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A study on optimization of polling schedule to minimize the number of frames for in-vehicle UWB wireless network†

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Abstract: This paper discusses a polling and scheduling method for UWB-based in-vehicle networks. In IEEE 802.15.4a/z, conveying as much sensor data as possible in a Physical layer Protocol Data Unit (PPDU) is more efficient. Therefore, this paper proposes a scheduling scheme that minimizes the number of frames to be transmitted by adjusting the readout phase of periodic sensor data. Compared to existing methods, our proposed method can aggregate sensor data into fewer frames, resulting in a decreased loss rate in our experiment.

Keywords: UWB, in-vehicle networks, polling scheduling

Classification: Wireless Communication Technologies

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†This paper is an improved version of Refs. [1, 2] including a new scheduling method and an extended version of Ref. [3] including new experimental results.

1 Introduction

In collaboration with DENSO TEN Limited and the Advanced Telecommunications Research Institute International (ATR), we have been trying to reduce the size of automotive wire harnesses by substituting them for a combination of UWB (Ultra-Wideband) and PLC (Power Line Communication) to improve the fuel efficiency of automobiles [1].

Ref. [1] presents polling-type media access control and scheduling optimization for in-vehicle UWB wireless networks. It proposes that data aggregation by minimizing the polling in an in-vehicle UWB network is effective regarding data loss rate. Ref. [2] proposes that in periodic sensor data readout, more efficient data aggregation can be achieved by adjusting the sensor data readout phase. These two related works raise the following questions concerning our previous work. First, the objective function was set to minimize the number of polling, which left room for data aggregation. Second, the slave terminal to be read and the data to be read were set as variables in our optimization problem formulation, which is redundant.

This paper is α n extended version of Ref. [3] and the contributions of this paper are the following:

1. A new scheduling scheme that minimizes the number of transmitted frames
2. The simplification of the optimization problem formulation by removing the slave terminal to be read from the variables
3. Experimental results demonstrating the effectiveness of our new method

2 System overview

2.1 UWB/PLC integrated in-vehicle network

Figure 1(a) presents our UWB/PLC integrated in-vehicle network that consists of one master terminal (MT) and five slave terminals (ST). The Electronic Control Unit (ECU) periodically reads out data from sensors connected to the ST.

Each sensor has a specific readout cycle, depending on its type. Figure 1(b) shows an example of the number of sensors connected to each ST and their cycles when the data transfer load is about 250 kbit/s. The delay from when the ECU desires to read the data to when the data is received is considered the read delay. In-vehicle 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, etc. This research assumes that UWB conveys a 250 kbit/s load with non-low latency data and PLC conveys the remaining non-low latency and low latency data. The target communication quality for the UWB part on which we focus on is a data loss rate no greater than 10^{-3}, and a readout delay within 25 ms.

2.2 Polling control

In IEEE802.15.4a, Clear Channel Assessment (CCA) is enabled by periodically inserting a preamble symbol into the data symbol [4]. However, this is optional and is not implemented in UWB modules from NXP Semiconductors or Decawave (now Qorvo). Therefore, this research employs an MT-driven polling-based media access control.

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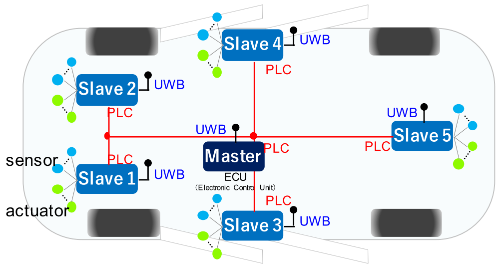


(a) System overview

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

(b) Number of sensors and readout cycles

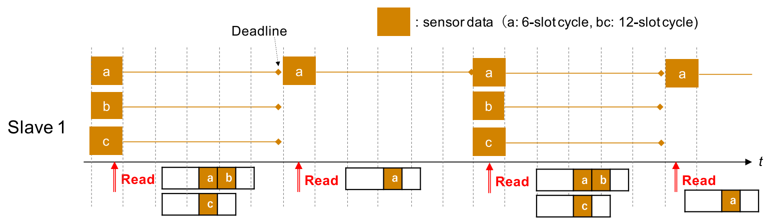
Fig. 1. UWB/PLC integrated in-vehicle network

When and which sensor data is read is determined by offline scheduling. The schedule is generated slot-by-slot, with a single ST communicating per slot. The readout period of each sensor is an integer multiple of the slot time. Polling is conducted in order from ST1 to ST5. Specifically, in the example shown in Fig. 1, the slot time is set to 4 ms (the common divisor of the number of readout cycles), and it is necessary to poll each ST at least every 24 ms (the minimum readout cycle). Furthermore, after allocating slots to ST1 through ST5, an additional non-allocated slot is kept. This empty slot is used as a margin for retransmission in case of communication failure. The cycle then repeats.

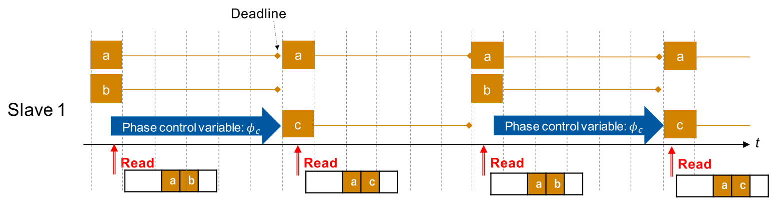
When a slot begins, the MT sends a polling frame to the intended ST. If the MT receives no response frame, it judges that the polling has failed. The MT will then repeat polling until it succeeds or the slot expires. If all polls for an allocated slot fail, the MT will continue polling this ST in the next slot as long as the delay constraint is satisfied, even if polling another ST is scheduled. That is, the retransmission process is prioritized, and the entire polling process eventually shifts.

3 Adjustment of data readout phase

In this section, we discuss ideas for phase control to reduce the number of frames transmitted. Figure 2 shows the case without and with phase control. In this example,



(a) Without phase control



(b) With phase control

Fig. 2. Data readout phase control

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three types of periodic data are read out before the deadline. Assuming that up to two datum can be transmitted in one frame, six frames are needed in Fig. 2(a). In Fig. 2(b), the period is shifted according to the variable that controls the phase, reducing the number of frames required for transmission to four.

4 Optimization of polling scheduling

In this section, we explain how to generate a schedule that aggregates readouts and minimizes the number of frames using integer programming. For each slave terminal, the following linear programming-based optimization is applied to derive the schedule.

4.1 Variable definitions

The variables used in the formulation are defined below:

- T: Schedule cycle (least common multiple of readout cycles)
- δ: Slot duration in milliseconds
- C: Minimum readout cycle of sensor data
- D: Allowable readout delay in milliseconds
- M: Maximum readable data size in bytes in a polling
- N: Maximum number of datum that can be stored in a single frame
- k: Index of allocatable slots for an ST
- $\mathcal{S}$: Set of sensors
- $\mathcal{J}_s$: Set of readout data for sensor s
- $\mathcal{J}$: Set of readout data of all sensors,
- $a_{s,j}$: Desired readout time in milliseconds for data j of sensor s
- $r_{s,j}$: Allocated readout time in milliseconds for data j of sensor s
- $x_{s,j,k}$: Binary variable, 1 if data j of sensor s is readout in the kth slot, otherwise 0
- f_k: Integer variable, indicating the number of frames transmitted in the kth slot
- ϕ_s: Integer variable, indicating the number of phase shift slots for the sensor s

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

4.2 Objective function and constraints

We formulate a multi-objective function to reduce the total number of frames and avoid unnecessary polling delays. Recall that each ST is polled every C/δ slots, i.e., six slots. Therefore, the kth allocatable slot for ST n is the $\{(C/\delta)k + (n-1)\}$th slot. The details are shown below:

Minimize

$$\alpha \sum_{k=0}^{T/C} f_k + (1-\alpha) \sum_{s \in \mathcal{S}} \sum_{j \in \mathcal{J}_s} \left\{ r_{s,j} - (a_{s,j} + \phi_s \delta) \right\}, \qquad (1)$$

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subject to

$$r_{s,j} - (a_{s,j} + \phi_s \delta) \le D - \delta, \quad \forall j \in \mathcal{J}_s, \forall s \in \mathcal{S}, \tag{2}$$

$$a_{s,j} + \phi_s \delta - r_{s,j} \le 0, \quad \forall j \in \mathcal{J}_s, \forall s \in \mathcal{S}, \tag{3}$$

$$\sum\nolimits_{k=0}^{T/C} x_{s,j,k} = 1, \quad \forall j \in \mathcal{J}_s, \forall s \in \mathcal{S}, \tag{4}$$

$$\sum\nolimits_{s \in \mathcal{S}} \sum\nolimits_{j \in \mathcal{J}_s} x_{s,j,k} \le M, \quad 0 \le k \le T/C, \tag{5}$$

with

$$r_{s,j} = C \sum\nolimits_{k=0}^{T/C} k x_{s,j,k}, \quad \forall j \in \mathcal{J}_s, \forall s \in \mathcal{S}, \tag{6}$$

$$\begin{aligned} f_k = \min \left\{1, \sum\nolimits_{s \in \mathcal{S}} \sum\nolimits_{j \in \mathcal{J}_s} x_{s,j,k} \right\} - \min \left\{N, \sum\nolimits_{s \in \mathcal{S}} \sum\nolimits_{j \in \mathcal{J}_s} x_{s,j,k} \right\} \\ + \min \left\{N+1, \sum\nolimits_{s \in \mathcal{S}} \sum\nolimits_{j \in \mathcal{J}_s} x_{s,j,k} \right\}, \quad 0 \le k \le T/C. \end{aligned} \tag{7}$$

The weight α is large enough to sufficiently minimize the number of frames while reducing the readout delay sum. In this paper, we set $\alpha = 0.5$.

Expression (7) converts the number of datum to the number of frames necessary to send them. It can be rewritten as follows by using the SOS2 (Special Ordered Set of Type 2) auxiliary variables $t_1, \ldots, t_5$ and $z_1, \ldots, z_4$ [5].

$$\begin{pmatrix} \sum_{s \in \mathcal{S}} \sum_{j \in \mathcal{J}_s} x_{s,j,k} \\ f_k \end{pmatrix} = t_1 \begin{pmatrix} 0 \\ 0 \end{pmatrix} + t_2 \begin{pmatrix} 1 \\ 1 \end{pmatrix} + t_3 \begin{pmatrix} N \\ 1 \end{pmatrix} + t_4 \begin{pmatrix} N+1 \\ 2 \end{pmatrix} + t_5 \begin{pmatrix} 2N \\ 2 \end{pmatrix} \tag{8}$$

subject to

$$t_1 + t_2 + t_3 + t_4 + t_5 = 1, \quad t_1, \ldots, t_5 \ge 0, \tag{9}$$

$$z_1 + z_2 + z_3 + z_4 = 1, \quad z_1, \ldots, z_4 = 0 \text{ or } 1, \tag{10}$$

$$t_1 \le z_1, \quad t_2 \le z_1 + z_2, \quad t_3 \le z_2 + z_3, \quad t_4 \le z_3 + z_4, \quad t_5 \le z_4. \tag{11}$$

5 Experiments

To verify the effectiveness of our new formulation, we conducted a simple experiment in which we measure the data loss ratio. The experiment was conducted in an Electromagnetic Compatibility (EMC) tent manufactured by Medical Aid Co and one MT and five STs were configured as shown in Fig. 1(a) using a Qorvo DWM3000 UWB radio. In addition, up to 4 interfering UWB modules are introduced. The amount of data to be transmitted is that shown in Fig. 1(b) with a total load of 250 kbit/s. The configuration used was channel 9 (center frequency 7987.2 MHz, bandwidth 499.2 MHz), data rate 6.81 Mbit/s, and a preamble length 64 symbols (as opposed to the default 128 symbols). This change in the preamble length was made to increase the time available for retransmission in case of reception failure.

In the experiment, data transmission is based on the scheduling shown in Section 4. For comparison, a round-robin schedule with no phase adjustment and a schedule minimizing the number of polling with no phase adjustment were also evaluated. In the round-robin scheme, polling is scheduled repeatedly in the order of ST1 to ST5. That is, ST1 is polled after ST5. If there are no sensor data to be read, no polling is performed in that slot and the next ST is polled in the next slot.

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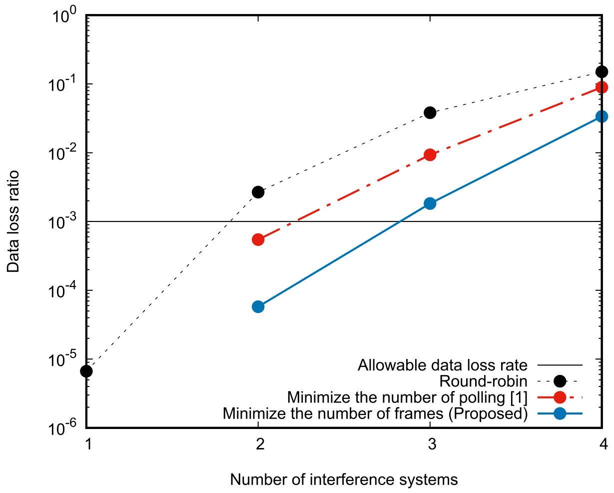

Fig. 3. Experimental results

The schedule minimizing the number of polling is computed based on our previous research [1]. Both of these schedules satisfy the allowable readout delay of 25 ms.

The experimental results are shown in Fig. 3. When the number of interfering systems was 0 with a minimized number of frames and minimized number of polls, the data loss rate was 0. The proposed scheduling successfully suppressed the data loss rate compared to the other two scheduling schemes. In the case of two interfering systems, the proposed scheduling achieved a target data loss rate of 10^{-3}, while the round-robin scheme did not. In the presence of three interfering systems, although the target data loss rate was not achieved, we observed a reduction in the data loss rate of approximately 89% compared to our previous research. From the above, the effectiveness of minimizing the number of frames necessary for the schedule is confirmed.

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