throughput decreases when there are few forward nodes. We presume that throughput is proportional to RA. N_{Side} is the number of heavy sideward nodes. If this number is large RA is small, and if this number small RA is large. Therefore, this number is in inverse proportion to RA. α is a constant for adjusting RA to a suitable value. If the deployment density of nodes is high, and load balancing needs to be performed more powerfully, the value of α needs to be large.

B. Receiver Node Side Control

Here, we describe receiver node control and consider the load distribution technique for determining the intermittent interval from the number of forward and backward nodes. Nodes with many backward (large load) and few forward (weak throughput) nodes consume excessive power to relay data. Such nodes should therefore have a longer intermittent interval to reduce the amount of data received. On the other hand, nodes with sufficient forward nodes and few backward nodes should use a shorter intermittent interval to increase the amount of data received, thus equalizing power consumption. Assigning intermittent intervals in consideration of throughput or load between nodes can equalize the number of times data is received.

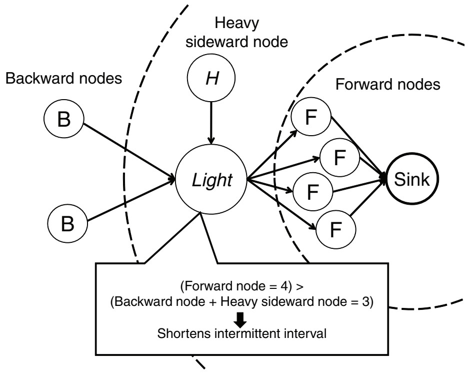


Fig. 8. A light node shortens its intermittent interval.

Here, we propose a technique for determining intermittent intervals which uses the RA value calculated in Step 2 of the previous section. We define T_0 as the initial intermittent interval, and T_t as the intermittent interval at time t.

- Light Nodes
  Light nodes raise their data relaying frequency when the number of forward nodes N_f is larger than the sum of the number of backward nodes N_b and the number of heavy sideward nodes N_{Side} (Figure 8). The shortened intermittent interval is calculated according to Eq. (3). Note that there should be an upper limit to the value change to prevent increasing the load by too much.

$$T_{t+1} \leftarrow \max\left\{T_t \cdot \frac{N_b + N_{Side}}{N_f}, \frac{T_0}{2}\right\} \tag{3}$$

- Heavy Nodes
  A heavy node sets a longer intermittent interval to lower data relaying frequency when it does not have sufficient RA from light sideward nodes and forward nodes. This occurs when the backward node number N_b is larger than the sum of the forward node number N_f and the total RA of light sideward nodes N_{given} (Figure 9). The longer intermittent interval is calculated according to Eq. (4). Note that there should be an upper limit to the value change to prevent the node's relaying frequency from becoming too slow.

$$T_{t+1} \leftarrow \min\left\{T_t \cdot \frac{N_b}{N_f + N_{given}}, 2 \cdot T_0\right\} \tag{4}$$

IV. PERFORMANCE EVALUATION

This section evaluates performance of the proposed technique through simulation. First, the simulation scenario is explained. Next, the proposed technique and existing IRDT systems are compared. Comparison metrics are network lifetime, average delay, and packet collection ratio, and the network lifetime is the time until the first battery depletion. We also describe suitable positions for the sink in the apartment-type topology assumed in this study.

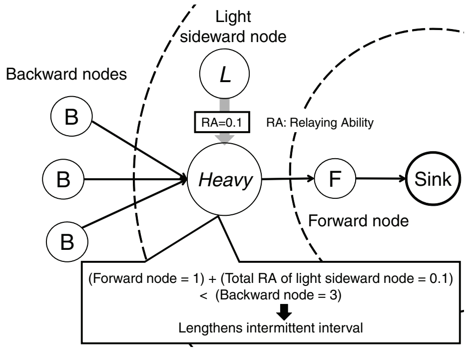


Fig. 9. A heavy node lengthens its intermittent interval.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Packet generation rate	0.001 packets/s
Initial battery ability	2 mAh
Initial intermittent interval	1 s
Current during transmission	20 mA
Current in the waiting state	25 mA
Current during reception	25 mA
Current in the sleep state	0 mA
Transmission rate	100 kbps
Packet size	128 bytes
Transmission range	10 m

A. Simulation Scenario

Table I shows the main simulation scenario parameters. Each sensor node sends its original data packet to the sink node in 1000 s on average. Our system is based on a multi-hop routing method, so each node relays the data of a node with one more hop to the sink node than itself. Data aggregation at each node is not considered in this system. We assume a network with the topology shown in Figure 4. Here, the sink node is at the bottom center, and the remaining 119 nodes randomly transmit packets to the sink node at a predefined rate. The 119 nodes are one to six hops away from the sink node, and nodes with the same number of hops are shown in the same color. Our target application is an automatic gas metering system, so we used a grid-like topology based on a real apartment building, shown in Figure 4. The building has 17 stories, each of which has 7 rooms. We assume that each room has one gas meter, and meters cooperate to form a network. We suppose that the height of each room is 3 m and breadth is 4 m. Since most apartment management offices are on the first floor, the sink node is deployed there.

B. Numerical Results

1) Power consumption and network lifetime: This section compares power consumption in IRDT and the proposed technique. In existing IRDT systems that consider only the number of hops to the sink, network topology can result in differing loads between nodes with the same number of hops. As Figure 10(b) shows, this difference in load results in significantly different power consumption. In the proposed technique, however, heavy nodes dynamically shift traffic to light sideward nodes through load balancing and adjustment of the intermittent interval, allowing more balanced power consumption. As Figure 10(a) shows, equalizing power consumption between nodes with the same number of hops extends network lifetime. This figure also shows how raising the packet generation ratio per node affects network lifetime. Increased network load decreases network lifetime, meaning the proposed technique is advantageous over IRDT.

2) Transmission delay: This section compares average delay in IRDT and the proposed technique. Figure 11 shows changes in the average packet delay when the packet generation ratio increases. Simulation results show that average delay is smaller in the proposed technique than in IRDT. Furthermore, even small network load increases result in increased average delay times, but the increase is more pronounced under IRDT. Traffic increases will unavoidably result in ID receipt delays and thus data transmission delays, but the proactive use of sideward nodes in the proposed technique should result in improved load tolerance over IRDT.

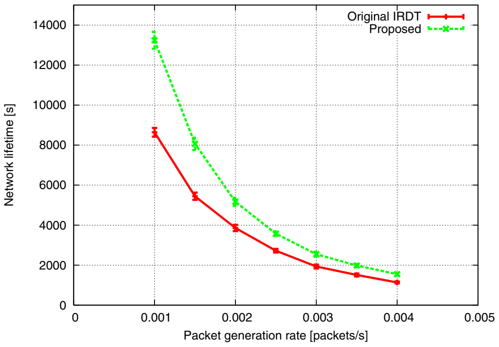
3) Packet collection ratio: Finally, we compare packet collection ratios in the proposed technique and IRDT. Figure 12 shows how the packet collection rate changes when the per-node packet generation ratio increases. The packet collection ratio falls with increased network load in both systems. As traffic increases, the probability of packet collisions and hidden terminal problems will also increase, lowering the packet collection ratio. Both the proposed technique and IRDT maintain a certain packet arrival ratio at each hop count and each node, but the proposed technique results in an approximately 3% lower packet collection ratio.

The lower packet collection ratio in the proposed technique is likely due to an increased probability of packet collisions, resulting from the increased traffic to light nodes. IRDT uses a contention-based MAC protocol in which packet collisions and hidden terminal problems will occur with some probability, but a sufficiently low network load will result in a very low packet drop ratio. In our simulation network load was very close to that limit, so applying our method pushed the single-hop node communication frequency over the limit, resulting in an additional 3% packet drops at light single-hop nodes. Potential solutions for this problem are the addition of a back-off function or reduction of network load.

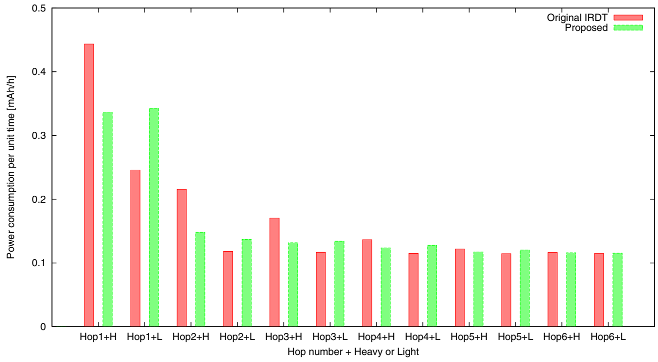
V. CONCLUSION

We proposed load-balancing techniques for the receiver-driven asynchronous system IRDT, for networks with a sufficiently dense topology or sufficiently long communication range. The proposed load balancing technique consists of sender and receiver node controls. Sender node control makes nodes proactively transmit to sideward nodes. Receiver node control adjusts the node data relay load by changing the intermittent interval.

Evaluation showed that compared with existing IRDT systems the proposed technique prolonged network lifetime by about 53% and decreased average delay time by about 21%.



(a) Comparison of network lifetime.



(b) Average power consumption by hop count.

Fig. 10. Comparison of power consumption.

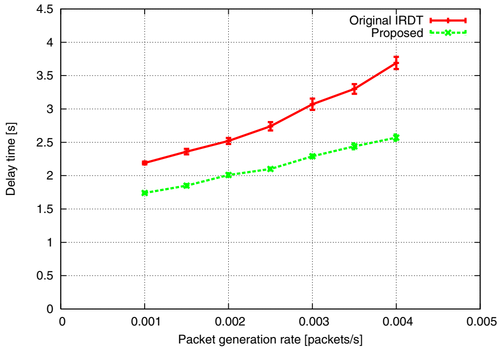


Fig. 11. Comparison of transmission delay.

The packet drop ratio was approximately 3% higher than that of existing IRDT systems, owing to the increased traffic at single-hop nodes. We suggest the addition of a back-off function and reduction of network load as possible solutions to this problem. Areas for future study are evaluations of other network topologies and other simulation scenarios, and investigations into system robustness after node addition or failure.

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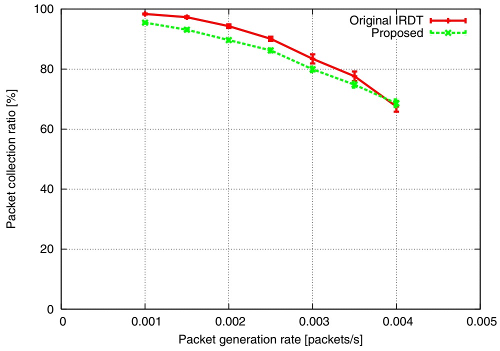

Fig. 12. Comparison of packet collection ratio.

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