Research on Calculation Method of Period and Deadline of Frame in Automotive Electronic and Information Integrated Control System

Jian Hu, Gangyan Li, Ye-Qiong Song

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Jian HU[1)], Gangyan LI[1)] and Yeqiong SONG[2)]
[1)]School of Mechanical and Electronic Engineering, Wuhan University of Technology
122, Luoshi Road, 430070, Wuhan, Hubei Province
P. R. China
hujian@whut.edu.cn, gangyanli@whut.edu.cn
[2)]LORIA - Equipe TRIO
615, Rue Du Jardin Botanique, 54600 Villers Les Nancy
France
song@loria.fr

Abstract: **With the increase of the complexity of automotive control, it is necessary to develop AEIICS (Automotive Electronic and Information Integrated Control System) for exchanging information between ECUs (Electronic Control Units) based on in-vehicle network technology. We named the parameter (or variable) contained in and transmitted by frame as signal. Period and deadline are basic temporal characteristics for signal and frame. Designers mainly focus on directly designing the period and deadline of frame but omit the temporal characteristic relationship between signal and frame. In this paper, we researched on the calculation method of period and deadline of frame according to the temporal characteristic of signal. Based on the period of signal, we proved the period of frame is the minimal period of signals composing this frame. Considering the possible time offset between the production time of data of signal and the first transmission time of frame containing this data, we deduced the calculation formula of deadline of frame by applying GCRT (Generalized Chinese Remainder Theorem).**

Key-Words: **Automotive electronic; In-vehicle network; Networked control; Temporal characteristic; Real-time; GCRT**

1. INTRODUCTION

Nowadays, with the requirements of security, comfort and environment protection, automobiles are more and more equipped with ECUs (Electronic Control Units) to implement different control functions. These functions require the use of real-time and reliable exchange of information between different ECUs, sensors and actuators. But it is impossible to realize this exchange of information through the traditional point-to-point links which would induce a disproportionate length of cable, an increase of cost and production time, reliability problems and other drawbacks. Thus, it is essential to develop AEIICS (Automotive Electronic and Information Integrated Control System) with in-vehicle network for sharing information and implementing real-time and correlative control between ECUs [1].

At the beginning of 1980s the engineers of the automotive manufacturers assessed the existing field bus systems for their using in vehicles [2]. With the development of in-vehicle network technology, the typical in-vehicle network protocols are LIN [3], CAN [4]-[6], TTCAN [7]-[9], TTP/C [10], FlexRay [11], and MOST [12] etc. which have different characteristics and are applied in different automotive domains.

All kinds of status information and control information are basic parameters for well-working of AEIICS. In this paper, we named the parameter (or variable) transmitted through in-vehicle network as signal. The instance of signal, termed as the data of this signal, identifies different parameter value in AEIICS. For example, engine speed is a signal. 1000rpm is one data of engine speed and a parameter value of engine control system. In a word, the basic function of AEIICS is to share datum of signals between different ECUs based on in-vehicle network technology.

Signal transmission in AEIICS is implemented by frame which is the information unit exchanged in data link layer of ISO/OSI (International Standardization Organization/Open System Interconnect) Reference Model. Before sending signals, data link layer packages signals into frame with specific in-vehicle network protocol format. Every frame includes not only the data of signal but also some additional control information such as synchronization information, address information and error control information etc.

Currently, research of AEIICS focuses on network message scheduling, system performance analysis and system development method etc [13]. Period and deadline are primary parameters to describe temporal characteristics for signal and frame in AEIICS. In system design process, period and deadline of signal depend on sampling period of sensor, control algorithm and experience of system engineer etc., the period and deadline of frame depend on the temporal characteristic of signal. However, in current research and design of AEIICS, researchers and engineers mainly focus on directly designing the period and deadline of frame but omit the temporal characteristic relationship between signal and frame (such as SAE J1939 [14]). Because of directly specifying the period and deadline of frame in system design, it couldn't ensure the temporal characteristic of signal and there would be system security problem induced by this kind of design method.

In this paper, we mainly research on the calculation method of period and deadline of frame in AEIICS. This paper is organized as follows: In section 2, we described the characteristics of signal and frame of AEIICS with tuples respectively. In section 3, we defined the conditions with which the period of frame should be satisfied. We also presented and proved the calculation formula of period of frame according to the periods of signals. By illustrating the deadline of frame isn't always the minimal deadline of signals composing this frame, in section 4, we deduced the calculation formula of deadline of frame according to the temporal characteristics of signals. In section 5, we calculated the period and deadline of frame containing lighting control signals as a case study. Finally, in section 6 we concluded and presented future work.

2. FORMAL DESCRIPTION FOR CHARACTERISTICS OF SIGNAL AND FRAME IN AEIICS

Regarding temporal characteristic as the main description object, each signal s_i ($i \in Z^+$) in AEIICS is characterized by a tuple ($\dot{N}_i$, $\dot{T}_i$, $\dot{D}_i$, $\dot{C}_i$):

$\dot{N}_i$ is the node (i.e. ECU) sending s_i.

$\dot{T}_i$ is the production period of s_i. In practice the clocks of the nodes are not synchronized but it is assumed that the first production time of all signals on the same node takes place at the same time.

$\dot{D}_i$ is the deadline of s_i. It is the maximal interval between the production of s_i on the sending node and its reception by all consumers. Usually, it is assumed that the deadline of s_i is equal to its period: $\dot{D}_i = \dot{T}_i$.

$\dot{C}_i$ is the size of s_i in bits with the assumption that $\dot{C}_i$ is always smaller than or equal to the maximal data field size of frame (i.e. there is no segmentation of a signal). For CAN data frame, the maximal signal size is 64 bits because the maximal data field size of CAN data frame is 8 bytes.

Each frame f_j ($j \in Z^+$) in AEIICS is characterized by a tuple (N_j , T_j , D_j , C_j , P_j):

N_j is the node (i.e. ECU) sending f_j .

T_j is the transmission period of f_j . The value of T_j depends on the temporal characteristics of signals composing f_j .

D_j is the deadline of f_j . The value of D_j depends on the temporal characteristics of signals composing f_j .

C_j is the size of f_j in bits. It consists of the size of the data field and the size of the frame overhead.

P_j is the priority of f_j for the priority MAC protocol.

This paper focuses on how to obtain the period and deadline of frame according to the temporal characteristics of signals in AEIICS.

3. CALCULATION METHOD OF PERIOD OF FRAME BASED ON TEMPORAL CHARACTERISTICS OF SIGNALS

3.1 Problem description

It is assumed that frame f_k consists of signals { s_1^k , s_2^k , …, s_n^k }($k, n \in Z^+$). The periods of f_k and s_i^k ($i \in Z^+$) are T_k ($T_k \in Z^+$) and $\dot{T}_i$ ($\dot{T}_i \in Z^+$) respectively. As shown in Fig.3.1, the calculation problem of the period of f_k can be described as follows:

One finds out the maximal value of T_k which ensures that the data of s_i^k produced at $k_i * \dot{T}_i$ $(k_i \in \mathrm{N})$ can be transmitted before $(k_i + 1) * \dot{T}_i$ for $\forall$ $s_i^k \in$ { s_1^k , s_2^k , …, s_n^k }.

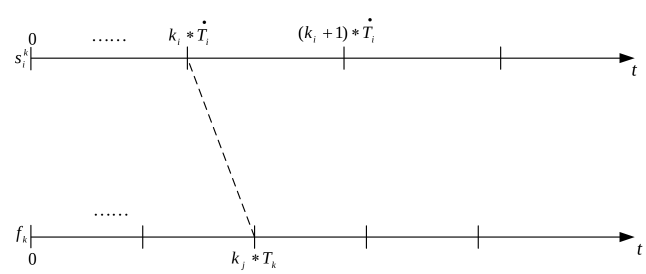

Fig.3.1 When f_k is transmitted with T_k , the data of s_i^k produced at $k_i * \dot{T}_i$ $(k_i \in \mathrm{N})$ can be transmitted before $(k_i + 1) * \dot{T}_i$.

3.2 Calculation method of period of frame

It is assumed that frame f_k consists of signals { s_1^k, s_2^k, …, s_n^k }($k,n \in Z^+$). The periods of f_k and s_i^k ($i \in Z^+$) are T_k ($T_k \in Z^+$) and $\dot{T}_i$ ($\dot{T}_i \in Z^+$) respectively. Every signal of { s_1^k, s_2^k, …, s_n^k } has the same first production time. $s_{\min}^k$ is the signal with the minimal period of signal set { s_1^k, s_2^k, …, s_n^k }, i.e. $\dot{T}_{\min} = \min$ { $\dot{T}_i \mid s_i^k \in$ { s_1^k, s_2^k, …, s_n^k }}. It is also assumed that the transmission time of f_k is synchronized with the production time of $s_{\min}^k$.

Before deducing the calculation method of period of frame, we firstly introduce one of the divisibility theorems.

Theorem 1: Assuming $b \in Z$ and $b \neq 0$, any integer a can be uniquely formulized as follows:

$$a = b * q + r$$

where $q, r \in Z$ and $0 \le r < |b|$.

For $\forall\ s_i^k \in$ { s_1^k, s_2^k, …, s_n^k }, applying theorem 1, the duration of s_i^k between $k_i * \dot{T}_i$ $(k_i \in N)$ and $(k_i+1) * \dot{T}_i$ is formulized by:

$$\Delta_i^k = q * T_k + r \tag{3.1}$$

where $q, r \in Z$ and $0 \le r < |T_k|$.

Setting $T_k = \dot{T}_{\min}$,

because

$$\Delta_i^k = (k_i+1) * \dot{T}_i - k_i * \dot{T}_i = \dot{T}_i \tag{3.2}$$

and $\dot{T}_i \ge \dot{T}_{\min}$,

thus:

$$\Delta_i^k = q * \dot{T}_{\min} + r \tag{3.3}$$

where $q, r \in Z$ and $q \ge 1$, $0 \le r < \dot{T}_{\min}$.

Therefore, f_k is transmitted for q ($q \in Z$ and $q \ge 1$) times during the duration [$k_i * \dot{T}_i$, $(k_i+1) * \dot{T}_i$), i.e. s_i^k contained by f_k is transmitted for q times. It ensures that the data of s_i^k produced at $k_i * \dot{T}_i$ $(k_i \in N)$ can be transmitted by f_k before $(k_i+1) * \dot{T}_i$.

It has proved $\dot{T}_{\min}$ can be the period of f_k. We will prove $\dot{T}_{\min}$ is the maximal allowed period of f_k by using reduction to absurdity as follows.

It is assumed that $\dot{T}_{\min}$ is not the maximal allowed period of f_k. Then there exists $(\dot{T}_{\min} + \varepsilon)$ $(\varepsilon \in Z^+)$ is the maximal allowed period of f_k, i.e. $T_k = \dot{T}_{\min} + \varepsilon$. According to formula (3.1), we obtain:

$$\Delta_i^k = q * (\dot{T}_{\min} + \varepsilon) + r$$

where $q, r \in Z$ and $0 \le r < (\dot{T}_{\min} + \varepsilon)$.

Setting $\dot{T}_i = \dot{T}_{\min}$,

according to formula (3.2):

$$\Delta_{\min}^k = \dot{T}_{\min} = q * (\dot{T}_{\min} + \varepsilon) + r \tag{3.4}$$

where $q, r \in Z$ and $q \le 0$, $0 \le r < (\dot{T}_{\min} + \varepsilon)$.

Therefore, when f_k is transmitted with period $(\dot{T}_{\min} + \varepsilon)$, it can't ensure that the data of s_i^k produced at $k_i * \dot{T}_i$ $(k_i \in N)$ will be transmitted by f_k before $(k_i+1) * \dot{T}_i$ during the duration [$k_i * \dot{T}_i$, $(k_i+1) * \dot{T}_i$).

Thus, the assumption is wrong.

Finally, we obtain the maximal allowed period of f_k, i.e. the period of f_k defined by us is:

$$T_k = \dot{T}_{\min} \tag{3.5}$$

4. CALCULATION METHOD OF DEADLINE OF FRAME BASED ON TEMPORAL CHARACTERISTICS OF SIGNALS

4.1 Problem description

When it is assumed that the transmission time of frame f_k containing signals { s_1^k, s_2^k, …, s_n^k }($k,n \in Z^+$) is synchronized with the production time of $s_{\min}^k$, we have known that the period of f_k is $\dot{T}_{\min}$, the minimal period of signal set { s_1^k, s_2^k, …, s_n^k }. So should we conclude that the deadline of f_k is the minimal deadline of the set { s_1^k, s_2^k, …, s_n^k }?

Because there is possible offset [15] between the production time of the data of signal and the first transmission time of the frame containing this data, the deadline of f_k is not the minimal deadline of signal set { s_1^k, s_2^k, …, s_n^k } .

The calculation problem of the deadline of f_k can be described as follows: for $\forall\ s_i^k \in$ { s_1^k, s_2^k, …, s_n^k }, one finds out the value of D_k which ensures that the response time of s_i^k satisfies with the requirement of deadline of s_i^k if the response time of f_k satisfies with the requirement of deadline of f_k.

In order to calculate the deadline of f_k, we firstly present and prove the mathematic formula between the production times of two periodic signals.

4.2 Relationship between the production times of two periodic signals

GCRT (Generalized Chinese Remainder Theorem): For any $1 \le i < j \le n$, a common residue equation set

$$\begin{cases} x \equiv a_1 (\bmod m_1) \\ x \equiv a_2 (\bmod m_2) \\ \vdots \\ x \equiv a_n (\bmod m_n) \end{cases}$$

has a solution if and only if:

$$a_i \equiv a_j (\bmod \gcd(m_i, \ m_j)) \tag{4.1}$$

When n=2, the common residue equation set

$$\begin{cases} x \equiv a_1 (\bmod m_1) \\ x \equiv a_2 (\bmod m_2) \end{cases}$$

has a solution if and only if

$$a_1 \equiv a_2 (\bmod \gcd(m_1, m_2)) \tag{4.2}$$

Given two periodic signals s_1 and s_2 with periods $\dot{T}_1$ and $\dot{T}_2$ $(\dot{T}_1, \dot{T}_2 \in Z^+)$, and the production time p_1 and p_2 $(p_1, p_2 \in \mathrm{N})$ respectively, it is assumed that they have the same initial time. We will deduce the relationship between p_1 and p_2 using GCRT.

Because s_1 and s_2 are periodic signals,

thus $\exists k_1, k_2 \in \mathrm{N}$, p_1 and p_2 can be formulized by:

$$p_1 = k_1 * \dot{T}_1$$

$$p_2 = k_2 * \dot{T}_2$$

Thus:

$$p_1 \bmod \dot{T}_1 = 0$$

$$p_2 \bmod \dot{T}_2 = 0$$

i.e.:

$$\begin{cases} 0 \equiv p_1 (\bmod \dot{T}_1) \\ 0 \equiv p_2 (\bmod \dot{T}_2) \end{cases}$$

Thus the common residue equation set

$$\begin{cases} x \equiv p_1 (\bmod \dot{T}_1) \\ x \equiv p_2 (\bmod \dot{T}_2) \end{cases}$$

has solution and the solution is x=0.

According to GCRT, we know:

$$p_1 \equiv p_2 (\bmod \gcd(\dot{T}_1, \dot{T}_2))$$

i.e. $\gcd(\dot{T}_1, \dot{T}_2) \mid p_1 - p_2$

thus $\exists q \in Z$,

$$p_1 - p_2 = q * \gcd(\dot{T}_1, \dot{T}_2) \tag{4.3}$$

This states that the interval between the production times of any two datum of two periodic signals always equals to the integer multiple of the great common division of their periods if these two periodic signals have the same initial time.

4.3 Calculation method of deadline of frame

It is assumed that frame f_k consists of signals { s_1^k , s_2^k , …, s_n^k }($k, n \in Z^+$). The period and deadline of s_i^k ($i \in Z^+$) is $\dot{T}_i$ ($\dot{T}_i \in Z^+$) and $\dot{D}_i$ ($\dot{D}_i \in Z^+$) respectively. Every signal of { s_1^k , s_2^k , …, s_n^k } has the same first production time. $s_{\min}^k$ is the signal with the minimal period of signal set { s_1^k , s_2^k , …, s_n^k }, i.e. $\dot{T}_{\min} = \min\{ \dot{T}_i \mid s_i^k \in \{ s_1^k, \ s_2^k, \ \ldots, \ s_n^k \}\}$. The period and deadline of f_k is T_k ($T_k \in Z^+$) and D_k ($D_k \in Z^+$) respectively. The transmission time of f_k is synchronized with the production time of $s_{\min}^k$. As shown in Fig.4.1, $Offset(T_k, \dot{T}_i)$ is defined as the time offset between the production time of the data of s_i^k and the first transmission time of f_k containing this data (because the data of s_i^k maybe be transmitted more than one time); $Offset_{\max}(T_k, \dot{T}_i)$ is defined as the maximal value of $Offset(T_k, \dot{T}_i)$.

Because there is possible time offset between the production time of the data of s_i^k and the first transmission time of f_k containing this data.

Thus the deadline of f_k is defined as the minimal value of the difference between $\dot{D}_i$ and $Offset_{\max}(T_k, \dot{T}_i)$, i.e.:

$$D_k = \min\{\dot{D}_i - Offset_{\max}(T_k, \dot{T}_i) \mid s_i^k \in \{s_1^k, \ s_2^k, \cdots, \ s_n^k\}\}$$

Because $T_k = \dot{T}_{\min}$,

thus:

$$D_k = \min\{\dot{D}_i - Offset_{\max}(\dot{T}_{\min}, \dot{T}_i) \mid s_i^k \in \{s_1^k, \ s_2^k, \cdots, \ s_n^k\}\} .$$

Thus the key of calculating the deadline of f_k is to calculate $Offset_{\max}(T_k, \dot{T}_i)$.

In order to calculate $Offset_{\max}(T_k, \dot{T}_i)$, it is assumed that $\dot{t}_i$ is the production time of the data of s_i^k , t_k is the first transmission time of f_k containing this data. Then $Offset(T_k, \dot{T}_i)$ equals to $t_k - \dot{t}_i$.

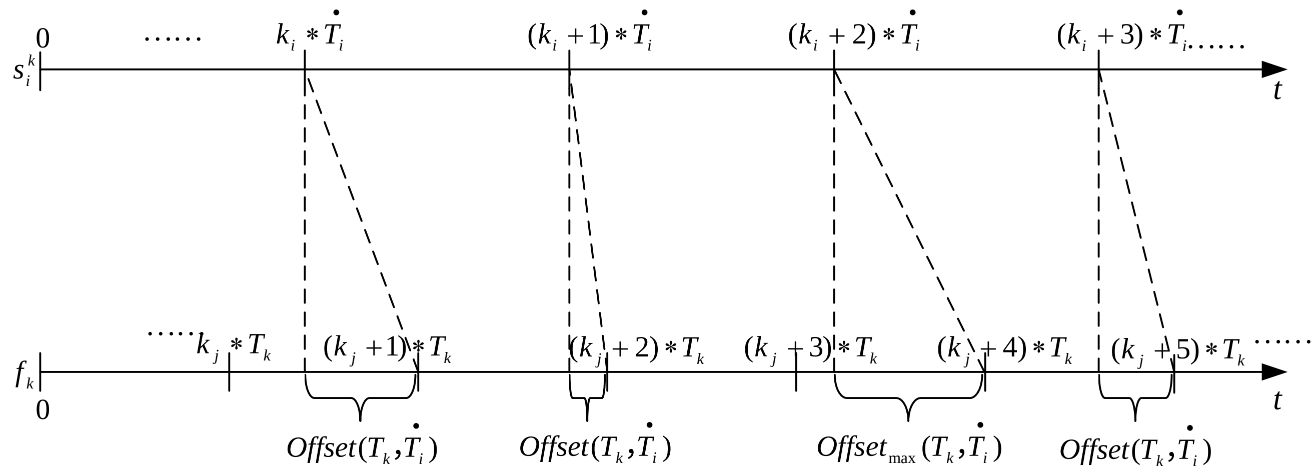

Fig.4.1 $Offset(T_k, \dot{T}_i)$: time offset between the production time of the data of s_i^k and the first transmission time of f_k containing this data; $Offset_{\max}(T_k, \dot{T}_i)$: the maximal value of $Offset(T_k, \dot{T}_i)$.

Because $T_k = \dot{T}_{\min}$,

thus:

$$t_k = k_{\min} * \dot{T}_{\min} \ (k_{\min} \in \mathrm{N})$$

$$\dot{t}_i = k_i * \dot{T}_i \ (k_i \in \mathrm{N})$$

Thus:

$$t_k - \dot{t}_i = k_{\min} * \dot{T}_{\min} - k_i * \dot{T}_i,$$

and

$$k_{\min} * \dot{T}_{\min} - k_i * \dot{T}_i \geq 0$$

According to the definiton of time offset:

$$t_k - \dot{t}_i < \dot{T}_{\min} \text{ (shown in Fig.4.2)}$$

i.e. $0 \leq k_{\min} * \dot{T}_{\min} - k_i * \dot{T}_i < \dot{T}_{\min}$

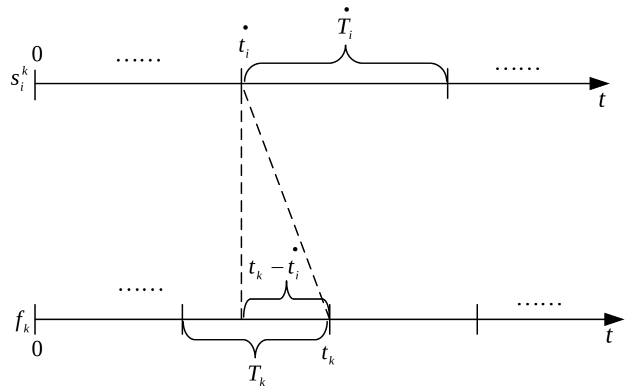

Fig.4.2 The relationship between $Offset(T_k, \dot{T}_i)$ and T_k

According to formula (4.3), the production times of any two datum of two periodic signals have the relationship as:

$$p_1 - p_2 = q * \gcd(\dot{T}_1, \dot{T}_2), \text{ i.e.:}$$

$$k_1 * \dot{T}_1 - k_2 * \dot{T}_2 = q * \gcd(\dot{T}_1, \dot{T}_2)$$

Setting $\dot{T}_{\min} = \dot{T}_1$, $\dot{T}_i = \dot{T}_2$,

thus:

$$k_{\min} * \dot{T}_{\min} - k_i * \dot{T}_i = q * \gcd(\dot{T}_{\min}, \dot{T}_i) \ (q \in \mathrm{N})$$

Thus the key of calculating the maximal value of $k_{\min} * \dot{T}_{\min} - k_i * \dot{T}_i$ is to calculate the maximal value of $q * \gcd(\dot{T}_{\min}, \dot{T}_i)$.

And because $\gcd(\dot{T}_{\min}, \dot{T}_i)$ is a constant,

thus the key of calculating the maximal value of $k_{\min} * \dot{T}_{\min} - k_i * \dot{T}_i$ is to calculate the maximal value of q.

We calculate the maximal value of q as follows:

Because $0 \leq k_{\min} * \dot{T}_{\min} - k_i * \dot{T}_i < \dot{T}_{\min}$, i.e.:

$$0 \leq q * \gcd(\dot{T}_{\min}, \dot{T}_i) < \dot{T}_{\min}$$

thus:

$$q < \frac{\dot{T}_{\min}}{\gcd(\dot{T}_{\min}, \dot{T}_i)}$$

And because $\gcd(\dot{T}_{\min}, \dot{T}_i) \mid \dot{T}_{\min}$,

thus:

$$\max(q) = \frac{\dot{T}_{\min}}{\gcd(\dot{T}_{\min}, \dot{T}_i)} - 1$$

Thus:

$$Offset_{\max}(T_k, \dot{T}_i)$$
$$= \max(k_{\min} * \dot{T}_{\min} - k_i * \dot{T}_i)$$
$$= \max(q) * \gcd(\dot{T}_{\min}, \dot{T}_i))$$

$$= \max(q) * \gcd(\dot{T}_{\min}, \dot{T}_i)$$

$$= (\frac{\dot{T}_{\min}}{\gcd(\dot{T}_{\min}, \dot{T}_i)} - 1) * \gcd(\dot{T}_{\min}, \dot{T}_i)$$

$$= \dot{T}_{\min} - \gcd(\dot{T}_{\min}, \dot{T}_i)$$

Thus:

$$D_k = \min\{ \dot{D}_i - Offset_{\max}(T_k, \dot{T}_i) \}$$

$$= \min\{ \dot{D}_i - \dot{T}_{\min} + \gcd(\dot{T}_{\min}, \dot{T}_i) \}$$

Therefore, the deadline of f_k :

$$D_k = \min\{ \dot{D}_i - \dot{T}_{\min} + \gcd(\dot{T}_{\min}, \dot{T}_i) \} \quad (4.4)$$

If $\dot{D}_i = \dot{T}_i$,

$$D_k = \min\{ \dot{T}_i - \dot{T}_{\min} + \gcd(\dot{T}_{\min}, \dot{T}_i) \} \quad (4.5)$$

5. CASE STUDY

There are many lighting control signals in AEIICS. We usually configure all these signals into one frame which is transmitted through in-vehicle network. Because of different importance, there are different sampling period and real- time request for each lighting control signal. As shown in Table 5.1, it is different for the periods and deadlines of these signals. Here we assume that the deadline of lighting control signal is equal to its period.

Table 5.1 Periods and deadlines of lighting control signals

Signal Name	Period (ms)	Deadline (ms)
Running Light Command	500	500
Alternate Beam Head Light Command	80	80
Low Beam Head Light Command	80	80
High Beam Head Light Command	80	80
Front Fog Lights Command	100	100
Right Turn Signal Lights Command	50	50
Left Turn Signal Lights Command	50	50
Back Up Light Command	50	50
Marker Light Command	500	500
Rear Fog Light Command	100	100
Lighting Data Request Command	500	500
Work Light Command	500	500

$$\dot{T}_{\min} = \min\{ \dot{T}_i \mid s_i^k \in \{ s_1^k, s_2^k, \ldots, s_n^k \} \}$$

$$= \min\{500, 80, 80, 80, 100, 50, 50, 50, 500, 100, 500, 500\}$$

$$= 50(\text{ms})$$

Applying formula (3.5),

$$T_k = \dot{T}_{\min}$$

$$= 50(\text{ms})$$

$$\dot{D}_{\min} = \min\{ \dot{D}_i \mid s_i^k \in \{ s_1^k, s_2^k, \ldots, s_n^k \} \}$$

$$= \min\{500, 80, 80, 80, 100, 50, 50, 50, 500, 100, 500, 500\}$$

$$= 50(\text{ms})$$

Applying formula (4.4),

$$D_k = \min\{ \dot{D}_i - \dot{T}_{\min} + \gcd(\dot{T}_{\min}, \dot{T}_i) \}$$

$$= \min\{500, 40, 40, 40, 100, 50, 50, 50, 500, 100, 500, 500\}$$

$$= 40(\text{ms})$$

According to the culculaiton results, we know the deadline of frame isn’t always equal to the minimal deadline of signals. It is essential to obtain the deadline of frame with formula (4.4) because it will affect on the analysis of system schdulability and the selection of nework transmission rate if we configure the deadline of frame as the the minimal deadline of signals composing this frame.

6. CONCLUSION

In this paper, we researched on the temporal characteristic relationship between signal and frame in automotive electronic and information integrated information control system. We proved the period of frame is the minimal period of signals composing this frame. By applying GCRT, we put forward the mathematic formula of the difference between the production times of two periodic signals. Based on this formula, we finally deduced the calculation formula of deadline of frame with the temporal characteristic of signals as input parameters. In SAE J1939 protocol, the periods and deadlines of some messages are specified, but others depends on the decision of system designer. The further research will focus on the conditions which make the period and deadline of frame equals to the minimal period and deadline of signals composing this frame and keep the period and deadline of frame when other signals are inserted into this frame.

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