Performance Evaluation of NeBuST-wide Burst Sensor Data Transmission Protocol

Hiroaki HIGAKI
Department of Robotics and Mechatronics
Tokyo Denki University
Senjyu-Asahi 5, Adachi, Tokyo 120-8551 Japan
Email: hig@higlab.net

Abstract—In an event-based sensor network, a sequence of burst sensor data messages are required to be transmitted in shorter transmission delay without losses. However, it is difficult due to limited communication buffers in intermediate sensor nodes in a wireless multihop transmission route to the sink node. This paper proposes NeBuST-wide routing and transmission protocols in which sensor data messages are transmitted along dynamically determined transmission routes in message-by-message manner. In case of a full communication buffer in the next-hop wireless sensor node, an intermediate node forwards data messages to another neighbor node to make detour transmissions for achieving shorter transmission delay and for avoidance of losses of the sensor data messages. In addition, this paper evaluates the performance of NeBuST-wide in comparison with the original NeBuST to make clear the effect of wider distribution of burst sensor data message transmissions and in comparison with a static multi-route transmission protocol.

I. INTRODUCTION

A wireless sensor network consists of multiple wireless sensor nodes and a sink node and sensor data messages are required to be transmitted within the required time. Until now, various methods for sensor data message transmissions have been proposed for sensor networks with regular and periodical transmission requests. However, in an event-driven sensor network, distribution of sensor data transmission requests is wide and the memory capacities in wireless sensor nodes are not always enough. Hence, buffer overflow might be caused and some sensor data messages might be lost. For reliable and stable transmissions of event-driven sensor data messages, they are forwarded only when there are enough amount of free communication buffer in a next-hop sensor node. In addition, in spite of this forwarding condition, end-to-end transmission delay of a sequence of sensor data messages are required to be shorter. This paper proposes NeBuST-wide which is an extension of NeBuST which achieves reduction of transmission delay caused by a sequence of filled communication buffers. NeBuST-wide uses dynamically determined detour routes more widely distributed than the original NeBuST.

II. WIRELESS SENSOR NETWORKS

A wireless sensor network consists of multiple wireless sensor nodes with wireless communication devices and a sink node. Sensor data messages containing sensor data achieved by the sensor nodes are transmitted to the sink node. A wireless multihop transmission route \( R = \langle S_0, \ldots, S_n \rangle \) from a source sensor node \( S^s (= S_0) \) to a destination sink node \( S^d (= S_n) \) is a sequence of intermediate sensor nodes \( S_i \) \((0 < i < n)\). Each intermediate sensor node \( S_i \) forwards sensor data messages from \( S_{i-1} \) to \( S_{i+1} \).

There are two kinds of sensor data messages as follows:
- Regular sensor data messages which are transmitted periodically from various sensor nodes.
- Event-driven sensor data messages which are transmitted from dedicated sensor nodes in an on-demand manner.

This paper discusses transmission methods for the latter. For transmissions of event-driven sensor data messages, constant high traffic communication is not always required to be supported. In case of an occurrence of an event, sensor data messages are burstly initiated and required to be transmitted without losses in a shorter delay. It is assumed that the capacity of the wireless sensor network is enough to transmit all the regular and event-driven sensor data messages. However, since many event-driven sensor data messages are initiated burstly, communication buffers in intermediate sensor nodes are temporarily filled. It may cause losses of the event-driven sensor data messages and their end-to-end transmission delay may get longer which are inadequate for sensor network applications.

III. PROBLEMS

Resources in a wireless sensor node are limited for smaller-sized implementation and its lower price. Not only its battery capacity but also its memory capacity are limited. Thus, in a wireless multihop transmissions of a sequence of event-driven sensor data messages along a wireless multihop transmission route \( R = \langle S_0, \ldots, S_n \rangle \), communication buffers in intermediate nodes \( S_i \) may be filled. Such filled communication buffers are caused around the sink node and intermediate sensor nodes at which multiple transmission routes join together when multiple sensor nodes transmit event-driven sensor data messages simultaneously as shown in Figure 1.

In wireless multihop communication, \( S_i \) contends with \( S_{i-2}, S_{i-1}, S_{i+1} \) and \( S_{i+2} \) which reduces transmission opportunities in \( S_i \). In widely available contention-based wireless LAN protocols [5], [6], contention avoidance is realized by introduction of randomly determined backoff periods. This provides long-term feasibility due to probably distributed backoff periods; however, short-term infeasibility is inevitable. This
The predetermined numbers of retransmissions causes maldistribution of transmission opportunities which causes filled communication buffers in the intermediate sensor nodes.

While a communication buffer in $S_i$ is filled, it is impossible for $S_1$ to receive a sensor data message forwarded by $S_{i-1}$. In this case, $S_{i-1}$ does not receive an acknowledgement message from $S_i$, and retransmits the sensor data message. After the predetermined numbers of retransmissions, $S_{i-1}$ discards the sensor data message. Each intermediate sensor node $S_i$ stores sensor data messages in its communication buffer for their retransmissions while it does not receive an acknowledgement message from its next-hop sensor node $S_{i+1}$. Due to less amount of communication buffers and maldistribution of transmission opportunities, the communication buffer of $S_i$ is filled temporarily and $S_i$ cannot forward sensor data messages to $S_{i+1}$. For sensor data message from $S_{i-1}$ to $S_i$, $S_i$ is required to transmit a buffered sensor data message to $S_{i-1}$ to make space in its communication buffer; however, it may contend with its 1-hop and 2-hop previous-hop intermediate sensor nodes $S_{i-1}$ and $S_{i-2}$ which are exposed and hidden nodes. Thus, communication buffers in $S_{i-1}, S_{i-2}, \ldots$ are also filled; that is, a sequence of communication buffers are filled as in Figure 2. Due to the same reason discussed above, it requires much more longer time to clear the sequence of filled communication buffers.

IV. RELATED WORKS

Wireless LAN protocols are not designed for wireless multihop communications. Its collision avoidance methods CSMA/CA and RTS/CTS reduce the performance of multihop transmissions of a sequence of sensor data messages. MARCHI [7] is a modified protocol for RTS/CTS control message exchanges to adapt to multihop transmissions. RH2SWL [2] avoids contentions between hidden nodes by a transmission power based routing protocol. These protocols concentrate only on transmission delay of a sequence of sensor data messages but do not consider the buffer capacities in intermediate sensor nodes. Various scheduling algorithms [1] for sensor data message transmissions have been proposed which reduce end-to-end transmission delay and indirectly reduce the required communication buffer capacities in intermediate sensor nodes. However, the transmission schedule is not flexible and an advertising method of the schedule and a close synchronization method among sensor nodes are required. Hence, it is difficult to apply them to transmissions of event-driven sensor data messages.

The authors have proposed NeBuST (Neighbor Buffering for Congested Sensor Data Transmissions) by which sensor data messages waiting for their spaces in the next-hop sensor nodes are forwarded to neighbor nodes nearer to the sink node for shorter end-to-end transmission delay. In order to store sensor data messages into communication buffers of sensor nodes nearer to the sink node, an intermediate sensor node $S_{i-1}$ forwards them to different neighbor sensor node $S'_{i+1}$ from its next-hop one $S_{i}$ as shown in Figure 3. $S'_{i+1}$ is a neighbor sensor node of both $S_{i-1}$ and $S_{i+1}$. In case that $S_{i-1}$ tries to forward a sensor data message to $S_i$ whose communication buffer is filled, $S_i$ transmits back a nack (negative acknowledgement) control message to notify its filled communication buffer. On receipt of the nack control message, $S_{i-1}$ tries to forward it to $S'_{i}$. If it is successful, transmission delay of the sensor data message is expected to be reduced since $S'_{i}$ is a neighbor sensor node of $S_i$. Otherwise, i.e., the communication buffer of $S'_{i}$ is also filled and $S_{i-1}$ receives a nack control message, $S_{i-1}$ stores the sensor data message to its own communication buffer.

![Fig. 3. Neighbor Buffering in Original NeBuST.](image)

V. PROPOSAL

A. NeBuST-wide

For transmissions of burst event-driven sensor data messages, the original NeBuST avoids additional transmission delay caused by a sequence of filled communication buffers by using communication buffers in 1-hop neighbor sensor nodes as backups. Sensor data messages are transmitted nearer to the destination sink nodes even while communication buffers in intermediate sensor nodes are filled. In a wireless multihop transmission route $\mathcal{R} = \langle S_0, \ldots, S_n \rangle$, sensor data messages buffered in a backup sensor node $S'_{i+1}$ is forwarded to $S_{i+1}$ which is a next-hop node of $S_i$ in $\mathcal{R}$.

As discussed in the previous section, communication buffers in any intermediate sensor nodes may be filled independently of distance to the sink node. Thus, a sequence of filled communication buffers may be configured even far from the sink node. In this case, the original NeBuST also contribute to reduce the transmission delay by using communication buffers in 1-hop neighbor sensor nodes as shown in Figure 4. However,
for avoidance of a sequence of filled communication buffers far from the sink node, since few concurrent transmissions of burst event-driven sensor data transmissions through neighbor sensor nodes are expected, wider distribution of sensor data message transmissions may reduce more transmission delay. Thus, this paper proposes an extension NeBuST-wide. Here, a backup sensor node $S'_{i}$ of $S_{i}$ does not always transmit to $S_{i+1}$ but also to its backup node $S''_{i+1}$. In addition, $S'_{i}$ also transmits sensor data messages to a backup node $S''_{i+1}$ of $S_{i+1}$ which may be away from $R$. Therefore, as shown in Figure 5, if a communication buffer in $S_{i}$ is filled, transmissions of sensor data messages are widely distributed and sensor data messages are transmitted and buffered in sensor nodes nearer to the sink node. The widely distributed transmissions becomes independent of $R$ and shorter end-to-end transmission delay is achieved.

![Fig. 4. Filled Communication Buffers in Original NeBuST.](image)

### B. Routing Protocol

In the extended NeBuST-wide proposed in the previous subsection, not only 1-hop neighbor sensor nodes $S'_{i}$ of intermediate sensor nodes $S_{i}$ in a wireless multihop transmission route $R = \langle S_{0}, \ldots, S_{n} \rangle$ but also other sensor nodes are engaged in transmissions of sensor data messages from $S_{0}$. There are many possible intermediate nodes widely distributed. Hence, differently from the reactive routing protocol in the original NeBuST, NeBuST-wide adopts a proactive routing protocol in which each sensor node maintains its next-hop sensor nodes for lower routing overhead. One of the possible methods for all the sensor nodes to achieve and update their next-hop sensor nodes is periodical flooding of a routing control message from the destination sink node.

![Fig. 5. Filled Communication Buffers in NeBuST-wide.](image)

Here, based on a well-known ad-hoc routing protocol TORA [4], each sensor node achieves and keeps its hop counts to the sink node. The sink node broadcasts a routing control message to which the initial hop count 0 is piggybacked. On receipt of the first arrived routing control message, a sensor node increments the piggybacked hop count and broadcasts it. On receipt of the last arrived routing control message, a sensor node determines its hop count as the minimum hop count piggybacked to the received routing control message. Then, it advertises a pair of its identification and hop count to its neighbor sensor nodes by broadcasting a routing control message containing it. By receipts of the routing control messages, a sensor node determines its next-hop nodes advertising the minimum hop counts. In addition, it also achieves its possible previous-hop sensor nodes whose hop counts are larger than its own hop count. A sensor node forwards sensor data messages to one of its next-hop sensor nodes whose communication buffers are not filled.

### C. Protocols

This section describes NeBuST-wide routing and data message transmission protocols proposed in this section.

#### [Routing Protocol]

1) The sink node broadcasts a routing control message $Rreq(s)$ with a sequence number $s$ periodically\(^1\). $Rreq(s)$ also carries a hop-count $Rreq(s).hop$ from the sink node which is initially 0.

2) On receipt of the first copy of $Rreq(s)$, a wireless sensor node $S_{i}$ registers $Rreq(s).hop + 1$ as its temporary hop

\(^{1}\)The interval depends on the degree of topology change of the wireless sensor network caused by mobility and failures of wireless sensor nodes.
count \( \text{hop}_i \). Then, \( S_i \) broadcasts a copy of \( \text{Rreq}(s) \) where \( \text{Rreq}(s).\text{hop} := \text{hop}_i \).

3) On receipt of another copy of \( \text{Rreq}(s) \), only if \( \text{Rreq}(s).\text{hop} + 1 < \text{hop}_i \), \( S_i \) registers \( \text{Rreq}(s).\text{hop} + 1 \) as \( \text{hop}_i \).

4) If \( S_j \) has received copies of \( \text{Rreq}(s) \) from all its neighbor wireless sensor nodes, \( S_i \) registers \( \text{hop}_i \) as its final (minimum) hop-count \( \text{hop}_j \), to the sink node. \( S_i \) broadcasts a routing control message \( \text{Rrep}(s) \) to which \( \text{hop}_i \) is piggybacked as \( \text{Rreq}(s).\text{hop} \).

5) On receipt of the \( \text{Rreq}(s) \) from \( S_i \), a neighbor wireless sensor node \( S_j \) registers a pair \( (S_i, \text{Rreq}(s).\text{hop}) \) into its routing table.  

A routing table of \( S_i \) is a set of pairs of its neighbor wireless sensor nodes \( S_j \) and their hop counts \( \text{hop}_j \) to the sink node. If \( \text{hop}_j < \text{hop}_i \), \( S_j \) is a candidate of its next-hop node. \( S_j \), with the minimum hop count \( \text{hop}_j \), is a default next-hop node of \( S_i \) and \( S_i \) forwards sensor data messages to \( S_j \) if a communication buffer of \( S_j \) is not full, i.e., \( S_j \) does not return a \textit{nack} control message for a reply to a data message.

**[Data Transmission Protocol]**

1) A wireless sensor node \( S_i \) which initiates a multihop transmission of a data message or receives a data message from one of its neighbor nodes transmits the data message to its default next-hop node \( S_j \) with the minimum hop count \( \text{hop}_j \) to the sink node.

2) If \( S_i \) receives an \textit{ack} control message from \( S_j \), \( S_i \) deletes the data message and the transmission is complete.

3) If the receipt of the \textit{ack} control message is timeout, \( S_i \) retransmits the data message to \( S_j \).

4) If \( S_i \) receives a \textit{nack} control message from \( S_j \) or the number of retransmissions reaches the predetermined upper limit, \( S_i \), transmits the data message to its another candidate of its next-hop node \( S_j \) whose hop count is less than its hop count, i.e., \( \text{hop}_j < \text{hop}_i \), according to Step 1).

5) If no \textit{ack} control message is received from its all next-hop candidate nodes, \( S_i \) stores the data message to its communication buffer. After a certain longer interval, \( S_i \) retries the transmission from Step 1).  

**VI. Evaluation**

This section evaluates the performance of NeBuST-wide. First, we evaluate it by comparison with the original NeBuST. During transmissions of a sequence of sensor data messages, sensor nodes nearer to the sink node than a threshold distance suspend forwarding sensor data messages in order to cause filled communication buffers temporarily. Then, the sensor nodes restart forwarding and end-to-end transmission delay of the sensor data messages are measured. As shown in Figure 6, sensor nodes with 100m transmission range and communication buffers for 5 sensor data messages are located in a lattice with 60m spaces. A source sensor node is 30 hops away from a destination sink node along a straight transmission route and transmits 30–50 sensor data messages per second for 0.5–2.0 second duration. Sensor nodes within 300m from the sink node suspend communication by transmitting back \textit{nack} control messages in duration 1.0 second after starting transmissions of sensor data messages. Here, the required time to transmit all the burst sensor data messages to the sink node is measured in the naive multihop transmission with \textit{nack} control message returns, in the original NeBuST and in NeBuST-wide.

![Fig. 6. Simulation Setting.](image)

Figure 7 shows the results with 1.0 second suspension period. In comparison with the naive multihop transmissions with \textit{nack} control message returns, NeBuST reduces 4.67% transmission delay. Thus, neighbor buffering in NeBuST contributes to reduction of end-to-end transmission delay. Furthermore, NeBuST-wide achieves 15.9% shorter transmission delay. Thus, wider distribution of sensor data message transmissions by extended neighbor buffering effects on the reduction of end-to-end transmission delay.

![Fig. 7. Transmission Delay with 1.0s Suspension.](image)

Figure 8 shows instances of transmission delay of all the sensor data messages in cases of 2.0 second burst period with 50 sensor data messages per second and 1 second suspension period. In NeBuST and NeBuST-wide, the front sensor data messages are buffered in an intermediate node along a transmission route and requires longer transmission delay; however the other sensor data messages are transmitted through detour routes even during the suspension period and the reduction of transmission delay is realized. Hence, though the tail sensor data messages require longer transmission delay in the naive transmissions with \textit{nack} control message returns due to the effect of the sequence of filled communication buffers, NeBuST and NeBuST-wide are less effected and transmission delay of the tail sensor data messages are much shorter than the others especially in NeBuST-wide.

Next, we compare it with another multi-route routing protocol AODVM [3] for node-disjoint ad-hoc routing. In a 2,000m \( \times \) 2,000m square field, the sink node is at the center of the field and 3,000 wireless sensor nodes with a 100m wireless transmission range and a communication...
buffer for 5 data messages are randomly distributed. AODVM detects multiple transmission routes in advance; however, NeBuST-wide dynamically changes transmission routes in a message-by-message manner. Figure 9 shows detected two node-independent transmission routes in AODVM and Figure 10 shows a default transmission route in NeBuST-wide. The randomly selected source wireless sensor node initiates 30–50 burst data messages in each second and the burst period is 1.5–3.0 second. For comparison of the two protocols, during 1.0–2.0 second in simulation time, all wireless sensor nodes return nack control messages in order to buffer some data messages in transmission.

VI. CONCLUSION

This paper proposes NeBuST-wide as an extension of NeBuST which realizes shorter delay transmissions of event-driven sensor data messages. In spite of less memory capacities in wireless sensor nodes, it avoids losses of sensor data messages caused by filled communication buffers and improves end-to-end transmission delay by wide distribution of sensor data message transmissions away from the original transmission route. For NeBuST-wide, routing and sensor data message transmission protocols are designed and the performance is evaluated by comparison with the naive transmissions and the original NeBuST. The proposed NeBuST-wide achieves shorter transmission delay due to avoidance of effects of sequences of filled communication buffers.

REFERENCES


