Unidirectional Link-Aware DTN-based Sensor Network in Building Monitoring Scenario

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***Abstract*—The performance of wireless sensor network in building monitoring system (BMS) is often deteriorated by intermittently-connected and unidirectional links occurring in building environment. With DTN-based approach, Potential-based Entropy Adaptive Routing (PEAR) protocol can achieve high reliability and scalability over intermittently-connected mesh network in the building scenario. However, the result of high delivery latency caused by ignoring the presence of unidirectional links may not be acceptable in BMS. In this paper, we propose *Unidirectional Link-Aware Next-hop Selection (ULANS)*, the technique of detecting unidirectional links and the new next-hop selection scheme for PEAR. The real-world experimental result shows that ULANS can avoid choosing unidirectional links as the next-hop and improve delivery latency of PEAR.**

***Keywords*—Unidirectional link, PEAR, DTN, Latency, WSN**

I. INTRODUCTION

Building monitoring system (BMS) gains much interest from many sectors these days. In BMS, large scale sensor network is deployed in the building to gather power consumption and building's environmental data. Wireless sensor network (WSN) has been proposed to used in BMS due to the ease of deployment and low maintenance cost. However, WSN always suffers from dynamic environment in the building. Intermittently-connected links also occur in such environment, even though all nodes are static deployment. Therefore, delay/disruption tolerant network's (DTN) approach, which always achieves high delivery ratio, plays an important role in BMS.

DTN takes hop-by-hop reliable message transfer to attain higher delivery ratio. Hop-by-hop reliability requires bidirectional communication to confirm message delivery. However, unidirectional links frequently occur in wireless ad-hoc network [1]–[4]. The unidirectional link arises between two connected nodes when only one of two nodes can directly send messages to the other. It may be caused by transmitter/receiver heterogeneity, power control of sensor node, interference or hidden terminal. This may reduce the performance of WSN regarding delivery latency.

Potential-based Entropy Adaptive Routing (PEAR) protocol [5], one of DTN-based routing protocol, has achieved 100% of delivery ratio over 10 hops in the 50 node-scale wireless mesh network [6]. Although the result showed PEAR's reliability and scalability, large delivery latency may not be acceptable in BMS [7]. After examining the behavior of PEAR, we found that the unidirectional link is one of the cause of high latency. PEAR assumes that all wireless links are bidirectional and chooses only the shortest path in the message delivery.

To avoid the unidirectional links in DTN-based routing protocol, we propose *Unidirectional Link Aware Next-hop Selection (ULANS)*, the simple technique of detecting the unidirectional links and the new next-hop selection scheme for DTN-based routing protocol. In this paper, we focus on PEAR as DTN-based routing scheme to study the effect of the unidirectional links and the improvement with our proposed ULANS in building monitoring scenario. The experimental evaluation shows that ULANS can alleviate this problem and improve PEAR's routing performance.

The rest of the paper is organized as follows. In Section II, we briefly explain the concept of PEAR. Section III presents our proposed method. Section IV shows the experiment and evaluation of the proposed method compared to the original PEAR. We give a discussion in Section V. Finally, Section VI concludes this paper.

II. POTENTIAL-BASED ENTROPY ADAPTIVE ROUTING

PEAR inherits potential-based routing protocol (PBR) and hop-by-hop store-and-forward mechanism from DTN. In PBR, each node has a positive scalar value indicating the distance from the destination called *potential*. The higher potential implies the further distance from the destination. Each node broadcasts advertise messages (ADV) periodically in order to update its potential with neighbor nodes and selects the lowest-potential neighbor as the next-hop.

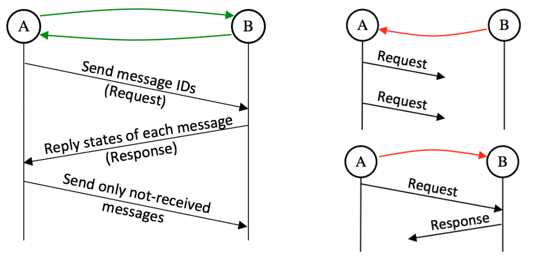
PEAR defines next-hop selection scheme as follows,

$$F^d_{max}(n) = \max_{m \in nbr(n)} \{V^d(n) - V^d(m)\} \quad (1)$$

$$NH^d(n) = \{k | k \in nbr(n), F^d_{max}(n) = V^d(n) - V^d(k)\} \quad (2)$$

where $nbr(n)$ denotes the set of neighbor nodes of node n, $V^d(n)$ represents the potential of node n for the destination d, $F^d_{max}(n)$ keeps the maximum difference between node n's potential and its neighbors' potential and $NH^d(n)$ is the next-hop of node n toward the destination d.

In store-and-forward mechanism, the messages are copied and stored in the intermediate nodes. Before forwarding the messages, nodes have an investigation to check whether their next-hops already have the messages. Firstly, the sender requests message information by sending all message ID stored in the buffer to the next-hop. Then, the next-hop replies the state of each message, i.e. already-received, not-received or delivered, with a response message. Finally, the sender sends only not-received messages to the next-hop and deletes delivered messages from the buffer. Fig. 1a illustrates the investigation when node B is the next-hop of node A.



(a) Bidirectional link (b) Unidirectional link

Fig. 1. The investigation when the link between A and B is (a) bidirectional and (b) unidirectional.

Owing to the investigation, nodes send the messages only when the investigation succeeds, i.e. when nodes receive the response from their next-hops. Thus, the bidirectional link is required in PEAR. However, PEAR is interested only the lowest-potential neighbor without being aware of the unidirectional links. The unidirectional links may interrupt the investigation (Fig. 1b). Consequently, the messages are delayed at the intermediate nodes resulting in high delivery latency.

III. Unidirectional Link Aware Next-hop Selection

In this section, we describe how Unidirectional Link-Aware Next-hop Selection (ULANS) works. We first give the definition of unidirectional link using in this paper. Then, we explain the method of detecting the unidirectional links. Finally, we present the new next-hop selection scheme for PEAR.

A. Unidirectional link

To classify the links at each node n, the link pointing outward from n is defined as *forward link* and the link directing to n is called *reverse link*. The definition is illustrated in the Fig. 2.

We define that any link becomes *unavailable* when the link cannot deliver any messages within a period of time called *Connectivity Time* (T_C). Supposing that node n is connected with node $k \in nbr(n)$, when we consider at node n, there should be both forward link to k and reverse link from k if the link is bidirectional. The link between n and k becomes unidirectional when the forward link to k is available but the reverse link from k is unavailable or vice versa. The example of the unidirectional link is shown in Fig. 3.

Here, T_C is the important factor to decide whether the link is unidirectional. Due to the fluctuation of wireless link, the messages could be lost, even though the link quality is good. T_C filters out ordinary message loss and confirms that the link is unidirectional.

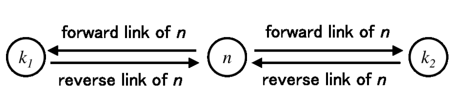


Fig. 2. The definition of links at node n.

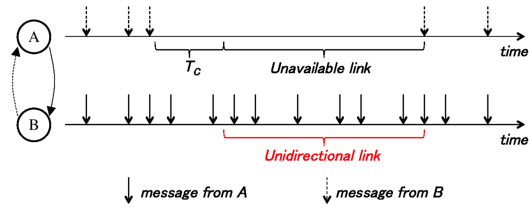


Fig. 3. Example of the unidirectional link between A and B.

B. Unidirectional Link Detection

To detect the unidirectional links, the neighbor table at each node must consist of (1) Reverse Link Lifetime and (2) Link status for every neighbor. Reverse Link Lifetime (RLL) is non-negative integer showing the time-to-live of the reverse link. Once RLL is set to non-zero value, RLL decreases every second. Link status (L) indicates whether the link is bidirectional. L is either available ('A') or unavailable ('U'); L is set to 'A' only when both reverse link and forward link are available and set to 'U' if the reverse link or the forward link is unavailable.

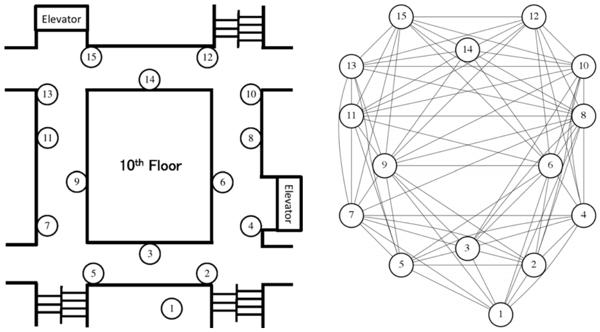
ULANS exploits the feature of PBR to detect the unidirectional links between nodes by observing the receipt of ADV at each node. Since each node broadcasts ADV periodically, nodes learn that the reverse links are unavailable when nodes do not receive ADV within T_C. Whenever nodes receive ADV from neighbors, nodes set RLL to T_C. Therefore, non-zero RLL indicates that the reverse link is available. Note that T_C must be more than ADV broadcast interval to detect the unidirectional links.

However, nodes cannot identify the presence of forward link by themselves. Thus, nodes embedded a neighbor list containing neighbor ID with non-zero RLL in ADV to inform other nodes. When nodes find themselves in the neighbor list, nodes perceive that the forward links are available as well. Then, nodes set L to 'A'. On the other hand, nodes realize that the links are unidirectional and set L to 'U' when their IDs are not in the neighbor list.

ADV reception and link information from neighbor nodes confirm the existence of reverse link and forward link respectively. Nodes know whether the forward links are available only when the reverse links exist. That is enough for DTN-based routing protocol because as long as the reverse links are lost, nodes cannot update neighbors' information or succeed the investigation. Therefore, forward link's information is unnecessary unless the reverse links are available.

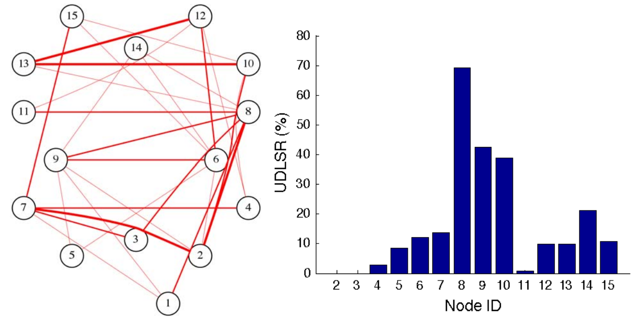
C. New scheme for the next-hop selection

As we mentioned before, PEAR's next-hop selection scheme chooses only the lowest-potential node to be the next-hop without being aware of the existence of the unidirectional links. In order to avoid this problem, ULANS modifies and proposes new scheme for the next-hop selection as shown in Eq. 3 and Eq. 4.



(a) (b)

Fig. 4. (a) Deployment configuration, (b) topology and connectivity of the experimented network.



(a) (b)

Fig. 5. (a) Unidirectional links existed in the network when T_C was 80 seconds. The thicker line indicates that the link became unidirectional more frequently. (b) Unidirectional link selection ratio of each node when T_C was 80 seconds.

$$F^d(n) = \max_{m \in nbr(n), L_{nm}=\text{`}A\text{'}} \{V^d(n) - V^d(m)\} \quad (3)$$

$$NH^d_{ULANS}(n) = \{k | k \in nbr(n), F^d(n) = V^d(n) - V^d(k)\} \quad (4)$$

where L_{nm} is the link status between node n and node m. ULANS adds one more condition to address the unidirectional links in the previous next-hop selection scheme. When nodes compare the potential with their neighbors, nodes consider only neighbors with the bidirectional links. As a result, ULANS forces nodes to choose only the lowest-potential neighbor with the bidirectional link as the next-hop.

IV. Experimental Evaluation

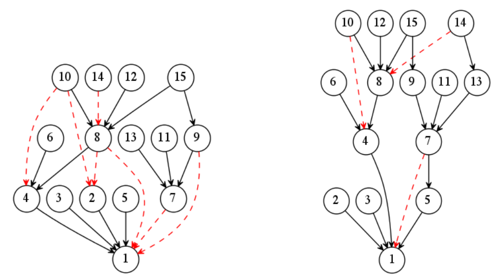
We studied the effect of unidirectional links in PEAR and evaluated ULANS on the testbed experiment. First of all, we describe our experiment setup, then present our study on the unidirectional links. Finally, the experiment results are shown and analyzed.

A. Experiment Setup

The experiment was carried out with 15 UTMesh nodes [8] on 10th floor of Eng. Bldg 2 in the University of Tokyo. UTMesh nodes were operating with Armadillo-220, Linux embedded computer with Wi-Fi (IEEE802.11) module. All nodes were powered by batteries and operated at the same transmit and receive power level. We set ADV broadcast, next-hop selection and system update interval to 10 seconds. To mock-up building monitoring system scenario, every node was configured to send 22- or 23-byte messages (depends on node ID) to node 1 every 30 seconds. Apart from the original PEAR, PEAR with ULANS was run with 3 different T_C, i.e. 40, 60, 80 seconds. We denote the experiment of PEAR with ULANS as ULANS(T_C). Each experiment took 1 hour. Fig. 4 shows the deployment, topology and connectivity of this experiment.

B. Effect of the unidirectional links in PEAR

We picked PEAR and ULANS(80) to observe the effect of the unidirectional links in this experiment. Fig.5a shows the presence of unidirectional links when T_C was 80 seconds. From our observation, most links became unidirectional during the experiment, though all nodes operated at the same power



(a) PEAR (b) ULANS(80)

Fig. 6. Delivery paths of (a) PEAR and (b) ULANS(80). Dashed line indicates the unidirectional link between a pair of nodes.

level. However, their occurrence was dynamic. The links became unidirectional temporarily and turned back to be bidirectional back and forth. Some links became unidirectional only for a short time, while some links turned into unidirectional in a long period. Links between nodes located far from each other often became unidirectional.

We also observed how PEAR selected the next-hop by examining Unidirectional Link Selection Ratio (UDLSR) and main delivery paths. UDLSR is the ratio of the number of times that nodes select next-hops with the unidirectional links to the number of times next-hop selection process is executed. Fig. 5b shows UDLSR of PEAR when T_C was 80 seconds. We can see that node 8, 9 and 10 gave high UDLSR corresponding to the main delivery paths of PEAR shown in Fig. 6a. Those nodes often chose next-hops with the unidirectional links. After applying ULANS (Fig.6b), those nodes avoided the unidirectional links and chose next-hops with better links.

C. Experiment Result

We evaluated the improvement of PEAR with ULANS by observing Investigation Success Ratio (ISR), delivery latency and hop count. Overall performance of experiments is presented in Table. I.

1) Investigation Success Ratio (ISR): Considering that the unidirectional links affect the investigation, the success of the investigation is examined. We define Investigation Success Ratio (ISR) as the ratio of the number of response messages

TABLE I. OVERALL PERFORMANCE.

Experiment	ISR(%)	Delivery Latency (s)			Hop count
		Avg	99%	Max	
PEAR	56.22	25.70	205.22	401.60	1.78
ULANS(40)	66.03	35.40	228.60	382.54	2.33
ULANS(60)	63.08	20.32	136.85	297.00	2.09
ULANS(80)	63.12	20.87	135.56	201.68	2.21

received to the number of request messages sent between each pair of nodes. ISR of the network was improved by 7-10% after applying ULANS to PEAR. In other words, avoiding the unidirectional links enhanced chances of sending the messages to the next-hop.

2) Delivery latency: Delivery latency is the amount of time that the message travels from the source to the destination. Fig. 7 shows the distribution of delivery latency in box plot. ULANS decreased maximum delivery latency, however, ULANS did not always decrease average delivery latency since ULANS(40) resulted higher value than the original PEAR. ULANS(60) and ULANS(80) outperformed PEAR by reducing average delivery latency by 20%. Maximum delivery latency was decreased by 26% in ULANS(60) and 50% in ULANS(80). Moreover, 99% of the messages were delivered 33% faster in ULANS(60) and ULANS(80).

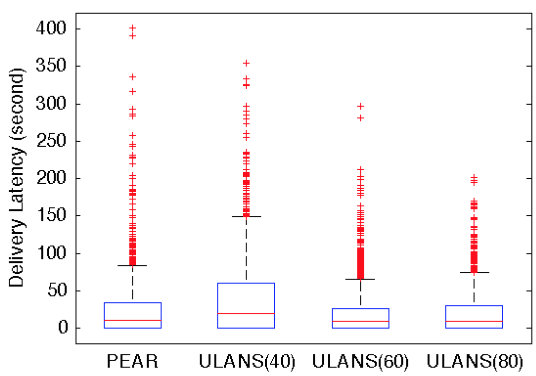


Fig. 7. Box plot showing the distribution of delivery latency.

3) Hop count: Hop count is the number of hops that messages travel from the source to the destination. While PEAR chose the farthest nodes, which were likely to connect with the unidirectional links, as the next-hop, ULANS avoided those nodes and selected closer nodes resulting in more hop counts. The messages delivering with more hop counts possibly gave higher delivery latency. This is why average delivery latency was not always improved in ULANS.

V. DISCUSSION

In accordance with the experiment results, the unidirectional links led to high delivery latency in PEAR. ULANS enhanced successful investigation and, as a result, decreased delivery latency. ULANS also collected data faster in comparison with PEAR. However, the increment of hop count could degrade the performance concerning delivery latency.

As we mentioned in Section. III-A, T_C is the significant parameter to filter out the unidirectional links. T_C must be set corresponding to ADV broadcast interval. Too small T_C is not enough for ULANS to decide whether ADV loss is caused by unidirectional links or just normal packet loss. Nodes may change next-hops unnecessarily leading to higher hop counts and, consequently, higher average delivery latency as in ULANS(40). On the other hand, large T_C may lead to slow detection. Seeing that different T_C gives different performance, T_C must be set appropriately.

We raised the problem of unidirectional links in DTN-based approach in this paper. However, there are other factors causing high delivery latency since ISR was still low even with ULANS. In our future works, we attempt to improve delivery latency by considering link quality or applying retransmission scheme to PEAR.

VI. CONCLUSION

In this paper, we studied the effect of unidirectional links in DTN-based routing protocol. Unidirectional links often arise in wireless network, though all nodes are static. DTN-based approach achieved reliability and scalability in intermittently-connected wireless network, however, unawareness of unidirectional link sometimes causes high delivery latency.

We proposed Unidirectional Link Aware Next-hop Selection (ULANS) for PEAR. ULANS detects the unidirectional links by exploiting the feature of PEAR and avoids the unidirectional links with the new next-hop selection scheme. ULANS was evaluated with the testbed experiment in building monitoring scenario. The experimental evaluation confirmed that ULANS can avoid the unidirectional links and improve the performance of PEAR.

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