# Reliable EH-WSNs based Bridge Monitoring System by Adjusting Sleep Timing with Beacon Signal and Forwarding Overheard Packets

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***Abstract*—EH-WSNs (Energy Harvesting Wireless Sensor Networks) have been received much attention to realize long-lived structural monitoring system on the bridge. In order to deliver more packets to the sink, it is necessary for sensors to adjust their sleep/wake-up timing. In this paper, we propose a beacon-based sleep control scheme in the EH-WSNs based bridge monitoring system. In the proposed scheme, each sensor sends a beacon which makes sensors in the same bridge foot transit to the sleep state to decentralize their receiving states. By dispersing receiving states among sensors, our scheme increases the chance that at least one sensor can receive packets and thus improves the packet delivery ratio. We also propose an overhearing scheme to decrease the packet loss among neighborhood bridge foots. Each active sensor overhears a packet broadcast by the same bridge foot's sensors and then forwards it to the next bridge foot when the sending chance comes. This way might be able to decrease the packet loss, and thus the packet delivery ratio improves. To show the effectiveness of the proposed scheme, we evaluate against two different structural models. The first model we evaluate is a bridge whose foots have the same number of sensors. The other one is a bridge whose sensors get less as one goes to the center. The simulation results show that our proposed scheme can improve the packet delivery ratio compared with the conventional scheme.**

## I. Introduction

In 2007, Minnesota I-35 bridge collapsed because of aging [1]. Since then, a long-lived bridge monitoring system is an urgent demand of our lives. One cannot directly inspect bridge foots because it is difficult to enter. Recently, EH-WSNs (Energy Harvesting Wireless Sensor Networks) using EH technology in WSNs have been received much attention to realize a long-lived bridge monitoring system [2]–[4]. EH-WSN consists of two types of nodes, which are the EH sensor node (hereafter, we denote it as a sensor) and the sink node. Multiple sensors are fixed in each bridge foot. Sensors periodically record the data e.g., change of bridge foot, and send them to the sink node. A sensor has a battery and charges with environmental energy, e.g., solar and/or wind power. Each sensor transits to one of the three states; charging, receiving, and transmission. First, sensors charge power enough to send and receive one packet. After that, sensors transit to the receiving state which receives a packet. Then, sensors transit to the transmission state when the channel is idle and a packet exists in the queue. Each sensor repeats these three states. In most cases, a bridge is long and thus a sensor might relay packets sent by farther sensors to the sink node. Thanks to EH technology, it is possible for sensors to operate semipermanently without battery replacement.

However, the charging amount by the environmental energy is quite small and varies depending on the environmental condition. GR-DD (Geographic Routing with Duplicate Detection) is a MAC (Media Access Control) scheme suited for the bridge monitoring system [5]. Each sensor broadcasts sensed data to the sink with the aid of EH sensors in neighbor bridge foots. When receiving an already received packet, a sensor drops it to reduce redundant sensor data. However, a packet is lost when no active sensor exists in the next bridge foot. Therefore, an adequate sleep/wake-up control scheme is required to make a situation where at least one sensor is ready to receive a packet.

In this paper, we propose a reliable EH-WSN based bridge monitoring scheme by adjusting sleep timing with the beacon signal and forwarding overheard packets. The key idea of our scheme is to disperse the sleep timing of each EH node to increase the chance that at least one EH node is active. After charging the power enough to send and receive a packet as well as send a beacon signal, each sensor sends a beacon signal at first to sensors in the same bridge foot with a fixed probability. Each sensor on the same bridge foot which receives a beacon signal transits to the charging state again. Therefore, our scheme shortens time when some active sensors in receiving state simultaneously exist. We also propose an overhearing scheme that each sensor overhears a packet transmitted from the same bridge foot to decrease opportunities when no receiving sensor exists in the next bridge foot. If a sensor overhears a packet that has already broadcast by itself, it drops the packet to avoid a packet from looping in the same bridge foot. Our two proposals decrease packet loss situation.

We evaluate the packet delivery ratio of our scheme and the conventional scheme GR-DD by the computer simulation. We consider two bridge types; one is the normal bridge where sensors are equally fixed in each bridge foot and the other one is the arch bridge where less sensors are set in the center of a bridge. We show that our scheme outperforms GR-DD in terms of the packet delivery ratio regardless of bridge types.

The reminder of the paper is structured as follows: The conventional scheme is explained in Section II. Section III explains our proposed scheme. Simulation results and analysis are shown in Section IV. The paper concludes in Section V.

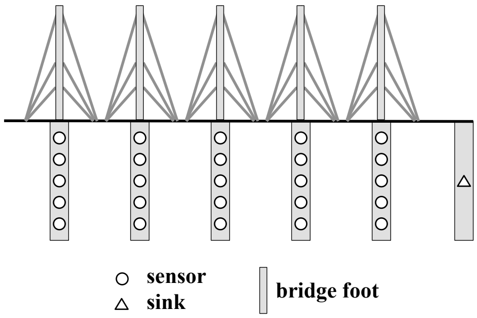



Fig. 1: A system model of the bridge monitoring system.

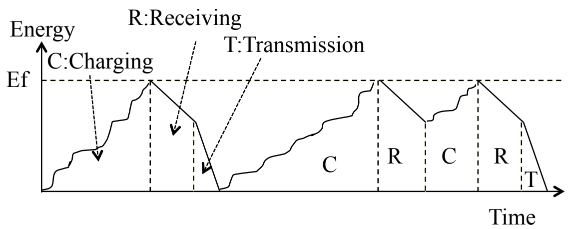



Fig. 2: Time series of energy model.

## II. Conventional Scheme

There are many MAC protocols for EH-WSNs e.g., [6]–[9]. Jaggi et al. propose a novel sensor activation decision protocol that take into account the event occurrence process [6]. Kansal et al. classify the type of energy harvest by the source of energy and theoretically show the power model in EH-WSNs [7]. Niyato et al. propose a energy management system that utilizes a game-theoretic approach [8]. Sharma et al. propose a theoretical models that maximizes the throughput and minimizes the mean delay of the data queue against a single node model [9]. We especially pay attention to GR-DD [5], which is a MAC protocol specific to the bridge monitoring system with EH-WSNs, since it is a specific routing protocol for the bridge monitoring system. Then, we explain the system model, data collection method, and the problem of GR-DD.

### *A. System Model*

Fig.1 indicates an example of a bridge monitoring system where sensors periodically sense the state of bridge foots. A bridge is supported by some bridge foots. Multiple sensors are fixed on each bridge foot. A sink is installed at one side of a bridge. Each sensor measures environmental information e.g., displacements of bridge foots, every 100 seconds. Each sensor broadcasts sensed data to adjacent sensors located in the nearer to the sink. These sensors repeat the procedures and the sink receives sensed data.

### *B. Protocol*

A sensor transits among the three states; the charging, receiving, and transmission state. Fig.2 indicates an example of sensor's residual energy with time. First, the sensor charges enough energy to send and receive one packet. The charging time fluctuates because their surrounding environment changes e.g., the strength of solar or wind power. Then, the sensor transits to the receiving state. The sensor can receive a packet in the receiving state. Then, the sensor transits to the transmission state when the channel is idle and the packet exists in the queue. If the channel is not idle, the sensor transits to the charging state. Similarly, if there is no packet in the queue, the sensor transits to the charging state. The sensor can broadcast a packet to the next bridge foot in the transmission state. If there are several data in the queue, the sensor broadcasts them one by one. After that, the sensor transits to the charging state. Fig.3 indicates an example of the data collection flow by GR-DD. When sensors receive the packet, they forward the packet to sensors which belong to the neighbor bridge foot. In GR-DD, when a sensor node receives a duplicated packet, it is dropped to reduce redundant packets.

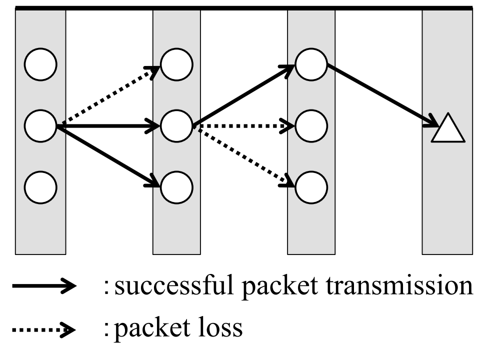



Fig. 3: An example of the data collection flow in GR-DD.

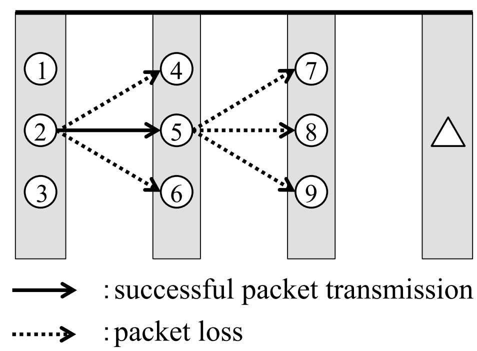
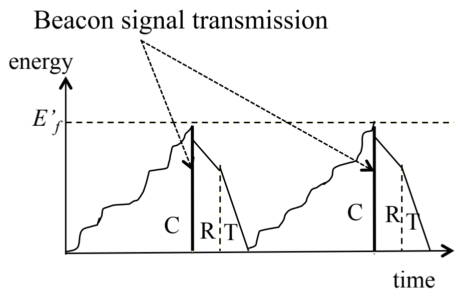


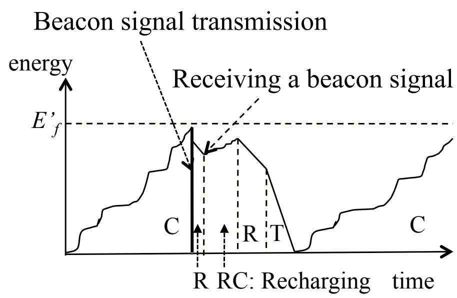

Fig. 4: An example of packet loss occurred in GR-DD.

### *C. Shortcomings of GR-DD*

An advantage of GR-DD is to reduce redundant packets by dropping duplicated packets. However, GR-DD requires many sensors in order to realize the high packet delivery ratio since when the number of sensors is less, the probability that at least one sensor can receive a packet becomes also small. Specifically, the receiving state accounts for about 6% of one cycle [5]. Fig.4 indicates an example of packet loss occurred in GR-DD. Sensor 1 broadcasts a packet to the next bridge foot. Only sensor 5 can receive the packet, and sensors 4 and 6 cannot receive it since they are not in the receiving state. Then, sensor 5 broadcasts the packet to the next bridge foot. However, sensors 7, 8, and 9 cannot receive it if they are not in the receiving state, and the packet loss occurs




(a) When a sensor did not received a beacon signal




(b) When a sensor received a beacon signal

Fig. 5: Time series of energy model in our scheme.

because receiving sensors do not exist. Moreover, the sensor which failed the transmission once does not send a packet again since it does not have the packet. Therefore, the packet loss opportunity increases and thus the packet delivery ratio decreases.

## III. Proposed Scheme

Here, we propose a more reliable EH-WSNs based bridge monitoring system to decrease packet loss opportunities. Our proposal is two-fold. The first proposal is to introduce the beacon signal that delays the sensor's wake-up timing to increase a probability which at least one sensor can receive packets. The second proposal is to let each sensor overhear a packet broadcast by sensors in the same bridge foot. These two proposals might reduce packet loss opportunity and thus it can bring about the better packet delivery ratio.

### *A. Protocol*

A sensor transits among five states; the charging, beacon signal transmission, receiving, recharging, and transmission state. Fig.5 indicates the relationship between the state cycle and residual energy in our scheme.

*1) Charging State:* At first, a sensor charges up to $E'_f$ which denotes enough energy to send and receive a data packet as well as send a beacon signal.

*2) Beacon Signal Transmitting State:* After the charging state, a sensor sends a beacon signal to sensors on the same bridge foot with a fixed probability $p$. The carrier sense is executed before transmitting a beacon signal to avoid a collision. We assume that collision of beacon signals can be ignored because a possibility that sensors send beacon signals simultaneously is expected low.

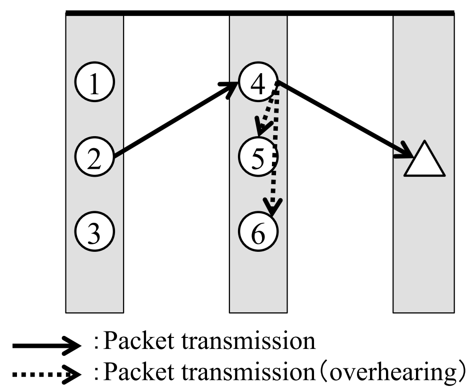



Fig. 6: An example of overhearing.

*3) Receiving State:* After the beacon signal transmitting state, a sensor can receive a packet or a beacon signal in the receiving state. Moreover, a sensor overhears a packet sent by a sensor in the same bridge foot. Based on the sender information in the beacon message header, a sensor identifies whether a beacon has come from a sensor in the same bridge foot or not.

In our scheme, a sensor does not drop overheard packets sent from sensors in the same bridge foot and forwards them in the next cycle. If a sensor overhears a packet that has already broadcast, it drops the packet to avoid a packet from looping in the same bridge foot. Fig.6 indicates an example of overhearing. Sensor 4 receives a packet from sensor 2 and broadcasts the overheard packet to the next bridge foot. If sensor 5 and 6 are in the receiving state, they can overhear the transmission of sensor 4. Then, sensor 5 and 6 can send the overheard packet to the next bridge foot in the next cycle. Using overhearing makes to increase packet transmission opportunity of each sensor, decreases packet loss opportunity, and thus it might improve packet delivery ratio.

*4) Recharging State:* A sensor which received a beacon signal transits to the recharging state. We set the length of recharging equals as the maximum period length of the receiving state in order to match the timing where a sensor which has sent a beacon signal finishes the receiving state. After the recharging state, a sensor transits to the receiving state.

*5) Transmitting State:* After the receiving state, a sensor transits to the transmission state if the channel is idle and packets exist in the queue. Otherwise, a sensor transits to the charging state. Similarly, if there is no packet in the queue, a sensor transits to the charging state.

### *B. Example*

In order to show the effectiveness of our scheme more clearly, we show an example of our scheme. Fig.7 indicates an example of the data collection flow in our scheme. The source sensor broadcasts a packet to sensor 1, 2, and 3 in the adjacent bridge foot. Sensor 2 which has received the packet transits to the transmitting state just after the receiving state and broadcasts the packet toward sensor 1 and 3, 4, 5, and 6. If sensor 4 in the receiving state receives the packet, it broadcasts

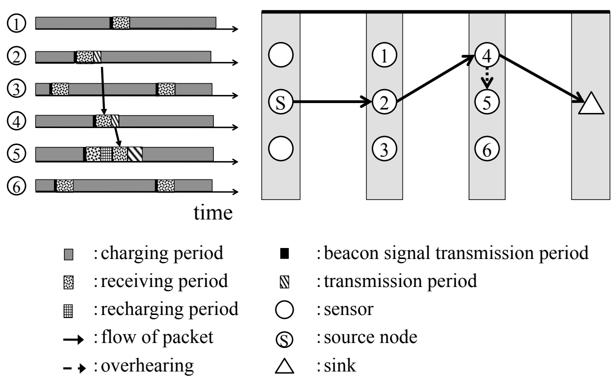



Fig. 7: Example of the data collection flow in our scheme.

TABLE I: Simulation parameters.

| Parameter | Value |
|---|---|
| Simulation area | 500 m × 50 m |
| Simulation time | 1000 sec |
| Number of sensors per a bridge foot | 4∼40 |
| Radio range | 100 m |
| Transmission power | 83.1 mW |
| Reception power | 76.2 mW |
| Bit rate | 250 Kbps |
| Beacon signal size | 160 bits |
| Data size | 800 bits |
| Charging time | 65 ∼ 95 ms |
| Data reception time | 6.4 ms |
| Data transmission time | 3.2 ms |
| Beacon transmission probability($p$) | 0.1∼1.0 |

the packet to the next bridge foot after the receiving state. Sensor 4 also sends a beacon signal after the charging state. Then, sensor 5 receives the beacon signal because it is the receiving state. Sensor 5 also transits to the recharging state. After the length of recharging period, sensor 5 broadcasts a packet to the next bridge foot.

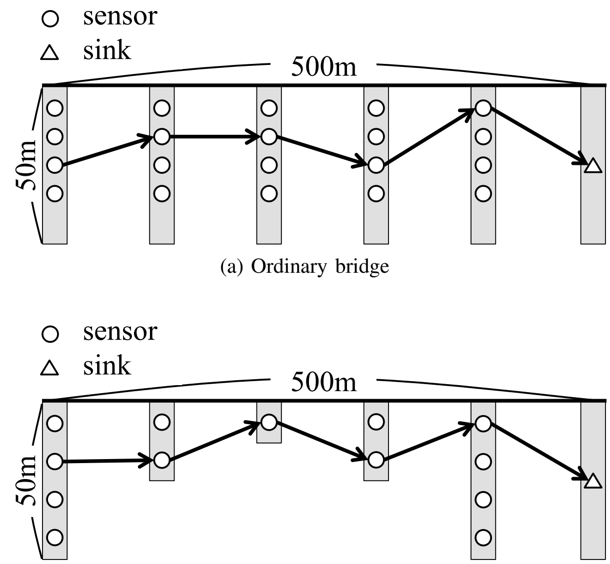
### *C. Discussion*

In our scheme, beacon signals make redundant sensors slept when a number of receiving sensors exist simultaneously. Therefore, beacon signals shift the timing of receiving state of them and shorten the period which no sensor in the receiving state exists. In our scheme, overhearing in the same bridge foot and forwarding its packet to the next bridge foot decreases packet loss opportunity. Therefore, our scheme can achieve data collection with high packet delivery ratio. On the other hand, our scheme may cause the delay due to making sensors recharge and overhearing.

## IV. Evaluation

### *A. Simulation Model*

We compare the proposed scheme with GR-DD in terms of the packet delivery ratio. We define the packet delivery ratio as the number of unique packets which the sink received versus the packets which the sources sent. We evaluate it under two bridge types; one is the normal bridge where the number of sensors are equally set in each bridge foot and the other one is the arch bridge where small number of sensors are set in the




(a) Ordinary bridge

(b) Arch bridge

Fig. 8: Simulation topology.

center of a bridge. Fig.8 indicates the simulation topology. The number of sensors in arch bridge is set up half as approaching from both ends to central bridge foot. We show simulation parameters in Table I based on the work in [5]. We define Prop. beacon and Prop. beacon + overhearing as the proposed scheme that only applies the beacon signal and the proposed scheme with the beacon signal and overhearing, respectively.

### *B. Packet Delivery Ratio versus Beacon Transmission Rate*

We clarify the relationship between the beacon transmission rate and the packet delivery ratio. Fig.9(a) shows the packet delivery ratio versus the beacon transmission probability against the ordinary bridge. We also vary the number of sensors in each bridge foot between 4 and 40. If the number of sensors in each bridge foot is less than 8, the packet delivery ratio is very low. On the other hand, the number of sensors in each bridge foot is large, the proposed scheme works well.

Fig.9(b) shows the packet delivery ratio versus the beacon transmission probability against the arch bridge. In the arch bridge, when the number of sensors in a bridge foot is large, beacons do not work well compared to the ordinary bridge, because the sensors around the center bridge foot cannot deliver a packet.

### *C. Receiving State Sensor Rate versus Number of Sensors in Bridge Foots*

Fig.10 indicates the receiving state sensor rate versus the number of sensors in each bridge foot in the ordinary bridge. We define receiving state sensor rate as the ratio which at least one sensor exists versus the simulation time. Fig.11(a) and Fig.11(b) indicate that the receiving state sensor rate versus the number of sensors in the central and edge bridge foot, respectively. In the arch bridge, the number of sensors in the edge bridges are maximum among bridges foots, whereas that of central bridge foot is minimum. From Fig.11(a), our scheme

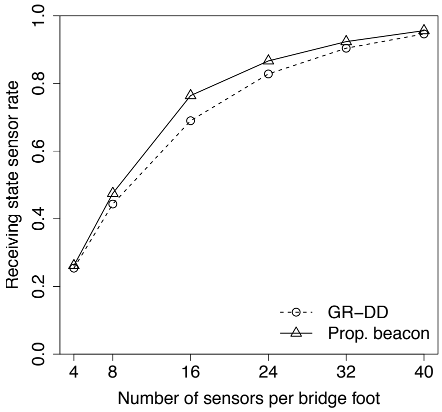
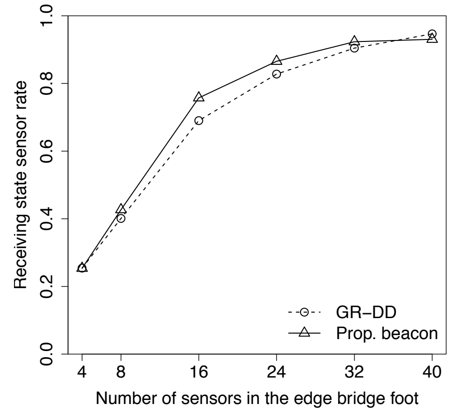
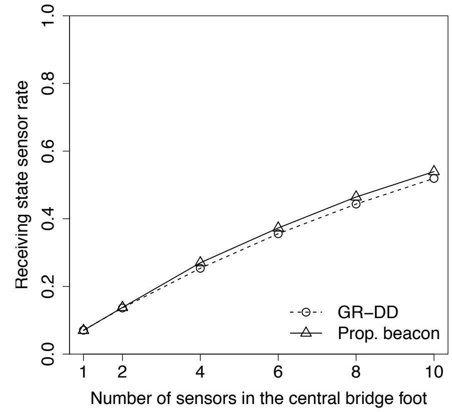



Fig. 10: Receiving state sensor rate versus the number of sensors in each bridge foot (ordinary bridge).

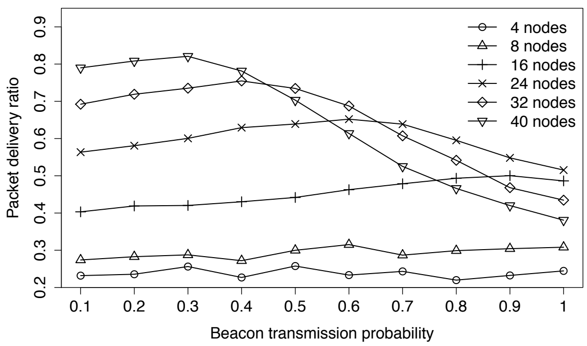



(a) Edge bridge foot

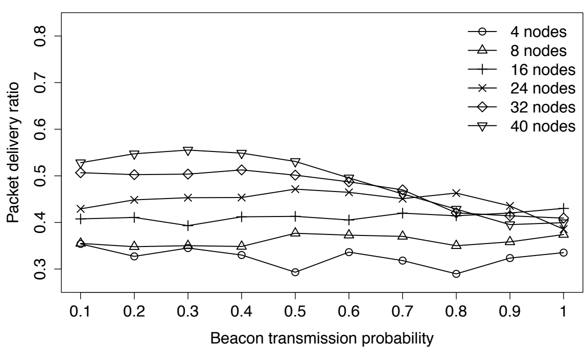



(b) Central bridge foot

Fig. 11: Receiving state sensor rate versus the number of sensors in each bridge foot (Arch Bridge).

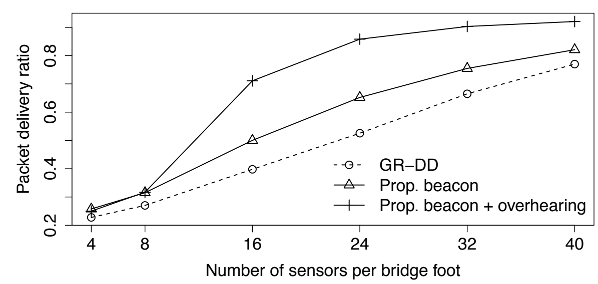



(a) Ordinary bridge

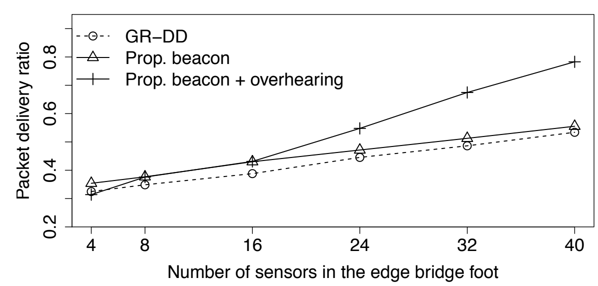



(b) Arch bridge

Fig. 9: Packet delivery ratio versus the beacon transmission rate.




(a) Ordinary bridge



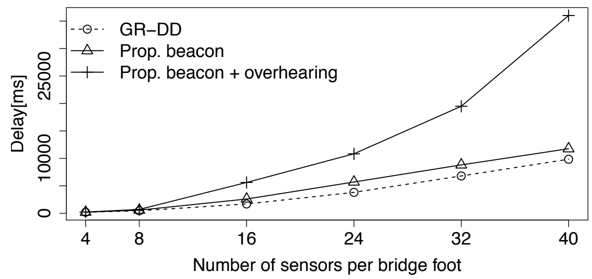

(b) Arch bridge

Fig. 12: Packet delivery ratio versus the number of sensors in each bridge foot.

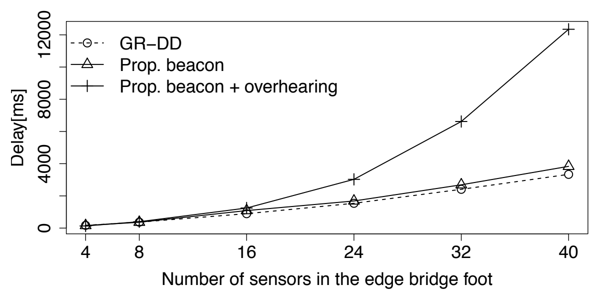
achieves the better receiving state sensor rate when the number of sensors in the bridge foot is between 8 and 32. Fig.11(b), our scheme also improves the receiving state sensor rate as the number of sensors increases. This is due to the effect of the beacon signal that disperses the sleep timing of sensors.

### *D. Packet Delivery Ratio versus Number of Sensors in Each Bridge Foot (Ordinary Bridge)*

Fig.12(a) indicates the packet delivery ratio versus the number of sensors in each bridge foot in the ordinary bridge. From Fig.12(a), we can see that the proposed scheme with only a beacon signal method improves the packet delivery ratio




(a) Ordinary bridge




(b) Ordinary bridge

Fig. 13: Packet delivery delay versus the number of sensors in each bridge foot.

by 18 % compared to GR-DD. In the conventional scheme, packet loss occurs when no receiving sensors exists. On the other hand, in our scheme, beacon signals make the redundant sensors slept when receiving sensors in bridge foots exist at the same time. Comparing with Fig.10, our scheme with a beacon signal directly improves the packet delivery ratio. From Fig.12(a), we can also see that the proposed scheme with a beacon signal and overhearing significantly improves the packet delivery ratio by 61 % compared to GR-DD. This means that many duplicated packets are dropped in GR-DD. Fig.12(b) indicates that the packet delivery ratio versus the number of sensors in each bridge foot in the arch bridge. From Fig.12(b), our scheme with a beacon signal improves the packet delivery ratio by 6 % compared to GR-DD. This is because it decreases the packet loss using beacon signals which decentralize receiving sensors. The proposed scheme with a beacon signal and overhearing improves the packet delivery ratio by 47 % compared to the conventional scheme.

### *E. Packet Delivery Delay versus Number of Sensors in Each Bridge Foot*

Fig.13 indicates the packet delivery delay versus the number of sensors in each bridge foot in the ordinary and arch bridges. From these figures, we can see that the proposed schemes increase the packet delivery delay compared to GR-DD. In particular, our scheme with overhearing increases large delay. This is because each sensor delays the transmission due to overhearing. Therefore, if the sink needs collecting sensed data real-timely, our scheme with overhearing is not suited. On the other hand, our scheme is effective when the system wants to collect reliably sensed packets.

## V. Conclusion

In this paper, we have proposed a reliable EH-WSNs based bridge monitoring scheme with two proposals. The first proposal is to introduce the beacon signal that decentralizes sleep period of receiving sensors in order to shorten period which there is no receiving sensor in each bridge foot. The second proposal is to overhear the packet transmission by sensors in the same bridge foot in order to decrease packet loss opportunity. Simulation results indicate that the proposed scheme can achieve high packet delivery ratio in the normal bridge and in the arch bridge compared to the conventional method. In the normal bridge, packet delivery ratio improves by about 60 % compared to the conventional method. This is because beacon signals make the redundant sensors sleep when receiving sensors in bridge foots exist at the same time. The proposed scheme achieves high packet delivery ratio even though the number of sensors in each bridge foot is small. It is also shown that the proposed scheme increases the packet transmission probability compared to the conventional scheme.

## Acknowledgment

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