Optimizing Extensibility of CAN FD for Automotive Cyber-Physical Systems

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***Abstract*— Extensibility is an important optimization objective for the E/E architecture of automotive cyber-physical systems (ACPS), while little attention has paid to the extensibility-aware design of in-vehicle network. To address this problem, this paper formulates a trade-off problem that balances the bandwidth utilization and the extensibility from the initial design of CAN FD. We firstly propose a new extensibility model and the related evaluation metric, and then two optimization algorithms, namely, the mixed integer linear programming (MILP) approach and the simulated annealing (SA) based heuristic approach, are proposed to resolve the trade-off problem for mid-sized and industry sized signal sets, respectively. The experiment results show the efficiency of the proposed extensibility metric and the optimization algorithms. By comparing with state-of-the-art algorithm, the MILP reduces the increase range of the bandwidth utilization of the extended signal set by 18.17% to 57.64% averagely, and 49.22% to 89.40% maximally, with only 0.06% to 0.79% bandwidth utilization overhead; the SA approach can reduces the increase range of the bandwidth utilization of the extended signal set by 12.71% to 58.33% averagely, and 40.08% to 89.40% maximally, with only 0.06% to 0.8% bandwidth utilization overhead.**

***Index Terms*— Automotive cyber-physical systems, CAN FD, signal packing, bandwidth utilization, extensibility, optimization algorithms.**

I. Introduction

A. Background and Motivations

AUTOMOTIVE industry has undergone a drastic shift from mechanic-intensive to software-intensive automotive cyber-physical systems (ACPS) over the last couple of decades, and various sensors and actuators are introduced into the ACPS to implement different kinds of internet of vehicle functions [1]–[3], such as advanced driver assistance systems (ADAS), and *et al.* Thus, the data volume transferred inside the ACPS is daily increasing [4]. As foreseen by Intel that about 4000 GB data will be generated per day by an autonomous car including technical data, personal data, crowd-sourced and societal data [5]. Consequently, CAN with flexible data-rate (CAN FD) is proposed by Bosch as the next generation of CAN technology [6]. The key advantages of CAN FD are as follows: (1) the data phase bit-rate can reach as high as 8 Mbps, which can meet the constantly increasing bandwidth requirement; (2) the message payload can reach as big as 64 bytes, thus extra data contents such as message authentication code (MAC) and cyclic redundancy check (CRC) code can be accommodated to meet the security requirement and functional safety requirement [7], [8]; (3) CAN FD can keep the main software and hardware of CAN node unchanged, especially the physical layer [6], thus it is a low-cost bandwidth improvement approach by comparing with Real-Time Ethernet and FlexRay.

As the data volume transferred inside the ACPS is daily increasing, bandwidth is a scarce resource for in-vehicle networks. Consequently, many research focuses on minimize the bandwidth utilization for CAN and CAN FD by packing as many signals as possible into messages [9]–[17], [19]–[22]. However, for large-volume and long-lifetime ACPS, extensibility is also of great importance for in-vehicle networks of the ACPS, as the adding of new signals (signal size extension can be seen as a special case of new signal) is inevitable due to function upgrade or adding of new functions [23]. If extensibility is not considered during the initial design of ACPS, the adding of new signals would lead to the sharp increase of the bandwidth utilization. We indicate the set of new signals as the update signal set, and denote the combination of the current signal set and the update signal set as the extended signal set. In this paper, extensibility metric is defined to measure the ability of the design of CAN FD network to bound the difference between the bandwidth utilization of the current signal set and the extended signal set. Thus, there is a trade-off problem between bandwidth utilization and extensibility for the optimized design of CAN FD. The optimization of CAN FD frame packing is a typical NP hard problem [12], and this optimization problem becomes even more challenging if bandwidth utilization and extensibility are needed to be addressed together. This paper tries to solve this problem by proposing new signal packing algorithms for

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CAN FD, where the joint optimization of bandwidth utilization and extensibility are considered simultaneously. By improving extensibility for the design of CAN FD network, the increase of the bandwidth utilization will be bounded when new signals are need to be added.

B. Contributions

In this paper, we identify a new trade-off problem about the design optimization of CAN FD, and we propose two algorithms to resolve it to improve the extensibility of ACPS. To the best of our knowledge, no work addresses signal packing in the context of extensibility for CAN FD. In particular, the main contributions of this paper are summarized as follows: (1) we provide a new extensibility model and the corresponding extensibility metric for CAN FD; (2) we propose two algorithms, namely, the mixed integer linear programming (MILP) approach and the simulated annealing (SA) based heuristic approach for mid-sized and industry sized signal sets, respectively, to solve the above mentioned trade-off problem; (3) we conduct extensive experiments based on synthetic signal sets (with characteristics close to real system) and show the effectiveness of the proposed algorithms by comparing with state-of-the-art algorithm.

This paper is organized as follows: Section II surveys related work. Section III presents the system models, key assumptions and the formal definition of the research problem. Section IV gives a motivational example. Section V describes the proposed algorithms. Section VI presents the experimental results and the paper is concluded in Section VII.

II. Related Work

A. Related Works About the Signal Packing of CAN and CAN FD

Signal packing is a key problem for the design of CAN FD, only after signals are packed into messages according to the CAN FD specification, then they can be transferred on the bus. As signal packing of CAN FD is similar with that of CAN, we summarize the state-of-the-art works about the signal packing of both CAN and CAN FD together in this section.

Signal packing is a special case of bin packing problem, thus [9]–[15] proposed several heuristic methods to solve this problem for CAN. Sandstrom *et al.* [9] sorted the signals with deadlines and proposed the next-fit decreasing-based heuristic algorithm to minimize the bandwidth utilization, Pölzlbauer *et al.* [10] defined a bandwidth utilization metric and presented a next-fit decreasing-based heuristic algorithm to minimize the bandwidth utilization, Saket *et al.* [11] sorted the signals with periods and proposed a best-fit decreasing-based heuristic algorithm to minimize the bandwidth utilization. While for CAN FD, as the message payload can be varied from 1 to 64 bytes with 15 payload levels (1/2/3/4/5/6/7/8/12/16/20/24/32/48/64 bytes), the signal packing becomes even more complex. Bordoloi and Samii [12] proposed a dynamic programming method to minimize the bandwidth utilization, Ding *et al.* [13] gave a dedicated genetic algorithm to minimize the bandwidth utilization. Urul [14] presented a heuristic algorithm for both CAN and CAN FD, where signals with identical periods are packed together firstly, and then the packed messages are disassembled to further improve the bandwidth utilization. Xie *et al.* [15] proposed a similar heuristic algorithm, where signals are clustered based on their periods and then packed to minimize the bandwidth utilization. Besides the above mentioned heuristic algorithms, Natale *et al.* [16] modeled the signal packing as a mixed integer linear programming (MILP) problem to minimize the bandwidth utilization. Joshi *et al.* [17] firstly formulated the signal packing of multi-domain CAN FD as an integer linear programming (ILP) problem to minimize the bandwidth utilization, and then another greedy heuristic method is presented for industry-sized signal sets. Later, Joshi *et al.* [18] proposed to optimize the signal packing of CAN FD by assigning different offsets to signals. Furthermore, other objectives such as security [19]–[21] and the number of triggered message receiving interrupts on message receiving electronic control units (ECU) [24] are also integrated into the signal packing of CAN and CAN FD. But all the above research ignores the extensibility requirement for the design of CAN FD.

B. Related Works About Extensibility Optimization of ACPS

Extensibility metric and extensibility-aware design methods are of enormous significance for E/E architecture of ACPS [23], the literature on extensibility improvement of tasks is rich. For example, The concept of incremental design is given in [25], and a list scheduling method is used to accommodate new functionality without disturbing already running applications. Bate *et al.* [26] suggested a SA-based method to tolerate the change in task's execution time without missing end-to-end deadlines. Hamann *et al.* [27] suggested a genetic algorithm-based method to improve extensibility on multiple dimensions (including task execution time, period speedups and et al). Zhu *et al.* [28] measured extensibility on how much the task execution time can be increased without modifying system configuration or violating timing constraints. Gan *et al.* [29] modeled uncertainties in task execution using the percentile method and captured the uncertainties in the functionality requirements using future scenarios.

Extensibility optimization has not been addressed well enough for in-vehicle networks. For FlexRay, Ghosal *et al.* [30] introduced the concept of robustness to uncertainty in the message payloads, and an info-gap decision theory based approach is provided for analyzing robustness of message schedules. Schneider *et al.* [31] gave the notion of extensibility (accommodate future messages without changes to existing schedules), and metrics are proposed to quantify extensible schedules. Xie *et al.* [32] introduced an extensibility metric for evaluating the uncertainty in message size and proposed a heuristic algorithm to improve extensibility for message schedules. However, FlexRay is a time-triggered protocol, while CAN FD is an event-triggered protocol, the extensibility metrics and related optimization algorithms suggested for FlexRay can not be trivially adapted to CAN FD.

Pölzlbauer *et al.* [33] explored about the extensibility optimization of CAN, this work is closely related with our research, but there are three key differences as follows: (1) the maximal payload of CAN message is only 8 bytes, while the maximal payload of CAN FD message would be as big as 64 bytes, and there are 15 payload levels for CAN FD message (which are 1/2/3/4/5/6/7/8/12/16/20/24/32/48/64 bytes), which leads a much larger design space exploration problem for the design of CAN FD. (2) Pölzlbauer *et al.* [33] defined the extensibility as the the payload space under the constraint of not exceeding the maximal allowed payload, but besides this payload constraint, the payload space between adjacent payload levels can be as big as 16 bytes for CAN FD messages, which leaves much room for extensibility optimization of CAN FD. (3) Pölzlbauer *et al.* [33] did not considered the different extensibility requirement of messages with different periods. Besides the above mentioned works, other research also tried to improve the extensibility of CAN by assigning robust priorities to messages such as [34]–[36], they are orthogonal to our work.

III. System Models and Key Assumptions

A. Signal Model

We assume that ACPS is composed by several ECUs, and they are interconnected by CAN FD. ECU set is denoted as $ECU = \{E_1, E_2, \ldots E_k, \ldots E_{EN}\}$, where EN denotes the total number of ECUs. Each ECU includes a task set, and these tasks send signals to the tasks in other ECUs to realize the interconnection and cooperation. Signals are firstly packed into messages according to the CAN FD specification, and then messages are transmitted on the bus. The signal set sent by E_k is S_k, where $S_k = \{s_{k,1}, s_{k,2}, \ldots s_{k,i}, \ldots s_{k,SN_k}\}$, and SN_k denotes the total number of signals in S_k. Each signal is indicated with a 3-tuple: $s_{k,i} = \{b_{k,i}, t_{k,i}, d_{k,i}\}$, which indicates the size (in bytes), period (in ms) and deadline (in ms) of $s_{k,i}$, respectively. We assume that period and size are given for each signal, and signal's deadline equals to its period [9], [11], [12], [24]. For all equations in this paper, i and i' are the labels for signals, j and j' are the labels for messages, and k and k' are the labels for ECUs.

B. Message Model

We assume the packed message set from S_k is M_k, where $M_k = \{m_{k,1}, m_{k,2}, \ldots m_{k,j}, \ldots m_{k,MN_k}\}$, and MN_k indicates the total number of messages in M_k. The packed message set of all ECUs is denoted by M, where $M = \bigcup_{\forall k} M_k$, and MN indicates the total number of messages in M. Each message is denoted with a 9-tuple: $m_{k,j} = \{T_{k,j}, Z_{k,j}, , B_{k,j}, P_{k,j}, D_{k,j}, R_{k,j}, E_{k,j}, Ext_{k,j}, U_{k,j}\}$, which represents the period (in ms), priority, size (in bytes), payload (in bytes), deadline (in ms), worst-case response time (WCRT, in μs), worst-case transmission time (WCTT, in μs), extensibility and bandwidth utilization, respectively. Just like [12], [16], [19], [24], we reuse existing research results for priority assignment and WCRT analysis of CAN FD messages. We assume that only signals with harmonic period can be packed together, and message's deadline equals to its period [16], [17], [19], [24]. Thus, $T_{k,j}$ is calculated as follows:

$$T_{k,j} = gcd\{t_{k,i} | \forall s_{k,i} \in m_{k,j}\} \tag{1}$$

$B_{k,j}$ is the sum size of the included signals, so it is calculated as follows:

$$B_{k,j} = \sum_{\forall s_{k,i} \in m_{k,j}} b_{k,i} \tag{2}$$

The payload of CAN FD message can be: 1/2/3/4/5/6/7/8/12/16/20/24/32/48/64 bytes, respectively. Thus, $P_{k,j}$ is calculated as follows:

$$P_{k,j} = \begin{cases} B_{k,j} & \text{if } 0 < B_{k,j} \leq 8; \\ 12 & \text{if } 8 < B_{k,j} \leq 12; \\ 16 & \text{if } 12 < B_{k,j} \leq 16; \\ 20 & \text{if } 16 < B_{k,j} \leq 20; \\ 24 & \text{if } 20 < B_{k,j} \leq 24; \\ 32 & \text{if } 24 < B_{k,j} \leq 32; \\ 48 & \text{if } 32 < B_{k,j} \leq 48; \\ 64 & \text{if } 48 < B_{k,j} \leq 64. \end{cases} \tag{3}$$

Based on the above analysis, $E_{k,j}$ and $U_{k,j}$ are calculated as follows [12]:

$$E_{k,j} = 32 \times \tau_{arb} + (28 + 5 \times \left\lceil \frac{P_{k,j} - 16}{64} \right\rceil + 10 \times P_{k,j}) \times \tau_{bit} \tag{4}$$

$$U_{k,j} = \frac{E_{k,j}}{T_{k,j} * 1000} \tag{5}$$

where τ_{arb} and τ_{bit} indicate the time to transmit 1 bit during the arbitration phase and data phase, respectively.

C. Extensibility Model

The following two definitions are given to describe the slack space inside the message under the constraint of not exceeding the maximal allowed payload.

Definition 1: The Payload Level Slack Space (PLSS) is defined as the slack space left inside each message's payload level.

Fig. 1 shows a message with the size of 33 bytes, according to the CAN FD specification, its payload is 48 bytes. Thus, the PLSS of this message is 15 bytes. If a message has PLSS, new signals can be added into it without any bandwidth overhead, as it will not cause the increase of the message payload. $PLSS_{k,j}$ is calculated as follows for $m_{k,j}$:

$$PLSS_{k,j} = P_{k,j} - B_{k,j} \tag{6}$$

Definition 2: The Message Level Slack Space (MLSS) is defined as the slack space inside each message's payload under the constraint of not exceeding the maximal allowed payload.

Fig. 1 shows a message with the payload of 48 bytes, its MLSS is 16 bytes. If a message has MLSS, new signals can be added into it with a relatively smaller bandwidth overhead by comparing with adding new signals into a new null messages. $MLSS_{k,j}$ is calculated as follows for $m_{k,j}$:

$$MLSS_{k,j} = 64 - P_{k,j} \tag{7}$$

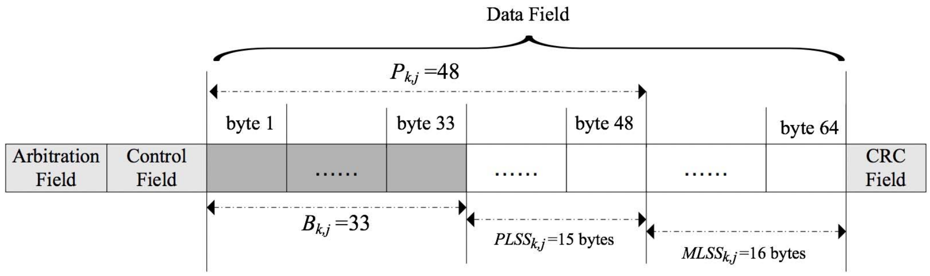


Fig. 1. The definition of PLSS and MLSS.

According to the guidelines on real-world automotive benchmarks given in [37], signals with different periods are with different shares in a signal set. Signals with the period of a large share are more likely to be added as new signals, thus large weights should be given to meet their extensibility requirement; while signals with the period of a small share are less likely to be added as new signals, thus small weights should be given to meet their extensibility requirement. As a result, messages with different periods have different extensibility requirements. We give the messages different weights based on their periods, and large weights are given to the messages which are more likely to be extended. Based on the above analysis, we propose a three dimensional extensibility model as Def.3 shows.

Definition 3: The Extensibility of a CAN FD Message is characterized with its payload level slack space, message level slack space and the period with different shares. Consequently, extensibility of $m_{k,j}$ is calculated as follows:

$$Ext_{k,j} = (W_p \times \frac{PLSS_{k,j}}{64 \times T_{k,j}} + W_m \times \frac{MLSS_{k,j}}{64 \times T_{k,j}}) \times W_t \quad (8)$$

where W_p and W_m indicate the weight assigned to PLSS and MLSS, respectively. When new signals need to be added into existing messages, the PLSS is better in keeping down the bandwidth utilization overhead by comparing with the MLSS, thus W_p is bigger than W_m generally. W_t indicates the weight assigned to messages with different periods. According to the guidelines on real-world automotive benchmarks given in [37], signals with period of 10/20/100 (in ms) are with much bigger share, thus bigger W_t will be assigned to the messages with period of 10/20/100 (in ms). The exact value of the above mentioned weights can be defined and adjusted by engineers according to the design requirement.

D. Problem Definition

For the optimized design of ACPS, we aim to increase the extensibility of the packed messages by balancing the bandwidth utilization and the extensibility during the signal packing of CAN FD. Thus, the objective function is defined as follows:

$$Obj = W_b \times \sum_{k=1}^{EN} \sum_{j=1}^{MN_k} U_{k,j} - W_e \times \sum_{k=1}^{EN} \sum_{j=1}^{MN_k} Ext_{k,j}; \quad (9)$$

where W_b and W_e indicate the weight assigned to bandwidth utilization and extensibility, respectively, and they can be defined and adjusted by engineers according to the design requirement.

TABLE I
SIGNAL PARAMETERS OF THE EXAMPLE SIGNAL SET

Signal	Period (ms)	Size (byte)
s_1	1	5
s_2	5	2
s_3	10	29
s_4	50	5
s_5	100	1
s_6	100	3
s_7	100	24

To sum up, the research problem of this paper is formulated as follows:

$$Minimize: \ Obj \quad (10)$$

where the following three constraints are observed:

(1) each signal is exactly packed into one message.

$$\sum_{j=1}^{MN_k} assign_{i,j}^k = 1 \quad (11)$$

where $assign_{i,j}^k$ is a binary variable indicating if $s_{k,i}$ is assigned to $m_{k,j}$ or not. If true, $assign_{i,j}^k = 1$; or else, $assign_{i,j}^k = 0$.

(2) messages have to finish the transmission within their deadline.

$$R_{k,j} \leq D_{k,j} \quad (12)$$

(3) message payload cannot exceed the allowed maximal payload.

$$P_{k,j} \leq 64 \quad (13)$$

IV. Motivational Example

Table I shows a signal set of seven signals. If we try to minimize the bandwidth (we denote this approach as the BUOpt), the packed message set is: $M' = \{M'_1, M'_2, M'_3, M'_4\}$, where $M'_1 = \{s_1, s_2\}$, $M'_2 = \{s_3, s_6\}$, $M'_3 = \{s_4, s_5\}$, $M'_4 = \{s_7\}$, where the bandwidth utilization of M' is 14.12%, and sizes of the packed messages are 7/32/6/24 bytes, respectively. We can get two facts from this example: (1) signals are

TABLE II
DESIGN RESULT OF THE EXAMPLE SIGNAL SET

	BUOpt	SA	MILP
Band utilization of current sig set (%)	14.12	14.15	14.15
Extensibility	1.02	1.06	1.06
Objective	4.63	4.60	4.60
Band utilization of extended sig set (%)	14.92	14.15	14.15

packed into one message as many as possible to decrease the bandwidth utilization overhead caused by arbitration field, control field and CRC field as shown in Fig. 1, such as M'_1 and M'_3; (2) there will be no PLSS in packed message, as if there is PLSS in a message, signals with large periods will be packed into it to take the PLSS. By doing this, the size of the messages with large periods will be decreased, thus the corresponding payload and the bandwidth utilization would also be decreased as well, such as M'_2. As there is no PLSS in packed messages, if new signals need to be added, the message payloads will be elevated to a higher level easily, and this would cause a big increase of the bandwidth utilization. For the given example, we assume there is a new signal s_n that needs to be added, where $s_n = \{2, 10, 10\}$, and s_n is packed into M'_2 to minimize the bandwidth utilization of M'. Although the size of s_n is only 2 bytes, the payload of M'_2 is elevated from 32 bytes to 48 bytes, and this leads the bandwidth utilization of M' to be increased from 14.12% to 14.92%. Although the bandwidth utilization is minimized by BUOpt for current signal set, as no PLSS is reserved beforehand, the adding of new signals would lead to a large increase of the bandwidth utilization of the extended signal set.

In this paper, we propose to improve the extensibility of CAN FD network by preserving some PLSS for the packed messages during the initial design process, especially for those messages with large extensibility requirements. According to the proposed two approaches in this paper (we denote them as the SA approach and the MILP approach, respectively), they achieve a better balance between bandwidth utilization and extensibility. For the given example, we assume the same parameter setup with the third experiment conducted in Section VI, and the packing result is the same for both the SA approach and the MILP approach. Specifically, the packing result is: $M'' = \{M''_1, M''_2, M''_3, M''_4\}$, where $M''_1 = \{s_1, s_2\}$, $M''_2 = \{s_3\}$, $M''_3 = \{s_4\}$, $M''_4 = \{s_5, s_6, s_7\}$, where the bandwidth utilization of M'' is 14.15%, and the size of the packed messages are 7/29/5/28 bytes, respectively. As there is PLSS in M''_2, s_n can be added without causing any increase of the message payload, thus the bandwidth utilization of M'' remains unchanged. As shown in Table II, the proposed approaches improves the extensibility of the packed message set from 1.02 to 1.06, which reduces the bandwidth utilization increase of the extended signal set from 0.8% to 0 with only 0.03% bandwidth utilization overhead.

We can see from this example that by trading the bandwidth utilization for extensibility during the design of CAN FD, it would bound the increase of the bandwidth utilization caused by new signals from function upgrade or new functions.

TABLE III
THE VARIABLES OF THE MILP FORMULATION

Name	Type	Definition	Property
$b_{k,i}$	real	the size of $s_{k,i}$	known
$t_{k,i}$	real	the period of $s_{k,i}$	known
M	real	a large constant for linearization	known
$assign^k_{i,j}$	binary	if $s_{k,i}$ is packed into $m_{k,j}$ or not	unknown
$taken_{k,j}$	binary	if some signals are packed into $m_{k,j}$ or not	unknown
$U_{k,j}$	real	the bandwidth utilization of $m_{k,j}$	unknown
$T_{k,j}$	real	the period of $m_{k,j}$	unknown
$D_{k,j}$	real	the deadline of $m_{k,j}$	unknown
$B_{k,j}$	real	the size of $m_{k,j}$	unknown
$E_{k,j}$	real	the WCTT of $m_{k,j}$	unknown
$P_{k,j}$	real	the payload of $m_{k,j}$	unknown
$R_{k,j}$	real	the WCRT of $m_{k,j}$	unknown
$hp^{k,k'}_{j,j'}$	binary	if $m_{k,j}$ has higher priority than $m_{k',j'}$	unknown
$block_{k,j}$	binary	the blocking time of $m_{k,j}$	unknown

V. THE PROPOSED ALGORITHMS

A. MILP Based Optimal Extensibility Improvement Algorithm

Based on the defined extensibility model, we first present an optimal algorithm to balance bandwidth utilization and extensibility for the design of CAN FD, where the signal packing of CAN FD is modeled as a MILP formulation and then solved with IBM's CPLEX tool. We indicate this approach as the MILP approach. Next, all the constraints and the objective function of the MILP formulation are described as follows. Table III gives the known and the unknown variables of the MILP formulation.

1) Constraints: Mapping Constraint. Equation (14) restricts that each signal is packed into one and only one message, Equations (15) and (16) denote if $s_{k,i}$ is packed into $m_{k,j}$ or not. If that is true, $taken(k, j)$ is 1; or else, $taken(k, j)$ is 0. All the other binary variables in this paper have a value of 1 if the condition is true and 0 otherwise.

$$\forall s_{k,i}, \quad \sum_{j=1}^{MN_k} assign^k_{i,j} == 1 \tag{14}$$

$$\forall s_{k,i}, \ m_{k,j}, \quad assign^k_{i,j} \ \leq \ taken_{k,j} \tag{15}$$

$$\forall s_{k,i}, \ m_{k,j}, \quad taken_{k,j} \ \leq \ \sum_{i=1}^{SN_k} assign^k_{i,j} \tag{16}$$

As we assume that only signals with harmonic period can be packed into one message, Equations (17) and (18) are used to express this constraint.

$$\forall s_{k,i}, \ m_{k,j}, \ t_{k,i} \mod T_{k,j} \neq 0 \rightarrow assign^k_{i,j} == 0 \tag{17}$$

$$\forall s_{k,i}, \ s_{k,i'}, \ m_{k,j}, \quad t_{k,i} \leq t_{k,i'} \wedge t_{k,i'} \mod t_{k,i} \neq 0 \rightarrow assign^k_{i,j} + assign^k_{i',j} \leq 1 \tag{18}$$

Timing Constraint: For the WCRT analysis of CAN FD messages, we have to assign each message a priority and analyze the blocking delay they would exprience.

a) Priority Assignment: According to the CAN FD specification, each message is assigned a unique priority. Thus, Equations (19) and (20) are used to restrict the priority order of any two messages, where $hp_{j,j'}^{k,k'}$ denotes if $m_{k,j}$ has higher priority than $m_{k',j'}$ or not. Equation (21) indicates the transitive property of the priority orders. For example, if $hp_{j,j'}^{k,k'} = 1$ and $hp_{j',j''}^{k',k''} = 1$, then $hp_{j,j''}^{k,k''} = 1$.

$$\forall m_{k,j},\ hp_{j,j}^{k,k} == 0 \tag{19}$$

$$\forall m_{k,j},\ m_{k',j'},\ hp_{j,j'}^{k,k'} + hp_{j',j}^{k',k} == 1 \tag{20}$$

$$\forall m_{k,j},\ m_{k',j'},\ m_{k'',j''},$$

$$hp_{j,j'}^{k,k'} + hp_{j',j''}^{k',k''} - 1 \ \leq\ hp_{j,j''}^{k,k''} \tag{21}$$

b) Blocking Delay Analysis: We employ the sufficient schedulability test proposed in [38] to analyze the blocking delay for each message, and it assumes that $m_{k,j}$ can either be blocked by lower priority messages or the previous instance of the same message. Thus, the blocking delay is calculated as follows:

$$\forall m_{k,j},\ m_{k',j'},\quad block_{k,j} = max(E_{k,j}, hp_{j,j'}^{k,k'} \times E_{k',j'}) \tag{22}$$

c) WCRT Analysis for Messages: We employ the schedulablity analysis method given in [38] to analyze the WCRT for each message like [12], [16]. Thus, $R_{k,j}$ is calculated as Equation (23) shows, where the third part indicates the preemption delay caused by higher priority messages.

$$\forall m_{k,j},\ m_{k',j'},\ R_{k,j} = block_{k,j} + E_{k,j} + \sum_{k'=1}^{EN} \sum_{j'=1}^{MN_{k'}} taken_{k',j'} \times hp_{j,j'}^{k,k'} \times \lceil \frac{R_{k,j} - E_{k,j}}{T_{k',j'}} \rceil \times E_{k',j'} \tag{23}$$

Equation (24) indicates the timing constraint on each message:

$$\forall m_{k,j},\quad R_{k,j} \leq D_{k,j} \tag{24}$$

2) Objective Function: For a given signal set and the extensibility model, we aim to balance the bandwidth utilization and the extensibility for the signal packing of CAN FD, thus the objective function of the MILP formulation is defined as Equation (25) shows. The proposed algorithms aim to improve the extensibility of CAN FD by minimizing the defined objective.

$$Objective:$$

$$\forall m_{k,j}, \sum_{k=1}^{EN} \sum_{j=1}^{MN_k} taken_{k,j} \times (W_b \times U_{k,j} - W_e \times Ext_{k,j}); \tag{25}$$

3) Conversion to Linear Constraints: The CPLEX tool is employed to solve the above defined MILP formulation, but some constraints need to be linearized before the implementation, such as Equations (3), (23) and (25). Due to the limited space, please refer to the [19], [21] for detailed description of the linearization methods.

B. SA Based Heuristic Extensibility Improvement Algorithm

Although the MILP formulation of the extensibility-aware signal packing problem can get the optimal result, it has relatively high time complexity, thus it can only be used for small or mid-sized signal sets. As a result, the SA-based heuristic approach (it is indicated as the SA approach) is further proposed for industry sized signal sets. The SA approach includes two steps, and the details about these two steps are described as follows.

1) Step 1: MILP-Based Initial Packing of Signal Clusters: The execution time of the MILP formulation increases exponentially with the increases of the signal numbers, thus we try to get an initial signal packing result with a divide and conquer method, where the signal set is firstly divided into several signal clusters, and then the signal clusters are fed into the MILP formulation separately to get an initial packed message set with relatively low bandwidth utilization. As existing research indicate that bandwidth utilization generally has more weight than the extensibility for the E/E architecture of ACPS, an initial packed message set with relatively small bandwidth utilization would be a good start point for extensibility improvement. We conduct experiment based on 50 signal sets with 100 signals in each signal set, the average bandwidth utilization difference between the MILP-based packing of signal clusters and the MILP-based packing of the whole signal set is only 0.13%.

Algorithm 1 Divided MILP for Signal Packing

Input: signal set S_k
Output: packed message set M_k
$sigsub\_num = 0$; //the number of signal subsets
$cur\_period = 0$; //the period of current signal subset
sort signals in order of increasing period with Merge Sort algorithm
for $i = 1$ to SN_k **do**
  if $(t_{k,i} \neq cur\_period)$ **then**
    $sigsub\_num = sigsub\_num + 1$;
    $cur\_period = t_{k,i}$;
  end if
  add $s_{k,i}$ into $S_{k,sigsub\_num}$;
end for
$M_{k,1} = \text{MILP}(S_{k,1} \cup S_{k,2} \cup S_{k,3} \cup S_{k,4})$
$M_{k,2} = \text{MILP}(S_{k,5} \cup S_{k,6})$
$M_{k,3} = \text{MILP}(S_{k,7} \cup S_{k,8} \cup S_{k,9})$
$M_k = M_{k,1} \cup M_{k,2} \cup M_{k,3}$

Signal period determines the period of the packed messages and consequently the bandwidth utilization of the corresponding packed message set, thus we divide the signal set into signal clusters based on signal period [14], [15]. Packing signals with close period into the same message would lead to a packed message set with low bandwidth utilization [11], [14], thus we divided the signals with close period into one cluster. According to the guidelines on real-world automotive benchmarks given in [37], signals can be divided into nine signal subsets with different periods and with different shares. As Algorithm 1 shows, we firstly divide the signal set into nine signal subsets based on their periods (line 1 to line 10). And then we further divide the signal subsets into three signal clusters based on the shares of signal period and input them into the MILP formulation, where the three signal clusters are: $S_{k,1} \cup S_{k,2} \cup S_{k,3} \cup S_{k,4}$, $S_{k,5} \cup S_{k,6}$ and $S_{k,7} \cup S_{k,8} \cup S_{k,9}$, respectively (line 11 to line 13). The share of signals and consequently the number of signals inside the three clusters are close to each other, thus the time complexity of the MILP-based packing of the three signal clusters can be reduced to a large extent by comparing with the MILP-based packing of the whole signal set. Finally, we combine the packed messages of the three signal clusters as the initial signal packing result (line 14). As only one signal cluster is inputted for packing each time and the schedulability analysis is removed, this divide and conquer approach can be extended to be used for signal sets of about 600 signals, which represents the signal set of industry size [16], [17], [19].

2) Step 2: SA-Based Heuristic Extensibility Improvement: As SA-based algorithm shows efficiency in similar research [33], SA-based heuristic algorithm is employed in step 2 to further improve the extensibility of the initial packed messages generated by step 1. Details about the SA-based step 2 is shown in Algorithm 2.

In the algorithm 2, the parameters of the SA is firstly set (line 1 to line 6). And then, there is a while loop for the SA-based searching of extensibility improved packing result (line 7 to line 29). For the SA algorithm, two heuristic searching steps are conducted with equal probability to find a neighboring solution, which are signal migration (line 11 to line 18) and signal exchange (line 20 to 26). For signal migration, we firstly random choose a signal (line 12) to be migrated, and then search among the messages with equal or smaller period and the null message for the destination message (line 13). The reason that we only consider the messages with equal or smaller period is to ensure that the destination message's period is not decreased after the signal migration, which would lead to the increase of the bandwidth utilization of the message set. As the bandwidth utilization usually has a higher weight than the extensibility, we have to keep the bandwidth utilization overhead caused by extensibility improvement to a relatively low level. Next, the signal migration is implemented and the M_k is updated (line 14), and the objective is analyzed (line 15). If a neighboring solution with a smaller objective value is found, it is stored as the best solution found so far. Otherwise, it is accepted with a certain probability dependent on the objective value's difference and current annealing temperature (line 16 to line 18).

For signal exchange, we firstly random choose two signals belonging to two different messages, and one constraint on this choice is that the signal exchange will not cause the change of their belonging messages' period (line 20). And then, the signal exchange is implemented and the M_k is updated (line 21), and the objective is analyzed (line 22). If a neighboring solution with a smaller objective value is found, it is stored as the best solution found so far. Otherwise, it is accepted with a certain probability dependent on the objective value's difference and current annealing temperature (line 23 to line 25). For both signal migration and exchange,

Algorithm 2 Simulated Annealing Based Extensibility Optimization Algorithm

Input: initial message set by Algorithm1: M_k
Output: extensibility improved message set: $M_{k'}$

1: $T_{ini} = 1$; //initial temperature
2: $T_{ter} = 0.00001$; //terminating temperature
3: $step\_num = 100$; //number of neighbor solutions tried at each temperature
4: $\sigma = 0.95$; //cooling factor
5: obj_ini = Obj_analysis(M_k);
6: $T = T_{ini}$;
7: **while** $T > T_{ter}$ **do**
8:   **for** $i = 1$ to $step\_num$ **do**
9:     $M_{k'} = M_k$;
10:     $flag$ = random(0, 1);
11:     **if** ($flag \leq 0.5$) **then**
12:       m_sig = Rand_Chose(S_k);
13:       d_mess = Mess_search(M_k);
14:       migrate s_{k,m_sig} to m_{k,d_mess} and update M_k;
15:       obj_cur = Obj_analysis(M_k);
16:       **if** $(obj\_cur < obj\_ini) \vee (e^{(obj\_ini - obj\_cur) \div T} >$ random(0, 1)) **then**
17:         $M_{k'} = M_k$;
18:       **end if**
19:     **else**
20:       $[e\_sig1, e\_sig2]$ = Rand_Chose2(S_k);
21:       exchange e_sig1 and e_sig2, and update M_k;
22:       obj_cur = Obj_analysis(M_k);
23:       **if** $(obj\_cur < obj\_ini) \vee (e^{(obj\_ini - obj\_cur) \div T} >$ random(0, 1)) **then**
24:         $M_{k'} = M_k$;
25:       **end if**
26:     **end if**
27:   **end for**
28:   $T = T \times \sigma$
29: **end while**

the reason that we sometimes accept the neighboring solution with an un-optimized objective value with a certain probability is to escape from local optima in the pursuit of global optimal solutions.

VI. Experiment Results

We perform extensive experiments based on synthetic signal sets to verify the effectiveness of the proposed algorithms. The synthetic signal sets are randomly generated according to the guidelines on real-world automotive benchmarks [37], Table IV shows the distribution of signal periods and sizes. As the signal packing is implemented for each ECU, we consider the signal packing of CAN FD for one ECU only in all the experiments, but the proposed algorithms can be easily extended to the design of CAN FD with several ECUs. We generate 20 update signal sets for each configuration, and the bandwidth utilization of the extended signal set is the average value of that of the 20 extended signal sets. As the best-fit decreasing approach showed efficiency

TABLE IV
SIGNAL PARAMETERS AND DISTRIBUTIONS

Period (ms)	Share	Size (bytes)	Share
1	4%	1	35%
2	3%	2	49%
5	3%	4	13%
10	31%	5-8	0.8%
20	31%	9-16	1.3%
50	3%	17-32	0.5%
100	20%	33-64	0.4%
200	1%		
1000	4%		

in minimizing the bandwidth utilization for signal packing problem [11], [24], it is used to pack the new signals of the update signal set into the existing messages in this paper. As we surveyed in Section II that most existing research tried to minimize the bandwidth utilization for the design of CAN FD, thus we compare the proposed approach with the above mentioned state-of-the-art approach (we indicate it as the BUOpt approach) to verify their effectiveness, please refer to [16], [17], [19] for details about the MILP formulation of the BUOpt approach. The arbitration phase bit-rate and data phase bit-rate are set as 500 kbps and 2 Mbps [12], [15], [19], respectively. Consequently, $\tau_{arb} = 2$ μs and $\tau_{bit} = 0.5$ μs. The experiments are conducted on an OS X(v10.13.1) machine running on 2.3 GHz the 7th generation Intel i5 core with 8 GB main memory. We use CPLEX 12.7 as the MILP solver, and the code is implemented in Matlab 2017a.

A. Experiment 1: Weight Configuration Exploration

There are four weights included in the proposed optimization problem, which poses great challenge about how to decide the concrete value for these weights. Consequently, we conduct experiments to explore the different configurations of the defined weights. But it is worthy to point out that no configuration of weights is suitable for all signal sets, they should be adjusted by engineers according to the design requirement and analysis result.

1) Exploration of Different Configurations of $\frac{W_b}{W_e}$ and $\frac{W_p}{W_m}$: Existing research indicates that bandwidth utilization is the most important evaluation metric for the network architecture of ACPS, thus we give a bigger weight to bandwidth utilization than extensibility. The PLSS can accommodate new signals without bandwidth overhead, thus we also give a bigger weight to PLSS than MLSS. We assume that both W_e and W_m are set as 1, and different configurations of $\frac{W_b}{W_e}$ and $\frac{W_p}{W_m}$ are evaluated in this experiment. To clarify the influence of different configurations of $\frac{W_b}{W_e}$ and $\frac{W_p}{W_m}$, we set W_t as 1 for all messages. In this experiment, we set the number of signals in current signal set is 100, and assume that the signal number will be increased by 30% in extended signal set. The BUOpt approach and the MILP approach are employed in this experiment, and the experiment results are shown in Table V, Table VI and Table VII, where Table V and Table VI describe the bandwidth utilization and extensibility of the packed message set for current signal set, Table VII describes the bandwidth utilization of the packed message set for extended signal set.

As Table V and Table VI show that when W_b has a small value (for example when $W_b = 2$), the MILP approach is willing to take more bandwidth utilization to trade for extensibility. This is because a small W_b means that the extensibility has close weight to bandwidth utilization, thus the MILP approach gets a large extensibility with a big bandwidth utilization overhead. As Table VII shows that although the MILP approach get a larger extensibility than the BUOpt approach, it triggers too much bandwidth utilization overhead, thus it also gets a bigger average bandwidth utilization for the extended signal set.

As the increases of the W_b, the weight difference between the bandwidth utilization and the extensibility also increases as well, thus as Table V and Table VI show that less bandwidth utilization will be used to trade for extensibility. And for a given W_b, along with the increases of the W_p, the extensibility and the bandwidth utilization overhead also increases as well (as Table V and Table VI shows), and the average bandwidth utilization of the extended signal set shows a decreasing trend (as Table VII shows). But as the W_b increases, less bandwidth utilization will be used to trade for extensibility, thus the range is reduced for both the extensibility improvement and the reduction of the average bandwidth utilization of the extended signal set (as Table VI and Table VII shows). To sum up, due to the uncertainty about the size and period of the newly added signals, W_b and W_p should be chosen reasonably, it is not reasonable to trade too much bandwidth utilization for extensibility improvement.

2) Exploration of Different Configurations of W_t: We integrate message's different extensibility into the extensibility model, and this is quantitatively described by assigning different W_t to messages with different periods. Table IV shows the distributions of different periods, we divide the periods into three clusters based on their distribution, which are $p\_cluster_1 = \{1, 2, 5, 50, 200, 1000\}$, $p\_cluster_2 = \{100\}$, $p\_cluster_3 = \{10, 20\}$, respectively. Signals with period belonging to the $p\_cluster_3$ is the mostly likely new signals to be added, signals with period belonging to the $p\_cluster_2$ is next, and signals with period belonging to the $p\_cluster_1$ is the least likely new signal to be added. Thus, we give the messages different W_t based on their periods, and big weight is given to the messages that are more likely to be extended. W_1, W_2 and W_3 are defined for messages with period belonging to $p\_cluster_1$, $p\_cluster_2$ and $p\_cluster_3$, respectively. We conduct this experiment to evaluate the effectiveness of the different configurations of W_t when $\frac{W_b}{W_e}$ and $\frac{W_p}{W_m}$ are set as 4 and 4, respectively.

As Table VIII shows, the configuration of W_t do influences the tradeoff between the bandwidth utilization and the extensibility, thus it is reasonable to consider the different requirements of the messages with different periods. However, the value of W_t should not be set too big for those message with periods of large distributions, or else those signals that with periods of large distributions will be dispersedly packed

TABLE V
BANDWIDTH UTILIZATION OF CURRENT SIGNAL SET(%)

	BUOpt	MILP					
		$W_p = 2$	$W_p = 3$	$W_p = 4$	$W_p = 5$	$W_p = 6$	$W_p = 7$
$W_b = 2$	19.58	22.45	22.28	22.29	22.29	22.29	22.29
$W_b = 3$	19.58	19.58	19.63	19.63	19.63	19.64	19.64
$W_b = 4$	19.58	19.58	19.58	19.58	19.63	19.63	19.63
$W_b = 5$	19.58	19.58	19.58	19.58	19.58	19.63	19.63
$W_b = 6$	19.58	19.58	19.58	19.58	19.58	19.58	19.63
$W_b = 7$	19.58	19.58	19.58	19.58	19.58	19.58	19.63

TABLE VI
EXTENSIBILITY OF CURRENT SIGNAL SET

	BUOpt	MILP					
		$W_p = 2$	$W_p = 3$	$W_p = 4$	$W_p = 5$	$W_p = 6$	$W_p = 7$
$W_b = 2$	1.11	1.71	1.68	1.69	1.70	1.71	1.71
$W_b = 3$	1.11	1.12	1.14	1.15	1.16	1.17	1.18
$W_b = 4$	1.11	1.12	1.12	1.13	1.16	1.16	1.17
$W_b = 5$	1.11	1.12	1.12	1.13	1.13	1.16	1.17
$W_b = 6$	1.11	1.12	1.12	1.13	1.13	1.14	1.17
$W_b = 7$	1.11	1.12	1.12	1.13	1.13	1.14	1.14

TABLE VII
AVERAGE BANDWIDTH UTILIZATION OF EXTENDED SIGNAL SET (%)

	BUOpt	MILP					
		$W_p = 2$	$W_p = 3$	$W_p = 4$	$W_p = 5$	$W_p = 6$	$W_p = 7$
$W_b = 2$	27.39	28.70	28.07	28.04	28.04	28.04	28.04
$W_b = 3$	27.39	27.03	26.88	26.88	26.88	26.88	26.88
$W_b = 4$	27.39	27.03	27.03	27.03	26.88	26.88	26.88
$W_b = 5$	27.39	27.03	27.03	27.03	27.03	26.88	26.88
$W_b = 6$	27.39	27.03	27.03	27.03	27.03	27.03	26.88
$W_b = 7$	27.39	27.03	27.03	27.03	27.03	27.03	27.03

into several messages. Although this would lead to the large improvement of extensibility, it will lead to too big average bandwidth utilization of the extended signal set as well. For example, when W_1, W_2 and W_3 are set as 1/3/3.5, respectively, the average bandwidth utilization of the extended signal set is as large as 58.35% for the MILP approach (the number of packed message is 62), while the average bandwidth utilization of the extended signal set is only 29.27% for the BUOpt approach (the number of packed message is 7). To sum up, different extensibility requirement of messages should be considered properly by giving the W_t a relatively small value.

B. Experiment 2: Comparison With the State-of-the-Art Work

In this experiment, we assume that the number of signals varies from 60 to 180 for each ECU. Based on the results of the first experiment, we set the weights as the median value, where W_b and W_p are set as 5, $W_1/W_2/W_3$ are set as 1/1.5/2, respectively. We define three update scenarios for current signal set, where the number of signals will be increased by 10%, 20% and 30%, respectively. The experimental results of the three approaches are illustrated from Table IX to Table XI, where Table IX shows the bandwidth utilization and extensibility of the packed message set for current signal set, and the bandwidth utilization overhead of the MILP and SA; Table X shows the average bandwidth utilization of extended signal set, and Table XI shows the bandwidth utilization of the extended signal set when the MILP approach and the SA approach get the maximal reduction of bandwidth utilization by comparing with the BUOpt approach.

The reduction ratio of the bandwidth utilization is defined as follows:

$$Red\_Rat_x = \frac{BU\_EXT_{BUOpt} - BU\_EXT_x}{BU\_EXT_{BUOpt} - BU\_CUR_{BUOpt}} \quad (26)$$

where x can be MILP or SA, the BU_EXT and BU_CUR denote the bandwidth utilization of the extended signal set and the current signal set, respectively.

The bandwidth utilization overhead is defined as follows:

$$BU\_OverHead_x = BU\_CUR_x - BU\_CUR_{BUOpt} \quad (27)$$

TABLE VIII

EXPERIMENT RESULTS FOR EXPLORATION OF W_t

	$W_1=1$ $W_2=1$ $W_3=1$	$W_1=1$ $W_2=1.5$ $W_3=2$	$W_1=1$ $W_2=2$ $W_3=2.5$	$W_1=1$ $W_2=2.5$ $W_3=3$	$W_1=1$ $W_2=3$ $W_3=3.5$	$W_1=1$ $W_2=3.5$ $W_3=4$
Band utilization of current signal set with BUOpt (%)	22.21	22.21	22.21	22.21	22.21	22.21
Band utilization of current signal set with MILP (%)	22.26	22.29	22.29	23.13	53.52	55.07
Band Overhead of MILP (%)	0.05	0.08	0.08	0.92	31.31	32.86
Extensibility of current signal set with BUOpt	1.03	1.03	1.03	1.03	1.03	1.03
Extensibility of current signal set with MILP	1.11	1.16	1.18	1.60	15.34	18.08
Band utilization of extended signal set with BUOpt (%)	29.27	29.27	29.27	29.27	29.27	29.27
Band utilization of extended signal set with MILP (%)	28.49	28.35	28.35	28.31	58.35	59.89

TABLE IX

EXPERIMENT RESULTS OF CURRENT SIGNAL SET

	$SigNum=60$			$SigNum=100$			$SigNum=140$			$SigNum=180$		
	BUOpt	MILP	SA	BUOpt	MILP	SA	BUOpt	MILP	SA	BUOpt	MILP	SA
Bandwidth utilization(%)	17.36	17.58	17.58	28.81	29.60	29.61	36.21	36.53	36.36	41.80	41.86	41.86
Extensibility	1.25	1.34	1.34	0.83	1.27	1.27	0.83	1.28	1.08	0.82	1.11	1.11
Bandwidth overhead(%)	-	0.22	0.22	-	0.79	0.8	-	0.32	0.15	-	0.06	0.06

TABLE X

AVERAGE BANDWIDTH UTILIZATION OF EXTENDED SIGNAL SET (%)

	$SigNum=60$			$SigNum=100$			$SigNum=140$			$SigNum=180$		
	BUOpt	MILP	SA	BUOpt	MILP	SA	BUOpt	MILP	SA	BUOpt	MILP	SA
$Percent=10\%$	19.06	18.25	18.25	31.69	30.03	30.01	39.40	37.67	38.12	51.16	47.97	49.97
$Percent=20\%$	19.73	19.24	19.24	35.25	34.29	34.31	42.38	40.21	40.68	53.13	49.56	49.21
$Percent=30\%$	21.55	20.46	20.46	36.13	34.80	34.84	44.41	42.10	42.51	53.51	51.27	51.03

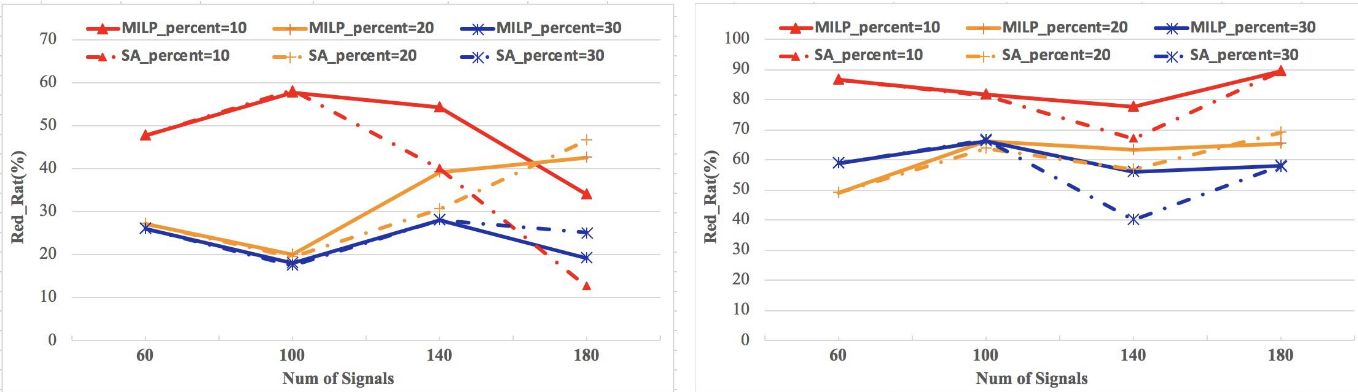
TABLE XI

BANDWIDTH UTILIZATION OF EXTENDED SIGNAL SET WITH MAXIMAL DIFFERENCE (%)

	$SigNum=60$			$SigNum=100$			$SigNum=140$			$SigNum=180$		
	BUOpt	MILP	SA	BUOpt	MILP	SA	BUOpt	MILP	SA	BUOpt	MILP	SA
$Percent=10\%$	19.16	17.60	17.60	33.62	29.70	29.71	41.76	37.45	38.04	50.20	42.69	42.69
$Percent=20\%$	19.29	18.34	18.34	35.08	30.92	31.08	42.83	38.65	39.07	53.17	45.75	45.30
$Percent=30\%$	22.98	19.68	19.68	35.31	30.99	30.99	43.72	39.49	40.71	54.37	47.07	47.06

Based on the experiment results given from Table IX to Table XI, the average and maximal reduction ratio of the bandwidth utilization that can be obtained by MILP and SA are given as Fig. 2, where the solid lines and the dotted lines indicate the results obtained by MILP and SA, respectively. The bandwidth utilization overhead of the MILP and SA is given in Table IX.

We can see from Fig. 2 and Table IX that by comparing with the state-of-the-art algorithm for all possible configurations of experiment setup, the MILP approach can reduce the increase range of the bandwidth utilization of the extended signal set by 18.17% to 57.64% averagely, and 49.22% to 89.40% maximally, with only 0.06% to 0.79% bandwidth utilization overhead, and the SA approach can reduce the increase range of the bandwidth utilization of the extended signal set by 12.71% to 58.33% averagely, and 40.08% to 89.40% maximally, with only 0.06% to 0.8% bandwidth utilization overhead.



(a) average reduction ratio (b) max reduction ratio

Fig. 2. The reduction ratio of the bandwidth utilization obtained by MILP and SA.

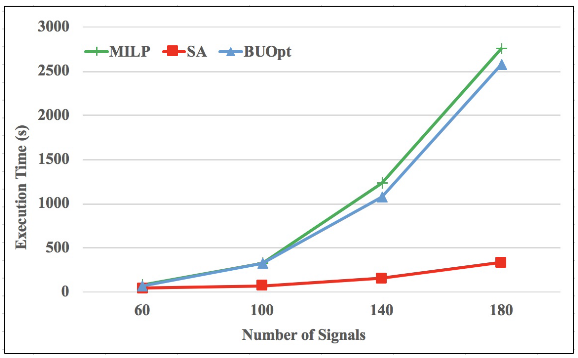


Fig. 3. The execution time of the three methods.

As Fig. 3 shows, the execution time is close for the MILP and the BUOpt approach, which grow exponentially with the increases of the signal numbers, and these two approach cannot get the packing result within 10 hours when the number of signals exceeds 180. While the SA approach is quite extensible, thus it can be applied to industry sized CAN FD systems.

VII. Conclusion

Although extensibility is an important design objective for E/E architecture of ACPS, it gets less attention for the design of in-vehicle networks. To fill this gap, this paper proposes a new trade-off problem between bandwidth utilization and extensibility for the signal packing of CAN FD. Three key techniques have been developed in this paper: (1) we give a three dimensional extensibility model and the related extensibility metric to quantitatively describe the extensibility of the message set; (2) the proposed MILP approach is suitable for mid-sized signal sets, which formulates the extensibility-aware signal packing into a MILP problem, and it is solved with the IBM's CPLEX tool to get the optimal result. By comparing with the state-of-the-art algorithm, the increase range of the bandwidth utilization of the extended signal set can be reduced by 18.17% to 57.64% averagely, and 49.22% to 89.40% maximally, with only 0.06% to 0.79% bandwidth utilization overhead; (3) another SA-based heuristic method is proposed for industry sized signal sets, which firstly divides the signal set into signal clusters and do the signal packing for each signal cluster, and then the SA-based searching is executed to resolve the trade-off problem. By comparing with the state-of-the-art algorithm, the increase range of the bandwidth utilization of the extended signal set can be reduced by 12.71% to 58.33% averagely, and 40.08% to 89.40% maximally, with only 0.06% to 0.8% bandwidth utilization overhead.

In our future work, we will investigate the extensibility-aware design of ACPS from the system level's point of view.

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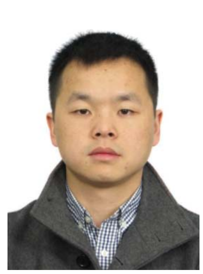

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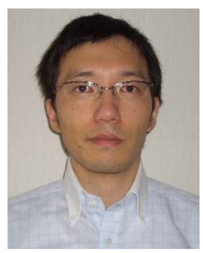

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