Analysis of Message Transmission Time Based on CAN Bus Stuffing Mechanism

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Abstract. The main performance index in CAN bus is closely related to the transmission time (message length) of the transmission message. As the CAN bus adopts the bit-stuffing mechanism, the transmission time of the message in the CAN bus is random variable with the change of the message data. Based on the inherent potential bit-stuffing mechanism of the CAN bus, this paper studied stuffing-bit from the point of probability of stuffing. CAN bus bit-stuffing model was constructed with standard format data frame as an example. The stuffing-bit probability distribution curves of standard frame with different bytes were obtained by simulation. By analyzing the simulation curves, it was found that the worst-stuffing-bit-method used in the previous computation was difficult to reflect the random characteristics of the message transmission time. Combined with the stuffing-bit probability distribution curves, the statistical characteristics of standard frame message transmission time were deduced through formula, which will provide theoretical basis for further research on the random characteristics of CAN bus performance index.

Introduction

CAN bus is widely used in distributed monitoring and control system. The main reason is that the CAN bus is a multi-master bus, and it has the advantages of high reliability, good real-time performance, and high data transmission rate[1,2].

CAN bus adopts the asynchronous serial communication mode. This communication mode does not transmit the clock synchronization signal. Each receiver samples according to its own internal clock. However, the clock of each receiver cannot be exactly the same. After a period of error, the communication error will occur. Therefore, the system needs to use the external synchronization method, and the clocks of all the nodes are synchronized once every other time to eliminate accumulated errors. The CAN bus specifies that the jumping edge of the signal is a synchronous signal. After a comprehensive analysis, the CAN bus stipulates that the maximum period of synchronization is 5 bits. But the transmitted message content can't be changed every 5 bits. Therefore, the CAN bus is further standardized: if there are 5 consecutive same polarity bits in the transmitted message, an opposite polarity bit will be inserted, that is stuffing bit[3]. Due to the stuffing bit, the bit number of the transmission message in the bus is random. Therefore, it is necessary to treat the transmission bit and transmission time in the message as a random variable to study the performance of the bus system.

Based on the bit stuffing mechanism of CAN bus, the statistical characteristics of message transmission time were studied in detail, and obtained through simulation and formula. This can provide a reasonable theoretical basis for future analysis of random characteristics of CAN bus performance indicators.

Analysis of Stuffing Bit Model

In the CAN messages, only the data frame and the remote frame will be stuffed in bits, while the overload frame and the error frame are fixed format, without bit stuffed. In addition, only part of the
data frame and the remote frame structure are bit stuffed, including the frame start, arbitration field, control field, data field, and CRC sequence, while the rest are not bit stuffed. CAN protocol stipulates that when the controller detects five consecutive same polarity bits in the bit-flow from the frame start to the CRC sequence, it will automatically insert one bit of the opposite polarity[4,5]. Figure of bit stuffing is shown as Figure 1.

![Figure 1. Figure of bit stuffing.](image1)

The worst case for bit stuffing is to insert a bit of opposite polarity every 4 bits, as shown in Figure 2. At this point, the number of stuffing bits is the most, that is, the number of the worst stuffing bits is \[
\left\lfloor \frac{n-1}{4} \right\rfloor.
\]

\((n\text{ is the number of bits participating in the bit stuffing}).\)

![Figure 2. Worst-case bit stuffing.](image2)

The total length of a CAN message \((L_m)\) when no bit stuffing is done is:

\[
L_m = 8d_m + g + 13
\]  

(1)

In the formula (1) \(d_m\) indicates data bytes in the transfer message, and takes 0-8. \(8d_m+g\) is the total bits stuffed in the message (\(g=34\) in standard format; \(g=54\) in extended format). The remaining 13 bits including CRC delimiter, acknowledge field, end of frame field, and interframe space do not participate in bit stuffing.

![Figure 3. Standard format data frame filling structure.](image3)

When the bit stuffing is completed, the total length of the CAN message \((L'_m)\) becomes:

\[
L'_m = 8d_m + g + 13 + x
\]  

(2)

In the formula (2) \(x\) is the total stuffing bits.

As the CAN protocol stipulates, the bits in the filling area of the data frame are not completely random. The values and positions of some bits in filling area are fixed, and affect the stuffing bit \(x\). For example, the SOF, RTR, IDE, and r0 in the standard format data frame are all fixed, and in the filling area, as shown in Figure 3. The bit filling area and the fixed bits in the extended format data frame are as shown in Figure 4.
Simulation of Stuffing Bit Model

In fact, the stuffing bit is very difficult to achieve the “worst-case”. In the references [6] and [7], the stuffing bit was analyzed from probability, and the stuffing bit probability distribution curves of different data bytes were obtained by different ways. However, from the analysis of section 1, we know that there are several bits in the filling area of data frame whose values and positions are fixed. So it is necessary to be considered comprehensively when analyzing the stuffing bits in the message.

In order to analyze the probability distribution of stuffing bits, we constructed a CAN bus bit stuffing model \( P(S_i, l) \). The model consists of some binary bit streams \( S_i \) randomly generated, and \( l \) is the length of bit stream \( S_i \). The generation of each bit stream must meet the following three conditions: 1. The probability of each bit in the bit streams appears 0 or 1 the same, are 0.5; 2. Bit and bit are independent of each other; 3. The value and position of some fixed bits in the filling area are considered. \( (l \) takes \{34,42,50,58,66,74,82,90,98\} in standard format data frame; \( l \) takes \{34,42,50,58,66,74,82,90,98\} in extended format data frame)

Take the standard format data frame as an example. From the analysis in section 1, we know that 4 bits in the filling area of the standard format data frame are fixed. Moreover, the data frame control field has a 4-bit data length code (DLC), and the DLC value of data frame for a specific bytes is also determined. Take 2 bytes data as an example, the DLC code is 0010. Therefore in the standard format with 2 bytes data, there are 50 bits to participate in the bit stuffing, of which 8 bits are fixed.

Based on the analysis above, binary stream filling model \( P(S_i, l) \) was constructed considering the values and locations of the 8 fixed bits. By counting the stuffing bits of the simulation results, we can get the probability distribution maps of the stuffing bits in the standard frame. The stuffing bits probabilities distribution curve of CAN standard format messages with 8 bytes is shown as Figure 5.
And the stuffing probability distribution maps of data frames with 0~7 bytes are similar and will not be shown again.

**Statistical Calculation of Message Transmission Time**

The analysis of the previous section shows that the stuffing bit of the standard frame is a random variable (expressed as $X$). For a random variable, we often use its mean, moment to characterize it. According to the simulation curves in section 2, the mean ($\mu_x$, unit: bit), variance ($\sigma^2_x$, unit: bit$^2$), third moment ($\theta_x$, unit: bit$^3$), and fourth moment ($\eta_x$, unit: bit$^4$) of message stuffing bit $X$ were calculated by formula (3) - (6), shown as Table 1.

$$
\mu_x = E(X) \\
\sigma^2_x = E(X^2) - E^2(X) \\
\theta_x = E(X^3) - 3 \times E(X) \times E(X^2) + 2 \times E^3(X) \\
\eta_x = E(X^4) - 3 \times E^4(X) + 6 \times E^2(X) \times E(X^2) - 4 \times E(X) \times E(X^3)
$$

(3) (4) (5) (6)

Table 1. Standard frame stuffing bit statistics characteristics.

<table>
<thead>
<tr>
<th>Bytes</th>
<th>SC</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_x$</td>
<td></td>
<td>1.9501</td>
<td>2.0142</td>
<td>2.2523</td>
<td>2.6348</td>
<td>2.3354</td>
<td>2.5529</td>
<td>2.8317</td>
<td>3.3387</td>
<td>3.2991</td>
</tr>
<tr>
<td>$\sigma^2_x$</td>
<td></td>
<td>0.7592</td>
<td>0.8494</td>
<td>1.0198</td>
<td>1.3126</td>
<td>1.7937</td>
<td>1.9520</td>
<td>2.1506</td>
<td>2.6846</td>
<td>2.6800</td>
</tr>
<tr>
<td>$\theta_x$</td>
<td></td>
<td>0.4575</td>
<td>0.6104</td>
<td>0.6871</td>
<td>0.8774</td>
<td>1.0842</td>
<td>1.1823</td>
<td>1.2259</td>
<td>1.7552</td>
<td>1.7747</td>
</tr>
<tr>
<td>$\eta_x$</td>
<td></td>
<td>1.7489</td>
<td>2.4651</td>
<td>3.3949</td>
<td>5.5224</td>
<td>9.8902</td>
<td>11.4191</td>
<td>13.7619</td>
<td>22.1211</td>
<td>22.3140</td>
</tr>
</tbody>
</table>

(SC: statistical characteristics)

Table 2. Statistics characteristics of total length in standard frame.

<table>
<thead>
<tr>
<th>Bytes</th>
<th>SC</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_y$</td>
<td></td>
<td>48.9501</td>
<td>57.0142</td>
<td>65.2523</td>
<td>73.6348</td>
<td>81.3354</td>
<td>89.5529</td>
<td>97.8317</td>
<td>106.3387</td>
<td>114.2991</td>
</tr>
<tr>
<td>$\sigma^2_y$</td>
<td></td>
<td>0.7592</td>
<td>0.8494</td>
<td>1.0198</td>
<td>1.3126</td>
<td>1.7937</td>
<td>1.9520</td>
<td>2.1506</td>
<td>2.6846</td>
<td>2.6800</td>
</tr>
<tr>
<td>$\theta_y$</td>
<td></td>
<td>0.4575</td>
<td>0.6104</td>
<td>0.6871</td>
<td>0.8774</td>
<td>1.0842</td>
<td>1.1823</td>
<td>1.2259</td>
<td>1.7552</td>
<td>1.7747</td>
</tr>
<tr>
<td>$\eta_y$</td>
<td></td>
<td>1.7489</td>
<td>2.4651</td>
<td>3.3949</td>
<td>5.5224</td>
<td>9.8902</td>
<td>11.4191</td>
<td>13.7619</td>
<td>22.1211</td>
<td>22.3140</td>
</tr>
</tbody>
</table>

Combining the contents above, if the total length of a standard frame bit is considered as a random variable $Y$ (as $Y=X+8d_m+47$ in standard frame), the mean ($\mu_y$, unit: bit), variance ($\sigma^2_y$, unit: bit$^2$), third moment ($\theta_y$, unit: bit$^3$), and fourth moment ($\eta_y$, unit: bit$^4$) of $Y$ were figured out and shown as Table 2.

When we know the statistical characteristics of the total length of the standard frame, as the standard frame transmission time (represented by $Z$) is equal to the product of the total length of standard frame bit and the bit time of the standard frame (that is, $Z=Y \times \tau$, $\tau$: the bit time of data transmission, which is the reciprocal of the baud rate), it is easy to calculate the statistical characteristics of the message transmission time. The mean ($\mu_z$, unit: bit), variance ($\sigma^2_z$, unit: bit$^2$), third moment ($\theta_z$, unit: bit$^3$), and fourth moment ($\eta_z$, unit: bit$^4$) of $Z$ were figured out (we took the baud rate here 500Kbps) and shown as Table 3.
Table 3. Statistical characteristics of standard frame transmission time.

<table>
<thead>
<tr>
<th>Bytes SC</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>μx</td>
<td>97.9002</td>
<td>114.028</td>
<td>130.504</td>
<td>147.269</td>
<td>162.670</td>
<td>179.105</td>
<td>195.663</td>
<td>212.677</td>
<td>228.598</td>
</tr>
<tr>
<td>η</td>
<td>27.9824</td>
<td>39.4416</td>
<td>54.3184</td>
<td>88.3584</td>
<td>158.243</td>
<td>182.705</td>
<td>220.190</td>
<td>353.937</td>
<td>357.024</td>
</tr>
</tbody>
</table>

Combining the simulation results in sections 2 and the formulas in sections 3, we obtained the statistical characteristics of the standard frame transmission time varying with different message bytes. Using these statistical characteristics to analyze the CAN bus performance can effectively avoid the conservative results produced by adopting the traditional worst case method and better reflect the random characteristics of the CAN bus transmission process, which can make the simulation and experimental results more reasonable.

Summary
Since the analysis of CAN bus performance using the worst bit stuffing method is conservative, it can not reflect the random nature of the CAN bus data transmission process. In order to make the analysis of CAN bus more reasonable, based on the bit stuffing mechanism of CAN bus, the random characteristics of the stuffing bits were studied from the probability. Taking the standard frame as an example, CAN bus data stuffing bit model was constructed. Through programming simulation, we got the stuffing bit probability distribution curves with different bytes in standard frame. Combined with the simulation probability distribution curves and related formulas, we can deduce the statistical characteristics of the total length and transmission time of the standard frame, which will provide new ideas and reasonable theoretical basis for further research of other performance indicators in CAN bus system.

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References


[7] Li Fang. CAN Communication Experiment Platform&Scheduling Analysis Based on Probabiliy stuff-bits [D]. Tianjin University, 2005.