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A study on optimization of polling scheduling for in-vehicle UWB wireless networks*

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Abstract: This paper proposes a polling-scheduling for UWB-based in-vehicle networks. The proposed scheduling aims to reduce the preamble overhead by aggregating periodic data readout of the in-vehicle sensors. Experimental results show that the proposed scheduling successfully suppresses data loss rate compared to the cyclic scheduling.

Keywords: UWB, in-vehicle networks, polling-scheduling

Classification: Wireless Communication Technologies

References

[1] C. Ohta, T. Tanaka, H. Migita, S. Yamaguchi, M. Takenaka, P. Finnerty, and T. Kamada, "Optimization and implementation evaluation of polling scheduling for in-vehicle UWB communications," Proc. ISCIE General Conference 2022, May 2022 (to appear in Japanese).

[2] Y. Sadi and S.C. Ergen, "Optimal power control, rate adaptation, and scheduling for UWB-based intravehicular wireless sensor networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 1, pp. 219–234, Sept. 2013. DOI: 10.1109/TVT.2012.2217994

[3] M.S. Akbar, H. Yu, and S. Cang, "IEEE 802.15.4 frame aggregation enhancement to provide high performance in life-critical patient monitoring systems," *Sensors*, vol. 17, no. 2, Jan. 2017. DOI: 10.3390/s17020241

[4] M. Charlier, B. Quoitin, S. Bette, and J. Eliasson, "Support for IEEE 802.15.4 ultra wideband communications in the Contiki operating system," Proc. 2016 Symposium on Communications and Vehicular Technologies, Nov. 2016. DOI: 10.1109/SCVT.2016.7797662

[5] H.-B. Li, K. Takizawa, B. Zhen, and R. Kohno, "Accelerating low-rate wireless PAN with ultra-wideband technology," *IEICE Commun. Mag.*, vol. 2007, no. 2, pp. 2_74–2_84, Aug. 2007 (in Japanese).

[6] E.M.L. Beale and J.J.H. Forrest, "Global optimization using special ordered sets," *Mathematical Programming*, vol. 10, no. 1, pp. 52–69, Dec. 1976. DOI: 10.1007/BF01580653

*This paper is an extended version of [1] including new experimental results.

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1 Introduction

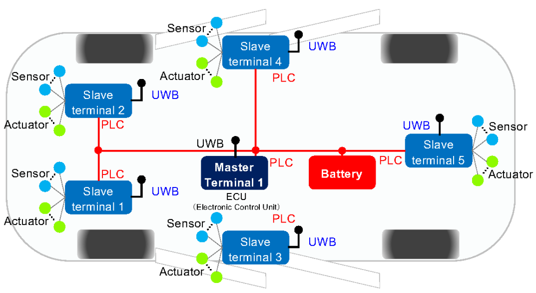
To reduce greenhouse gases emission, demand for improving the fuel efficiency of vehicles has been increasing. One such way is to reduce vehicle weight by trimming the wire harnesses as much as possible. For this sake, we are developing an integrated in-vehicle network consisting of Power Line Communication (PLC) and Ultra Wideband (UWB) with DENSO TEN Limited and Advanced Telecommunications Research Institute International (ATR) [1]. The power line needs to remain for electronics devices. Thus, PLC can utilize it as a communication medium. Further, replacing a part of the wire harnesses with wireless networks reduces wire harnesses. Impulse Radio-UWB (IR-UWB, in short UWB hereafter) specified in IEEE 802.15.4a/z is one of the candidates. This is because of its excellent penetration of the signal and robustness in multipath environments.

This paper focuses on in-vehicle wireless networks and proposes a polling-scheduling for UWB-based in-vehicle networks. As literature related to this work, for example, Ref. [2] proposes a scheduler for in-vehicle UWB wireless sensor networks considering periodic data readout. However, it does not consider data aggregation, which will be explain in Section 3. Regarding data aggregations, Ref. [3] shows the effectiveness of frame aggregation for vital sensing by IEEE 802.15.4. However, it does not take scheduling into account. Unlike the above, our scheduling aims to reduce the preamble overhead by aggregating periodic data readout of the in-vehicle sensors.

In what follows, we will explain our scheduling algorithm and show some experimental results.

2 UWB/PLC integrated in-vehicle network

Figure 1(a) shows our developing UWB/PLC integrated in-vehicle network, which consists of one master terminal (MT) and five slave terminals (STs). Multiple sensors



(a) System overview

Readout cycle (ms)	108	72	56	24
Slave terminal 1	2	10	12	16
Slave terminal 2	8	10	14	14
Slave terminal 3	4	6	14	16
Slave terminal 4	6	6	18	14
Slave terminal 5	4	10	16	14

(b) Number of sensors and readout cycles

Fig. 1. UWB/PLC integrated in-vehicle network

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and actuators are connected to each ST. The Electronic Control Unit (ECU) reads data from the sensors connected to the ST via the MT. It also sends control data to each actuator as needed.

Each sensor has a specific readout cycle based on its type. The length of sensor data is 6 bytes that consist of the sensor ID of 2 bytes and the sensor reading of 4 bytes. Figure 1(b) shows an example of the number of sensors connected to each ST and their cycles. In this case, the data transfer load is about 250 kbit/s.

The ECU cannot always read out at the desired timing because it can only read from one ST at a time. Therefore, the delay until the ECU actually receives the data is regarded as the readout delay. From this viewpoint, communications are categorized into low latency for safety data related to driving operation and non-low latency for body-equipment data related to wiper operation. For these, we aim to satisfy the following qualities:

- Low latency: data load 250 kbit/s, allowable data loss rate 10^{-4}, allowable readout delay 15 ms
- Non-low latency: data load 500 kbit/s, allowable data loss rate 10^{-3}, allowable readout delay 25 ms

We assume that UWB conveys the load of 250 kbit/s for non-low latency data while PLC does the rest for non-low latency data and low delay data.

3 Data aggregation oriented polling type MAC

In IEEE 802.15.4a/z, the maximum length of Physical Service Data Unit (PSDU) is 127 octets by default. Moreover, the preamble symbol is about eight times longer than the payload symbol. This leads to much preamble overhead in physical frames. For example, the preamble length is 128 symbols in the Qorvo DWM3000 used in the experiments. In this case, the preamble and payload parts have almost the same length [4]. Therefore, conveying as much sensor data as possible in a Physical layer Protocol Data Unit (PPDU) is more efficient.

In IEEE 802.15.4a, Clear Channel Assessment (CCA) is enabled by periodically inserting preamble symbols into the data symbols [5]. It is optional and not implemented in NXP Semiconductors or Decawave (currently Qorvo) UWB modules. Therefore, this study employs polling-type media access control in which the MT controls the media access of STs.

3.1 Frame format

Figure 2(c) shows the format of the polling frame and response frame. The polling frame from the MT to an ST includes the IDs of sensors to be read and data toward actuators. The response frame from the ST includes the readout data of the sensor specified in the polling frame.

3.2 Polling transmission/retransmission

When and which the ST is polled is determined by off-line scheduling. The scheduling is generated on a slot basis. (See Section 4.) Each sensor has a unique read cycle in milliseconds. Its period is assumed to be an integral multiple of the slot time.

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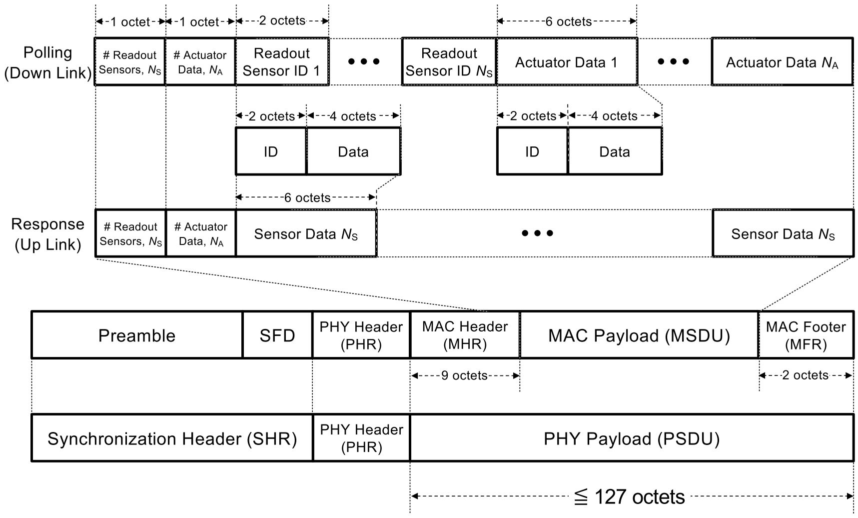

Fig. 2. MAC SDU format/PPDU format

The MT sends a polling frame to the intended ST when the slot begins. If the MT receives no response frame, it judges that the polling has failed. Then, the MT repeats polling until it succeeds as long as possible within the slot. If every polling fails eventually, the MT backlogs the readouts that possibly satisfy delay constraints even in the following slots. On the other hand, if time remains within the slot thanks to successful polling, the MT utilizes it for backlogged re-polling.

4 Optimization of polling-scheduling

This section explains how to generate the schedule that aggregates readouts using integer programming to minimize the number of polling.

4.1 Variable definitions

The variables used in the formulation are defined below:

- T: Scheduling cycle (least common multiple of readout cycles)
- δ: Slot duration in milliseconds
- S: Total number of slots in scheduling cycle T
- D: Allowable readout delay in milliseconds
- M: maximum readable data size in bytes in a polling
- k: Slot number ($0 \leq k < S + D/\delta$)
- $\mathcal{N}$: Set of STs
- $\mathcal{J}_n$: Set of readout data for ST n
- $\mathcal{J}$: Set of readout data over all STs
- a_j: Desired readout time in milliseconds for readout data j
- v_j: Size of readout data j in bytes
- s_j: Allocated slot number for the readout data j
- $x_{j,k}$: Binary variable, 1 if data j is readout in the kth slot, otherwise 0

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- $y_{n,k}$: Binary variable, 1 if the kth slot is assigned to ST j, otherwise 0

It is assumed that time starts from 0 ms and slots are numbered in ascending order from zero.

4.2 Objective function and constrains

A multi-objective function is formulated to reduce the total number of polls to STs and avoid unnecessary polling delays as shown below:

$$\begin{aligned} \text{Minimize} \quad & \alpha \sum_{k=0}^{S+D/\delta-1} \sum_{n \in \mathcal{N}} y_{n,k} \\ & + (1-\alpha) \sum_{j \in \mathcal{J}} \left\{ s_j \delta - a_j \right\}, \end{aligned} \tag{1}$$

subject to:

$$0 \le a_j < T = \delta S, \quad \forall j \in \mathcal{J}, \tag{2}$$

$$s_j \delta - a_j \le D - \delta, \quad \forall j \in \mathcal{J}, \tag{3}$$

$$a_j \le s_j \delta, \quad \forall j \in \mathcal{J}, \tag{4}$$

$$\sum_{k=0}^{S+D/\delta-1} x_{j,k} = 1, \quad \forall j \in \mathcal{J}, \tag{5}$$

$$s_j = \sum_{k=0}^{S+D/\delta-1} k x_{j,k}, \quad \forall j \in \mathcal{J}, \tag{6}$$

$$y_{n,k} = \min \left\{ 1, \sum_{j \in \mathcal{J}_n} x_{j,k} \right\}, \quad \forall n \in \mathcal{N}, \tag{7}$$

$$\sum_{n \in \mathcal{N}} y_{n,k} \le 1, \quad 0 \le k \le S + D/\delta - 1, \tag{8}$$

$$\sum_{n \in \mathcal{N}} (y_{n,k} + y_{n,k+S}) \le 1, \quad 0 \le k \le D/\delta - 1, \tag{9}$$

$$\sum_{j \in \mathcal{J}} v_j x_{j,k} \le M, \quad 0 \le k \le S + D/\delta - 1. \tag{10}$$

Equation (7) can be rewritten as follows by using the SOS2 (Special Ordered Set of Type 2) auxiliary variables t_1, t_2, and t_3 [6].

$$\begin{pmatrix} \sum_{j \in \mathcal{J}_n} x_{j,k} \\ y_{n,k} \end{pmatrix} = t_1 \begin{pmatrix} 0 \\ 0 \end{pmatrix} + t_2 \begin{pmatrix} 1 \\ 1 \end{pmatrix} + t_3 \begin{pmatrix} |\mathcal{J}_n| \\ 1 \end{pmatrix}, \tag{11}$$

$$t_1 + t_2 + t_3 = 1, \quad t_1 \ge 0, \ t_2 \ge 0, \ t_3 \ge 0, \tag{12}$$

$$t_1 \le z_1, \quad t_2 \le z_1 + z_2, \quad t_3 \le z_2, \tag{13}$$

where z_1 and z_2 are auxiliary binary variables whose values are 0 or 1.

5 Experiments

Simple experiments were conducted in the Electromagnetic Compatibility (EMC) tent manufactured by Medical Aid Co., Ltd. to verify the effectiveness of the proposed scheduling. The target system consists of one MT and five STs as in Fig. 1. Interference systems consisted of one MT and one ST, they mimic the target system.

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Qorvo DWM3000 was used as a UWB radio device. Its configurations were channel 9 (center frequency 7987.2 MHz, bandwidth 499.2 MHz), data rate 6.81 Mbit/s, and preamble length 128 symbol. For the load of about 250 kbit/s, the situation shown in Fig. 1(b) was assumed. By halving the number of sensors, the lower load of 125 kbit/s was generated. The slot duration δ was set to 4 ms. The weight α in Eq. (1) was set as $\alpha = 1000/1001$.

For comparison, cyclic scheduling was also evaluated. In this method, polling is scheduled in order from ST 1 to 5, repeatedly; that is, ST 1 is polled after ST 5. In case of no sensor data to be read out for the intended ST, polling is not performed in that slot, and the next ST will be polled in the next slot.

Data loss rates are shown in Fig. 3. Note that both the cyclic scheduling and the proposed scheduling satisfy the allowable readout delay of 25 ms. The proposed scheduling successfully suppresses the data loss rate compared to the cyclic scheduling. In the case of the load of 250 kbit/s, the cyclic scheduling could not satisfy the allowable data loss rate of 10^{-3}. On the other hand, the proposed one could do when one interference system exists. In the case of the load 125 kbit/s, the proposed one provides a lower data loss rate than the allowable one of 10^{-3} even when three interference systems exist. From the above, the effectiveness of data aggregation is confirmed.

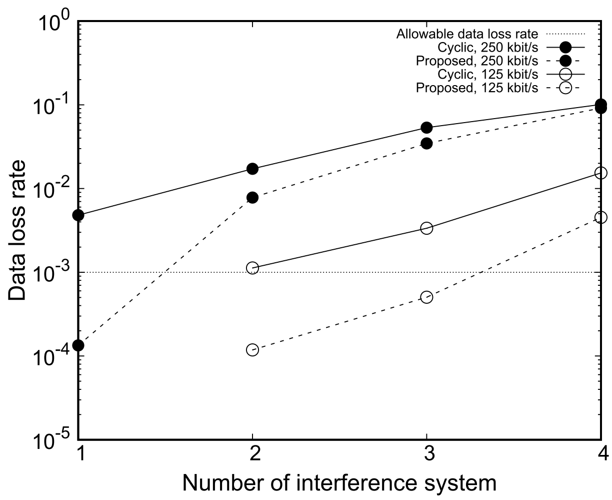

Fig. 3. Experimental results

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