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A rectangle bin packing optimization approach to the signal scheduling problem in the FlexRay static segment

Key words: FlexRay, Real-time applications, Rectangle bin packing, Schedule optimization, Slot multiplexing

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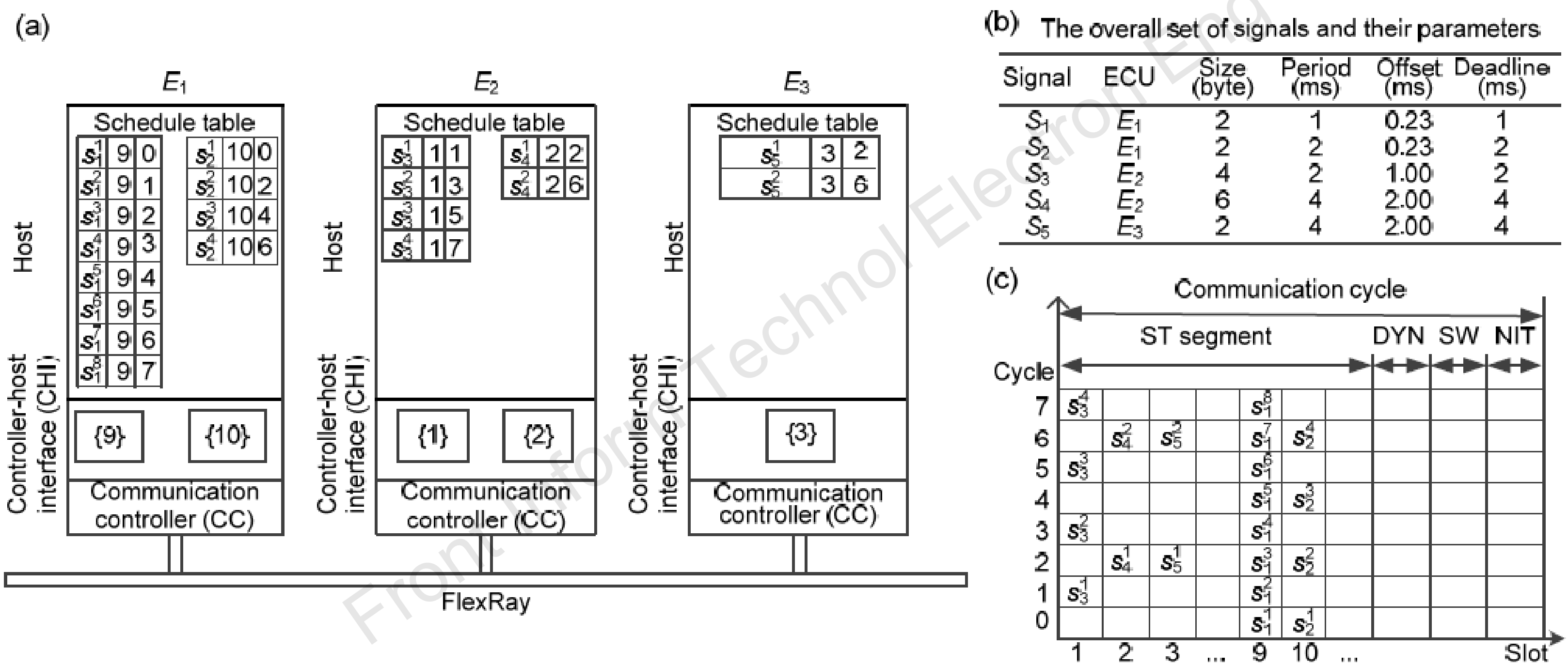
Introduction

- As FlexRay communication protocol is extensively used in distributed real-time applications on vehicles, signal scheduling in FlexRay network becomes a critical issue to ensure the safe and efficient operation of time-critical applications.

- With the significant increase in the number of signals in the FlexRay static segment, an optimal signal scheduling that satisfies the timing constraints of each of the signals while optimizing the minimum number of used slots is essential for future automotive networks with large volumes of data.

- A rectangle bin packing optimization approach to schedule communication signals with timing constraints into the FlexRay ST segment at minimum bandwidth cost has been presented in this work. The proposed approach, which is based on integer linear programming (ILP), supports both the slot assignment mechanisms provided by the latest version of the FlexRay specification, namely, the single sender slot multiplexing, and multiple sender slot multiplexing mechanisms.

System model in this work



Signal	ECU	Size (byte)	Period (ms)	Offset (ms)	Deadline (ms)
S_1	E_1	2	1	0.23	1
S_2	E_1	2	2	0.23	2
S_3	E_2	4	2	1.00	2
S_4	E_2	6	4	2.00	4
S_5	E_3	2	4	2.00	4

Fig. 1 Example of a FlexRay system model

(a) Schematic of ECUs connected by the FlexRay bus; (b) Overall set of signals; (c) Transmission process of each signal instance in the time-triggered system. ST: static; DYN: dynamic; SW: symbol window; NIT: network idle time

Slot multiplexing mechanism

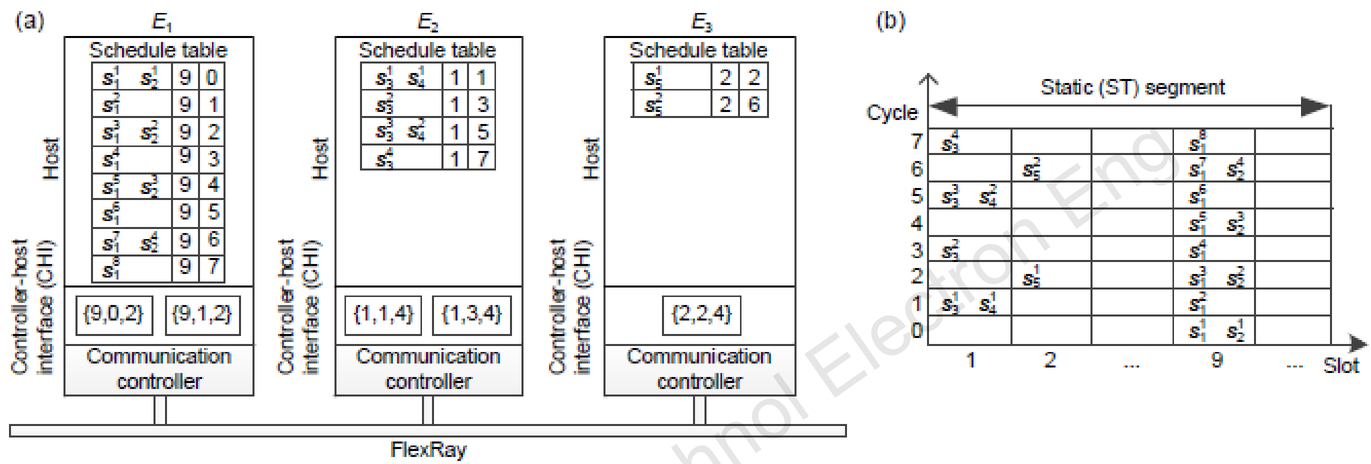


Fig. 2 Example of single sender slot multiplexing mechanism

(a) Schematic of ECUs connected by the FlexRay bus; (b) Transmission process of each signal instance in the time-triggered system

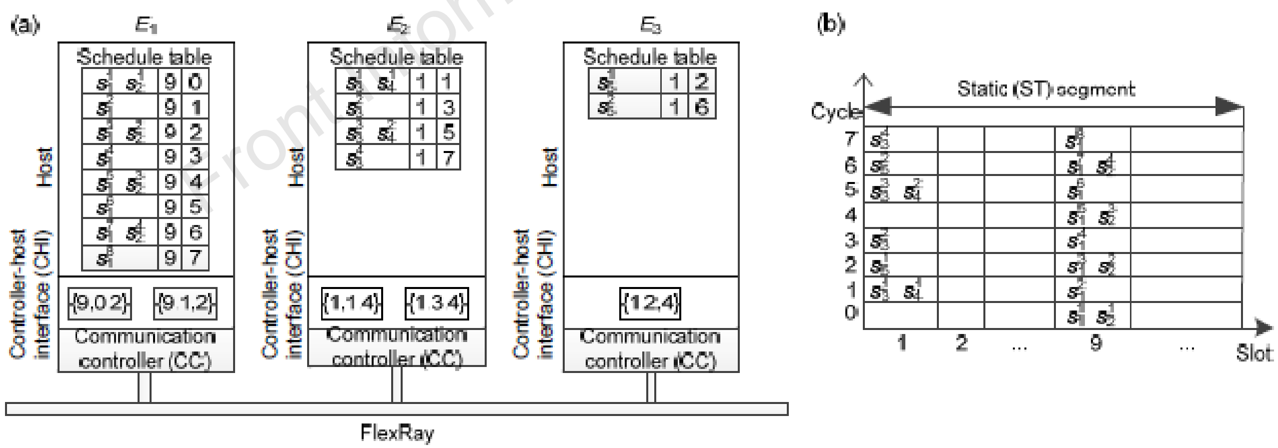


Fig. 3 Example of multiple sender slot multiplexing mechanism

(a) Schematic of ECUs connected by the FlexRay bus; (b) Transmission process of each signal instance in the time-triggered system

Signal scheduling optimization method (I)

Variables:

$$\alpha_s = \begin{cases} 1, & \text{slot } s \text{ is used}, \\ 0, & \text{otherwise}, \end{cases} \quad (s = 1, 2, \ldots, n_{\text{slot}})$$

$$\beta_{k,s,l} = \begin{cases} 1, & \text{instance } \tau_k \text{ is placed} \\ & \text{in slot } s \text{ at cycle } l, \\ 0, & \text{otherwise}, \end{cases} \quad (s = 1, 2, \ldots, n_{\text{slot}},\ l = 1, 2, \ldots, n_l)$$

$$\gamma_{e_p,s,l} = \begin{cases} 1, & \text{cycle } l \text{ of slot } s \\ & \text{belongs to ECU } E_p, \\ 0, & \text{otherwise}, \end{cases} \quad (E_p = 1, 2, \ldots, n, s = 1, 2, \ldots, n_{\text{slot}},\ l = 1, 2, \ldots, n_l)$$

$$\delta_{e_p,s} = \begin{cases} 1, & \text{slot } s \text{ belongs} \\ & \text{to ECU } E_p, \\ 0, & \text{otherwise}, \end{cases} \quad (e_p = 1, 2, \ldots, n,\ s = 1, 2, \ldots, n_{\text{slot}})$$

Signal scheduling optimization method (II)

Optimization objective: $$\min \sum_{s=1}^{n_{\mathrm{slot}}} \alpha_s .$$

Constraints:

$$\sum_{s=\mathrm{ss}'_k}^{\mathrm{fs}'_k} \beta_{k,s,\mathrm{sc}'_k} = 1,\ \forall k \mid q_k = 1 \vee \mathrm{sc}'_k = \mathrm{fc}'_k .$$

$$\sum_{s=\mathrm{ss}'_k}^{n_{\mathrm{slot}}} \beta_{k,s,\mathrm{sc}'_k} + \sum_{s=1}^{\mathrm{fs}'_k} \beta_{k,s,\mathrm{fc}'_k} = 1,\quad \forall k \mid q_k = 1 \vee \mathrm{sc}'_k = \mathrm{fc}'_k + 1.$$

$$\sum_{s=\mathrm{ss}'_k}^{n_{\mathrm{slot}}} \beta_{k,s,\mathrm{sc}'_k} + \sum_{s=1}^{n_{\mathrm{slot}}} \sum_{l=\mathrm{sc}'_k+1}^{\mathrm{fc}'_k-1} \beta_{k,s,l} + \sum_{s=1}^{\mathrm{fs}'_k} \beta_{k,s,\mathrm{fc}'_k} = 1,\ \forall k \mid q_k = 1 \vee \mathrm{sc}'_k \geq \mathrm{fc}'_k + 2.$$

$$\beta_{k,s,l} = \beta_{k+n,(l+n\cdot p_k)\bmod H},\ \forall k \mid q_k = 1,\ n = 1, 2, \ldots, (H / p_k) - 1.$$

$$\sum_{s=1}^{n_{\mathrm{slot}}} \sum_{l=0}^{n_l-1} \beta_{k,s,l} = 1,\ \forall k = 1, 2, \ldots, n_k .$$

$$\alpha_s = \beta_{k,s,l},\ \forall k = 1, 2, \ldots, n_k,\ s = 1, 2, \ldots, n_{\mathrm{slot}},\ l = 1, 2, \ldots, n_l .$$

$$\sum_{k=1}^{n_k} b_k \cdot \beta_{k,s,l} \leq b_{\mathrm{slot}},\ \forall s = 1, 2, \ldots, n_{\mathrm{slot}},\ l = 1, 2, \ldots, n_l .$$

Signal scheduling optimization method (III)

Constraints:

$$\beta_{k,s,l} \le \delta_{e_k,s},\ \forall s = 1, 2, \ldots, n_s,$$

$$\sum_{e_p=1}^{n} \delta_{e_p,s} \le 1,\ \forall s = 1, 2, \ldots, n_s,$$

$$\delta_{e_k,s} \le \sum_{k=1}^{n_k} \sum_{l=1}^{n_l-1} \beta_{k,s,l},\ \forall s = 1, 2, \ldots, n_s,$$

$$\beta_{k,s,l} \le \gamma_{e_k,s,l},\ \forall s = 1, 2, \ldots, n_s,\ l = 1, 2, \ldots, n_l,$$

$$\sum_{e_p=1}^{n} \gamma_{e_k,s,l} \le 1,\ \forall s = 1, 2, \ldots, n_s,\ l = 1, 2, \ldots, n_l,$$

$$\gamma_{e_k,s,l} \le \sum_{k=1}^{n_k} \beta_{k,s,l},\ \forall s = 1, 2, \ldots, n_s,\ l = 1, 2, \ldots, n_l.$$

Experimental results

Table 3 Comparison of the optimal approaches proposed by Tanasa *et al.* (2011), Lukasiewycz *et al.* (2009), and this study

Approach	Number of frames	Number of used slots
ILP in Tanasa *et al.* (2011)	24	24
ILP in Lukasiewycz *et al.* (2009)	24	17
ILP_MS in this study	24	12

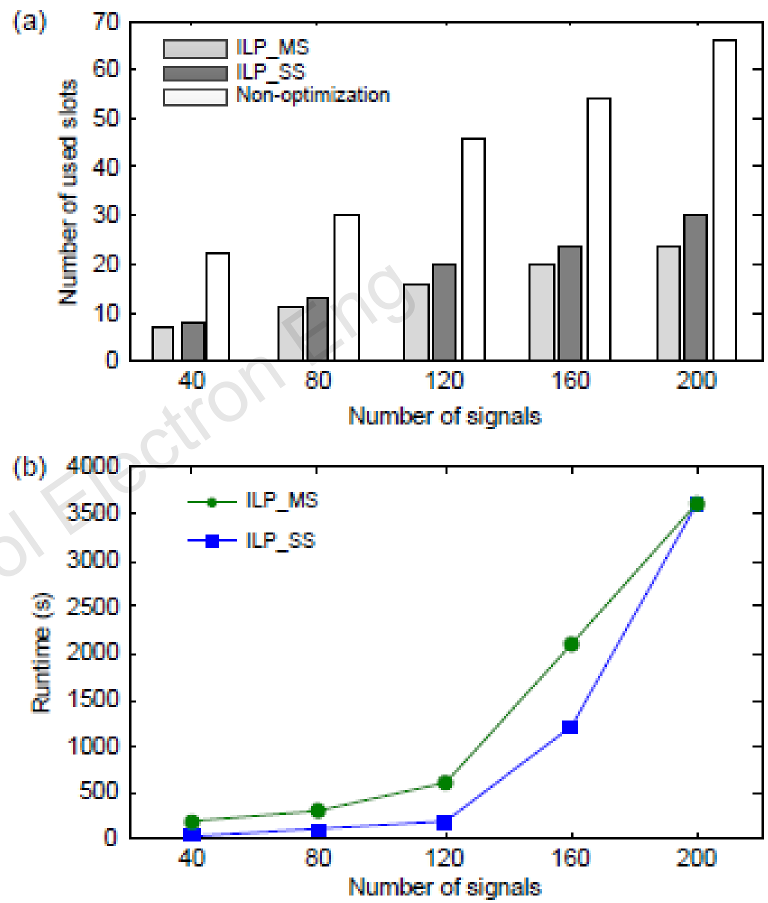


Fig. 5 Results of the synthetic case study

(a) The number of slots required by the ILP_MS, ILP_SS, and non-optimization approach for the test cases; (b) The corresponding runtime for both the ILP_SS and ILP_MS. ILP_SS: integer linear programming (ILP) approach based on the single sender slot multiplexing mechanism; ILP_MS: ILP approach based on the multiple sender slot multiplexing mechanism

Conclusions

- We presented a rectangle bin packing optimization approach based on ILP that is capable of scheduling communication signals with timing constraints into the FlexRay ST segment at minimum bandwidth cost.
- Our experimental results showed that the proposed approach, whether based on single sender slot multiplexing or multiple sender slot multiplexing mechanism, can achieve a well-optimized performance.
- Additionally, an automotive X-by-wire system case was used to to emphasize the superior performance of the proposed approach compared to those of existing optimal scheduling approaches.