Realtime Evaluation and Improvement of FF on Aperiodic Messages

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Abstract: How to support real-time traffic of important aperiodic messages using Foundation Fieldbus (FF) is investigated in this paper. An integrated worst-case response time (WCRT) analysis of aperiodic message indicates FF can't effectively guarantee real-time traffic of important aperiodic message despite FF providing such mechanisms as PT (Pass Token) priority and PT rotation period, etc. After finding the cause of current mechanism' deficiency, an improved mechanism proposed and validated with simulation in this paper. Further, some conclusions such as ongoing work are provided in this paper.
Keywords: Foundation Fieldbus, real-time, aperiodic traffic, response time, token circulation period.

1 Introduction[1]

Fieldbus, as infrastructure of communication to support real-time traffic among field devices in factory floor, is generally characterized by the obligation to respect stringent temporal constraints, which must be met in order to guarantee correctness and safe. Consequently, a significant issue is to take account of temporal property of fieldbus to guarantee timing requirement of field devices. Therefore, scholars, such as Burns, Shin, Song and Tovar, pay lots of attentions on evaluating and analyzing temporal property of many popular fieldbuses, such as CAN、PROFIBUS、P-NET、WorldFIP and FF (Simonot and Song 1996; Tindell and Burns, 1997; Zuberi, et al., 2000; 1990; Kim and Jeong, 1998; Shin and Chou, 1996; Tovar and Vasques, 1999; Wang, 2000; Wang and Sun, et al., 2001, Hong et al., 2002).

FF is characterized by explicitly distinguishing traffics into periodic and aperiodic, and by providing complete control function through specifying user layer protocol, including Function Block (FB) and Device Description (DD) (Fieldbus foundation, 1996). FF applies centralized distributed MAC to support periodic and aperiodic message respectively. As for FF, its periodic message is focusing on constructing schedule table and schedule algorithm, similar researches see (Raja et al., 1993, Almeida et al., 1999, Tovar and Vasques, 1999; Tover 2000, Z. Wang 2002). However, there is a complicated procedure for aperiodic message since it is concerned with periodic message transfer, PT priority and PT rotation period, et.al (Z. Wang 2003). Response time of aperiodic messages see (Z. Wang 2001), and detail analysis of PT token effect and its disadvantage under current mechanism see(Z. Wang 2003). The main focus of this paper is on how to effectively using PT token to meet temporal requirement of both kind of aperiodic messages simultaneously.

The rest of this paper are organized as follows. Section 2 describes the primary procedure of periodic and aperiodic message transfer in FF and then section 3 describes corresponding model. Subsequently, WCRT of both kind of aperiodic messages are analyzed in section 4 under different states of PT priority. Through above works, an improved APTCP counting mechanism and method of setting ISPTCP are proposed, which is validated with two simulations in section 6. Finally, some conclusions are given in section 7.

2 Foundation Fieldbus

FF explicitly distinguishes periodic and aperiodic messages and applies different strategies respectively, since the diversity of message traffic and the importance of guarantee of real-time message communication.

2.1 Message and token

FF applies centralized media access mechanism, and implements it using Link Active Schedule (LAS). LAS manages schedule of all messages in FF through giving token, which standards for access to FF. Any fieldbus device can only transmit its waiting messages after receiving token. For effectively managing both kinds of messages, FF provides two types of tokens.

The first one is scheduled token, refers to compel data (CD), which only support periodic messages. According to its stored predefined time, LAS gives access right to periodic messages through sending CD. Through a specific address stored in CD, LAS manages a periodic message to be transmitted within a node, which transmits the periodic message with corresponding address after receiving CD. The second token is unscheduled token, refers to pass token (PT), which gives aperiodic messages an opportunity. When left communication time between transfers of periodic message is enough, LAS sends PT to a node according to the stored address. The detail is shown in Fig.1.

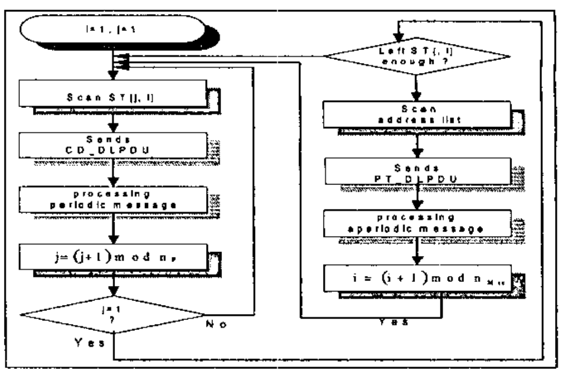

Fig.1 Procedure of LAS sending CD and PT

2.2 Link active schedule implementation

Temporal properties of all periodic messages within a FF segment are stored in LAS. According to these properties and a proper schedule algorithm, LAS generates a network schedule. In FF, the network schedule is stored in a schedule table (ST), which is made up of a set of basic schedule table, known as microcycle. Another important parameter associated with the ST is macrocycle.

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Definition 1: microcycle, the maximum rate at which LAS performs a set of scans of periodic messages.

Definition 2: macrocycle, the minimum duration during which the sequence of microcycles is repeated.

Usually, the microcycle and the macrocycle are respectively set equal to the highest common factor (HCF) and the lowest common multiple (LCM) of the required scan periodicities. Assume that within a FF there are 6 periodic messages shown in Table.1 to be transferred. According rule of HCF/LCM, the microcycle and macrocycle are set to 1ms and 12 ms respectively. A feasible schedule meeting is illustrated as Fig.2.

Table.1 Example set of periodic messages

Variable Identifier	Periodicity (ms)	Transaction duration(ms)
A	1	0.2
B	2	0.2
C	3	0.2
D	4	0.2.5
E	4	0.2.5
F	6	0.3

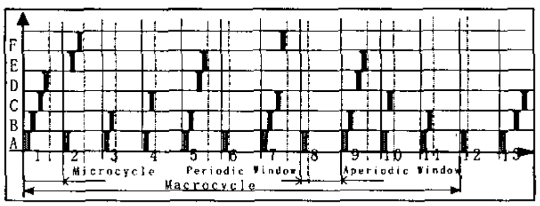

Fig.2 A feasible schedule for periodic messages in table.1

2.2 Procedure of aperiodic message transfer

In order to meet requirement of aperiodic messages with different levels of criticality in temporal aspect, FF provides PT priority and PT circulation period (PTCP).

Definition 3: PTCP is the duration that PT consecutively twice reaches a same node.

Within FF, there are two kinds of PTCP, Setting PT circulation period (SPTCP) and Actual PT circulation period (APTCP), where the former is set online or offline by an operator and the latter is measured online. APTCP equals to measured value of the duration that PT consecutively twice reaches a particular node with the least address (without losing generality, the least address is set as 1 in this paper).

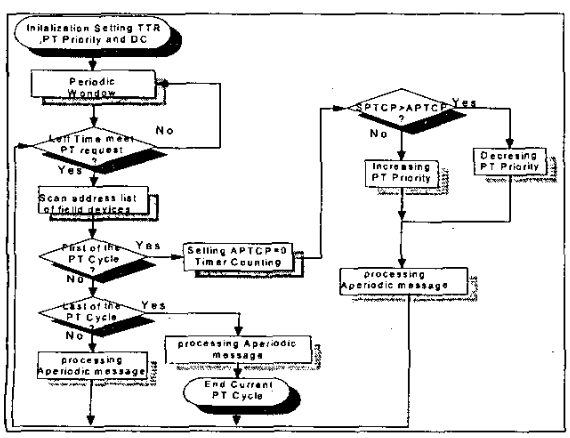

Fig.3 procedure of scheduling aperiodic message

Corresponding to aperiodic messages'priority, which is classified into Urgent, Normal and Available, PT priority is differentiated into corresponding three types too. For an aperiodic message, it is transmitted only when its priority is not less than current PT priority and its transfer time is less than maximum token hold time (MTHT), set in PT frame. PT returns LAS when no aperiodic message with proper priority exists or MTHT expires (Z.Wang 2003).

To enhance real-time response of critical aperiodic message and adapt load in FF, LAS online changes PT priority according to the difference of between SPTCP and APTCP. The detail is shown in Fig.3.

3 Model of Aperiodic Message Communication

3.1 Network and message model

Consider a DCS, wherein n_n nodes are interconnected by a FF network, and n_P periodic message $M_P^i = (C_P^i, T_P^i, D_P^i)$ $(i \in [1, n_P])$ and n_A aperiodic messages $M_A^i = (C_A^i, T_A^i, D_A^i)$ $(i \in [1, n_A])$ exist. T_P^i , D_P^i and C_P^i correspond to periodicity, deadline and transaction duration of periodic message M_P^i respectively; T_A^i , D_A^i and C_A^i correspond to periodicity, deadline and transaction duration of aperiodic message M_A^i respectively. For aperiodic message, its arrival duration normally is irregular, however minimum inter-arrival time is assumed here in order to guarantee its timing constraint.

Considering priority of an aperiodic message and its belonged node, the following concrete description is gotten (Available aperiodic message is neglected for paper space).

$$M_U^{i,j} = (C_U^{i,j}, T_U^{i,j}, D_U^{i,j}) \quad \left(j \in [1, n_U^i]\right) \tag{1}$$

$$M_N^{i,j} = (C_N^{i,j}, T_N^{i,j}, D_N^{i,j}) \quad \left(j \in [1, n_N^i]\right) \tag{2}$$

$$M_A^{i,j} = (C_A^{i,j}, T_A^{i,j}, D_A^{i,j}) \quad \left(j \in [1, n_U^i + n_N^i]\right) \tag{3}$$

$$\sum_{i=1}^{n_n} \left(n_U^i + n_N^i\right) = n_A \tag{4}$$

where, $M_U^{i,j}$ and $M_N^{i,j}$ corresponds to j^{th} Urgent and Normal aperiodic message in i^{th} node respectively.

3.2 PT visiting model

For describing behavior of a sequence by which PT visits a node, we introduce a pair of subscripts, $visit(c,i)$, where c indicates the order of PT visiting and i indicates the address of node being visited. That means $visit(c,i)$ indicate the instant of the beginning that PT visits node i at its c^{th} order. Let $APTCP(c)$ be the elapsed time of APTCP at its c^{th} order, that means $APTCP(c)$ beginning from PT visiting node 1 at its c^{th} order and ending with PT visiting node 1 at its $(c+1)^{th}$ order. Further, for describing the elapsed time of PT visiting i node and j node which starts from $visit(c,i)$ and ends at $visit(c,j)$, $Del_c^{i,j}$ is introduced.

The relationship among $visit(c,i)$, $Del_c^{i,j}$, $APTCP(c)$ and SPTCP are illustrated in Fig.4. Where $visit(c,i)$ owns property: 1) $visit(c,i)$ is followed by $visit(c,i+1)$

if $(i \neq n_n)$, otherwise by $visit(c+1,i)$. $visit(c,i-1)$ is the previous one before $visit(c,i)$ if $(i \neq 1)$, otherwise $visit(c-1,n_n)$ is; 2) $APTCP(c)$ equals to $visit(c,i+1)$-$visit(c,i)$ or $Del_c^{i,j}$. Further, $visit(c,i)$ and $Del_c^{i,j}$ meet,

$$\mathrm{Del}_c^{i,j} = \begin{cases} visit(c,i+j) - visit(c,i) & (i+j) \leq n_n \\ visit(c+(i+j-1)\ \%\ n,(i+j-1)\ Mod\ n_n) - visit(c,i) & (i+j) \leq n_n \end{cases} \quad (5)$$

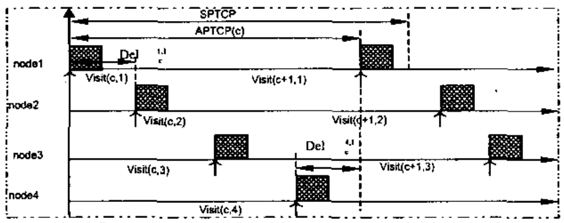

Fig.4 Parameters relationship among PT visiting model

3.3 Procedure of PT priority changing

From the introduction of section 2.3 we know, PT changes priority online at the instant of $visit(c+1,1)$ according to difference between $SPTCP$ and $APTCP(c)$, and the last PT priority just before $visit(c+1,1)$. Therefore, we have the following state transfer graph for PT priority as illustrated in Fig.5.

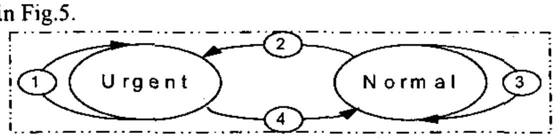

Fig.5 State transfer graph for PT priority

3.4 Queue delay for an aperiodic message

For convenient description of waiting procedure of aperiodic messages, we temporally neglect their priority, and just regard all aperiodic messages as the same priority.

As for $M_A^{i,j}$, it cannot be transferred immediately it arrives node i and must wait until arrival of PT to the same node. Further, $M_A^{i,j}$ is transferred according to FCFS (first come first service) rule within node i. Therefore, queue delay of $M_A^{i,j}$ consists of waiting arrival of PT to node i, transmitting other aperiodic messages arriving earlier in node i, and transmitting itself. It is obvious that the worst-case condition for $M_A^{i,j}$ is that the following two situations occur simultaneously: $M_A^{i,j}$ arrives node i just after PT leaves the same node, and all other aperiodic messages in node i arrive simultaneously except for $M_A^{i,j}$ arriving later. The according response procedure is indicated in Fig.6.

Let $R_A^{i,j}$ denote response time of aperiodic message $M_A^{i,j}$ under the worst-case situation, then,

$$R_A^{i,j} = \left(\mathrm{Del}_c^{i,1} - PT_f\right) + \sum_{x=i+1}^{N} \mathrm{Del}_c^{x,1} + \sum_{l=c+\lambda,x=1}^{N} \mathrm{Del}_l^{x,1} + \sum_{x=1}^{i-1} \mathrm{Del}_{c+\lambda+1}^{x,1} + \sum_{x=1}^{n_A^i} C_A^{i,x} \quad (6)$$

where λ denote the number of PT cycles that $M_A^{i,j}$ must wait for proper PT priority, PT_f denote PT sending and returning time without transmitting aperiodic message.

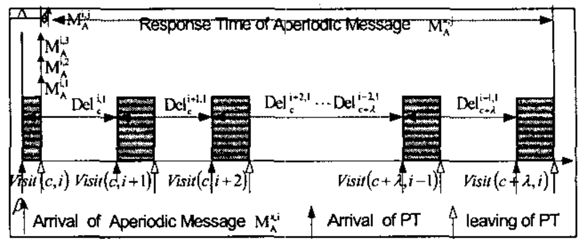

Fig.6. Response procedure of an aperiodic message

Note that Eq.(6) is only general expression of WCRT of any aperiodic message. Further, the last term in Eq.(6) maybe includes $C_A^{i,j}$ only instead of all aperiodic messages in node i. In fact, the concrete contains in the last term is related to all the previous terms in Eq.(6). The terms from the second to the fifth are related to priority of considered aperiodic message. Therefore, Eq.(6) is only an upper bound of WRCT.

3.5 Transfer capability of aperiodic window

WCRT of aperiodic message must be analyzed under different conditions because LAS online changes PT priority, which leads to different communication capability. Further, aperiodic message only is sent within aperiodic window, whose transfer capability varies in different microcycles. The portion of a microcycle reserved for periodic message is denoted as periodic window, whereas the time left after the periodic window is denoted as aperiodic window. LAS sends PT to aperiodic message only within aperiodic window, whose transfer capability varies in different instants and is related to the content in the corresponding periodic window (Z.Wang 2001). The transfers for two types of messages depend on schedule stored in their respective windows. Once all microcycles have been performed in the ST, LAS repeats the same network schedule from the beginning. Exact transfer capability of aperiodic window is key to evaluate WCRT of aperiodic message.

To get exact transfer capability of aperiodic window, we must consider periodic window's content, schedule of periodic messages, which is determined by arrival pattern of periodic messages. That means we have to calculate transfer capability of aperiodic window integrated arrival pattern of periodic messages.

Let $PW(i)$ and $AW(i)$ $(i \in [1, N_{Mic}])$ denote of i^{th} periodic window and aperiodic window respectively, where N_{Mic} denote number of microcycles within ST (Z.Wang 2001). If ST is constructed by rule of LCM and HCF, N_{Mic} equals to LCM/HCF of period of all periodic messages. Let W_A^i and W_P^i be time length of $AW(i)$ and $PW(i)$ respectively.

According to the above definition, we have

$$W_A^i = MicP - W_P^i \quad (7)$$

$$W_P^i = \sum_{j=1}^{n_p} (ST[j,i^*]) \times C_P^j \quad (8)$$

where $MicP$ denote time length of a microcycle, $ST[j, i^*]$ denotes whether periodic message j is scheduled in i^{th} microcycle. i^*=[(i-1) Mod N_{Mic}] denotes the order of i^{th}

microcycle in ST.

Let $\Omega_A^{i,j}$ denote number of microcycles for completing transfer of M_A^i under worst-case situation.

$$\Omega_A^{i,j}=\min(\psi)\cap\sum_{i=\beta}^{\beta+\psi-1}W_A^i\geq\sum_{k=1}^{n_A}f\left(C_A^K,\psi,\beta\right)\quad(9)$$

Note that in Eq.(9) don't contain C, the order of PT cycle or PT visiting, as Eq.(6) does. This is because actual traffic of aperiodic messages and aperiodic window are uncertain. Within Eq.(6), C is just for convenience of description. Further, Eq.(9) only explains how to calculate $\Omega_A^{i,j}$, particularly the load of aperiodic messages in the right part of Eq.(9). This part will be adjusted according to actual permitted load of aperiodic messages.

Another worthwhile to note within Eq.(9) is β, the order of aperiodic window. Since the variety of aperiodic window will lead to aperiodic message suffers different waiting times, which is determined by the transfer capability of aperiodic window from the arrival of the aperiodic message to completing its transfer. Therefore, we need the worst-case order of aperiodic window, that means aperiodic window starting from β owns the less transfer capability. That is,

$$\beta=\left(maw\middle|\max\left(\min(\psi)\cap\sum_{i=maw}^{maw+\psi-1}W_A^i\geq\sum_{k=1}^{n_A}f\left(C_A^i,\psi,\beta\right)\right)\right)\quad(10)$$

In the following section, β denotes the worst-case order of aperiodic window unless explicitly stated.

4 Response Time of Aperiodic Message

PT priority changes online according to the difference between SPTCP and APTCP. Correspondingly, an aperiodic message may experience different PT priorities during its responding procedure. Further, the traffic of aperiodic messages during the responding procedure is determined by PT priority. Therefore, we must analyze WCRT of an aperiodic message under different conditions.

4.1 Case1: PT priority keeping urgent

Under this scenario, only urgent aperiodic messages are sent. Accordingly, let $\overline{R}_U^{i,j}$ denote WRCT of $M_U^{i,j}$ in case1.

$$\overline{R}_u^{i,j}=(\overline{\Omega}_u^{i,j}-1)\times P_{\mathrm{Mic}}+\sum_{j=1}^{n_p}ST[j,(\beta+\overline{\Omega}_u^{i,j})^*]\times C_p^j+\sum_{k=1}^{n_u^i}C_u^{i,k}\quad(11)$$

where $\overline{\Omega}_U^{i,j}$ denote number of microcycles for completing transfer of $M_U^{i,j}$ under PT priority keeping urgent.

$$\overline{\Omega}_A^{ij}=\min(\psi)\cap\sum_{i=\beta}^{\beta+\psi-1}W_A^i\geq\sum_{k=1}^{n}\sum_{j=1}^{n_u^k}C_u^{kj}$$

4.2 Case2: PT priority changing from normal to urgent

Under this scenario, both urgent and normal aperiodic messages are able to be transferred before PT priority changing from normal into urgent. Accordingly, let $\tilde{R}_U^{i,j}$ denote WRCT of $M_U^{i,j}$ in this case.

$$\tilde{R}_U^{i,j}=(\tilde{\Omega}_U^{i,j}-1)\times MicP+\sum_{l=1}^{n_P}ST\left[l,\left(\beta+\tilde{\Omega}_U^{i,j}\right)^*\right]\times C_P^i+\sum_{l=1}^{n_U^i}C_U^{i,l}\quad(12)$$

where $\tilde{\Omega}_U^{i,j}$ denote number of microcycles for completing transfer of $M_U^{i,j}$ under case 2.

$$\tilde{\Omega}_U^{i,j}=\min(\psi)\cap\sum_{i=\beta}^{\beta+\psi-1}W_A^i\geq\sum_{k=i+1}^{n}\left(\sum_{l=1}^{n_U^k}C_U^{k,l}+\sum_{l=1}^{n_N^k}C_N^{k,l}\right)+\sum_{k=1}^{i}\sum_{l=1}^{n_U^k}C_U^{k,l}$$

It is obvious that urgent aperiodic messages in node 1 will suffer worst-case response time.

$$\tilde{R}_U^{1,j}=(\tilde{\Omega}_U^{1,j}-1)\times MicP+\sum_{l=1}^{n_P}ST\left[l,\left(\beta+\tilde{\Omega}_U^{1,j}\right)^*\right]\times C_P^i+\sum_{l=1}^{n_U^1}C_U^{1,l}\quad(13)$$

where $\tilde{\Omega}_U^{1,j}=\min(\psi)\cap\sum_{i=\beta}^{\beta+\psi-1}W_A^i\geq\sum_{k=1+1}^{n}\left(\sum_{l=1}^{n_U^k}C_U^{k,l}+\sum_{l=1}^{n_N^k}C_N^{k,l}\right)+\sum_{l=1}^{n_U^1}C_U^{1,l}$

4.3 Case3: PT priority keeping normal

Under this scenario, both urgent and normal aperiodic messages are allowing transferring. Let $\hat{R}_U^{i,j}$ and $\hat{R}_N^{i,j}$ denote WRCT of $M_U^{i,j}$ and $M_N^{i,j}$ respectively.

$$\hat{R}_U^{i,j}=(\hat{\Omega}_U^{i,j}-1)\times MicP+\sum_{l=1}^{n_P}ST\left[l,\left(\beta+\hat{\Omega}_U^{i,j}\right)^*\right]\times C_P^i+\sum_{l=1}^{n_U^i}C_U^{i,l}\quad(14)$$

$$\hat{R}_N^{i,j}=(\hat{\Omega}_N^{i,j}-1)\times MicP+\sum_{l=1}^{n_P}table\left[l,\left(\beta+\hat{\Omega}_N^{i,j}\right)^*\right]\times C_P^i+\sum_{l=1}^{n_N^i}C_N^{i,l}\quad(15)$$

where $\hat{\Omega}_U^{i,j}$ and $\hat{\Omega}_N^{i,j}$ respectively denote number of microcycles for completing transfer of $M_U^{i,j}$ and $M_N^{i,j}$ under case3.

$$\hat{\Omega}_U^{i,j}=\min(\psi)\cap\sum_{i=\beta}^{\beta+\psi-1}W_A^i\geq\sum_{k=i+1}^{n}\left(\sum_{l=1}^{n_U^k}C_U^{k,l}+\sum_{l=1}^{n_N^k}C_N^{k,l}\right)+\sum_{k=1}^{i}\sum_{l=1}^{n_U^k}C_U^{k,l}+\sum_{k=1}^{i-1}\sum_{l=1}^{n_N^k}C_N^{k,l}$$

$$\hat{\Omega}_N^{i,j}=\min(\psi)\cap\sum_{i=\beta}^{\beta+\psi-1}W_A^i\geq\sum_{k=i+1}^{n}\left(\sum_{l=1}^{n_U^k}C_U^{k,l}+\sum_{l=1}^{n_N^k}C_N^{k,l}\right)+\sum_{k=1}^{i}\left(\sum_{l=1}^{n_U^k}C_U^{k,l}+\sum_{l=1}^{n_N^k}C_N^{k,l}\right)$$

4.4 Case4: PT priority changing from urgent to normal

Within this scenario, both urgent and normal aperiodic messages can be transferred. Let $\ddot{R}_U^{i,j}$ and $\ddot{R}_N^{i,j}$ respectively denote WRCT of $M_U^{i,j}$ and $M_N^{i,j}$ in case 4.

As for urgent aperiodic messages, this scenario is familiar with section 4.2 except for normal aperiodic messages being allowed transferring only after PT priority changing into Normal.

$$\ddot{R}_U^{i,j}=(\ddot{\Omega}_U^{i,j}-1)\times MicP+\sum_{l=1}^{n_P}ST\left[l,\left(\beta+\ddot{\Omega}_U^{i,j}\right)^*\right]\times C_P^l+\sum_{l=1}^{n_U^i}C_U^{i,l}\quad(16)$$

where $\ddot{\Omega}_U^{i,j}$ denote number of microcycles for completing transfer $M_U^{i,j}$ under case4.

$$\ddot{\Omega}_U^{i,j}=\min(\psi)\cap\sum_{i=\beta}^{\beta+\psi-1}W_A^i\geq\sum_{k=i+1}^{n}\sum_{l=1}^{n_U^k}C_U^{k,l}+\sum_{k=1}^{i}\sum_{l=1}^{n_U^k}C_U^{k,l}+\sum_{k=1}^{i-1}\sum_{l=1}^{n_N^k}C_N^{k,l}$$

As for normal aperiodic message, its WRCT analysis is complicated because it is concerned with waiting number of PT cycles before PT priority descended to Normal. This procedure is not only related to urgent aperiodic message, but also to SPTCP. Here, only the maximum waiting number of PT cycles for PT priority descended to Normal from Urgent is analyzed, where urgent aperiodic messages arrive with its minimum intervals, as shown in Fig.7.

$$\ddot{R}_N^{i,j}=(\ddot{\Omega}_N^{i,j}-1)\times MicP+\sum_{l=1}^{n_P}ST\left[l,\left(\beta+\ddot{\Omega}_N^{i,j}\right)^*\right]\times C_P^l+\sum_{l=1}^{n_U^i}C_N^{i,l}\quad(17)$$

where $\ddot{\Omega}_N^{i,j}$ denote number of microcycles for completing transfer $M_N^{i,j}$ under case 4.

$$\ddot{\Omega}_N^{1,j} = \min(\psi) \cap \sum_{i=\beta+\ddot{\Omega}_U^{1,j}+\cdots+\ddot{\Omega}_{\phi,U}^{1,j}}^{\beta+\ddot{\Omega}_U^{1,j}+\cdots+\ddot{\Omega}_{\phi,U}^{1,j}+\psi-1} W_A^i \geq \tag{18}$$

$$\sum_{k=1}^{n}\left(\sum_{l=1}^{n_U^k}\left(\left\lceil \frac{Del_{c+\phi-1}^{1,j}+\psi\times MicP}{T_U^{k,l}}\right\rceil - \left\lfloor \frac{Del_{c+\phi-1}^{1,j}}{T_U^{k,l}}\right\rfloor\right)\cdot C_U^{i,j} + \sum_{l=1}^{n_N^k} C_N^{k,l}\right)$$

where ϕ denote the number of PT cycles before PT priority descended from Urgent to Normal, which meet:

$$\phi = \min\left(\varphi \middle| Del_{c+\varphi-1}^{1,n} > SPTCP \cap Del_{c+\varphi}^{1,n} < SPTCP\right) \tag{19}$$

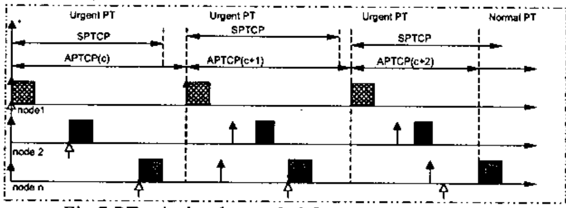

Fig.7 PT priority descended from Urgent to Normal

The calculation of ϕ (equals to 3 in Fig.7).is as followed:

$$\ddot{\Omega}_{1,U}^{1,j} = \min(\psi) \cap \sum_{k=\beta}^{\beta+\psi-1} W_A^k \geq \sum_{k=1}^{n}\sum_{l=1}^{n_U^k} C_U^{k,l}$$

$$Del_C^{1,n} = (\ddot{\Omega}_U^{1,j}-1)\times MicP + \sum_{l=1}^{n_P} ST\left[l,\left(\beta+\ddot{\Omega}_U^{1,j}\right)^{*}\right]\times C_P^l + \sum_{l=1}^{n_U^n} C_U^{n,l}$$

$$\ddot{\Omega}_{2,U}^{1,j} = \min(\psi) \cap \sum_{i=\beta+\ddot{\Omega}_{1,U}^{1,j}}^{\beta+\ddot{\Omega}_{1,U}^{1,j}+\psi-1} W_A^i \geq \sum_{k=1}^{n}\sum_{l=1}^{n_U^k}\left(\left\lceil \frac{Del_c^{1,n}+\psi\times MicP}{T_U^{k,l}}\right\rceil\right)\cdot C_U^{k,l}$$

$$Del_{c+1}^{1,n} = (\ddot{\Omega}_{2,U}^{1,j}-1)\times MicP + \sum_{l=1}^{n_P} ST\left[l,\left(\beta+\ddot{\Omega}_{2,U}^{1,j}\right)^{*}\right]\times C_P^l + \sum_{l=1}^{n_U^n} C_U^{n,l}$$

$$\ddot{\Omega}_{\varphi,U}^{1,j} = \min(\psi) \cap \sum_{i=\beta+\ddot{\Omega}_{1,U}^{1,j}+\cdots+\ddot{\Omega}_{\varphi-1,U}^{1,j}}^{\beta+\ddot{\Omega}_{1,U}^{1,j}+\cdots+\ddot{\Omega}_{\varphi-1,U}^{1,j}+\psi-1} W_A^i \geq$$

$$\sum_{k=1}^{n}\sum_{l=1}^{n_U^k}\left(\left\lceil \frac{Del_{c+\varphi-1}^{1,n}+\psi\times MicP}{T_U^{k,l}}\right\rceil - \left\lfloor \frac{Del_{c+\varphi-1}^{1,n}}{T_U^{k,l}}\right\rfloor\right)\cdot T_U^{k,l}$$

$$Del_{c+\varphi-1}^{1,n} = (\ddot{\Omega}_{\varphi,U}^{1,j}-1)\times MicP + \sum_{l=1}^{n_P} ST\left[l,\left(\beta+\ddot{\Omega}_{\varphi,U}^{1,j}\right)^{*}\right]\times C_P^l + \sum_{l=1}^{n_U^n} C_U^{n,l}$$

5 Improvement of APTCP Accounting Mechanism

5.1 Impact of PT priority on WCRT of urgent and normal aperiodic messages

The analysis in previous section indicates that WCRT of urgent and normal aperiodic messages badly vary under different conditions, such as cases 2 and 4. Since PT priority only changes when PT visit node 1 based on APTCP, SPTCP and actual load, the change of PT priority can't meet propose of guaranteeing urgent aperiodic message and best effort serve normal aperiodic message at all. That leads to lost control from with in whole a PT cycle, and cause delay response to actual load in FF. Within a PT cycle, the maximum load of normal aperiodic messages will meet urgent aperiodic message suffering larger delay, however this symptom can't be avoided unless completely prevent normal aperiodic messages with an enough less SPTCP. Consequently, normal aperiodic messages lost chance to be transfer forever, or suffer multiple PT cycle even they get a chance (this argument can refer to section 4.4). Therefore, we can argue that the goal of existing mechanism can't be realized. Consequently, an improved mechanism is necessary to enhance responsibility for actual load of aperiodic messages to guarantee their temporal constraint.

5.2 Improvement of APTCP counting mechanism

It is obvious that the new mechanism should timely respond real-time requirement of each Urgent aperiodic message in FF. For implementing the goal, the improved APTCP (IAPTCP) should timely indicate requirement of each Urgent aperiodic in each node. Naturally, improved mechanism proposed in this paper is that IAPTCP equals to the elapsed time between PT consecutively twice arriving the any same node instead of node 1 only. In the following, this paper introduces how to set ISPTCP (SPTCP under improved mechanism).

Let $IAPTCP(c,i)$ denote the elapsed time between $visit(c+1,i)$ to $visit(c,i)$, which is illustrated in Fig.9. It is obvious that new mechanism will maintain upper bound for WRCT of Urgent aperiodic message through an easy method by setting a proper ISPTCP.

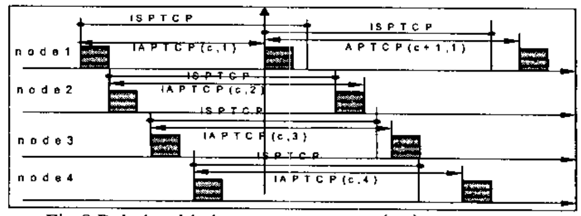

Fig.8 Relationship between $IAPTCP(c,i)$ and $ISPTCP$

Here, we take $M_U^{i,j}$ as example for explaining how to set ISPTCP. Assume that $M_U^{i,j}$ arrives node **i** just after PT leaves this node and assume the current PT priority is Normal; $IAPTCP(c,x)$ being larger than ISPTCP occurs at $visit(c+1,x)$, then PT priority changes from Normal to Urgent; PT priority at least keeps Urgent until $visit(c+1,i)$. In this scenario, we can determine the WCRT of $M_U^{i,j}$.

Let $R_U^{i,j}$ denote response time of $M_U^{i,j}$ under the new mechanism.

$$R_U^{i,j} = ISPTCP + (\zeta_U^{i,j}-1)\times MicP + \sum_{l=1}^{n_P} ST\left[l,\left(\beta+\zeta_U^{x,i}\right)^{*}\right]\times C_P^l + \sum_{l=1}^{n_U^i} C_U^{k,l} \tag{20}$$

where $\ddot{\zeta}_U^{x,y}$ denote the number of microcycles for completing transfer of $M_U^{i,j}$.

$$\ddot{\zeta}_U^{x,y} = \min(\psi) \cap \sum_{i=\beta}^{\beta+\psi-1} W_A^i \geq \ddot{\Psi}_U^{x,y}$$

$$\ddot{\Psi}_U^{x,y} = \begin{cases} \sum_{k=x}^{y}\sum_{j=1}^{na_U^k} C_U^{k,l} & (y > X) \\ \sum_{k=x}^{n}\sum_{l=1}^{n_U^k} C_U^{k,l} + \sum_{k=1}^{y}\sum_{j=1}^{na_U^k} C_U^{k,l} & (y < X) \end{cases}$$

For conveniently describing WCRT of $M_U^{i,j}$, let $\ddot{\xi}_U^{i,x}$ denote the left delay after promotion of PT priority which occur at instant of $visit(c,x)(x \geq i)$ or $visit(c+1,i)$ $(x < i)$ under the new mechanism.

$$\ddot{\xi}_U^{i,x} = (\ddot{\zeta}_U^{x,i}-1)\times MicP + \sum_{l=1}^{n_P} ST\left[l,\left(\beta+\ddot{\zeta}_U^{x,i}\right)^{*}\right]\times C_P^l + \sum_{l=1}^{n_U^i} C_U^{k,l} \tag{21}$$

ISPTCP should guarantee time constraints of Urgent aperiodic message, so that it must meet,

$$ISPTCP^{i} + \ddot{\xi}_{U}^{i,x} = \ddot{R}_{U}^{i,j} \le D_{U}^{i,j} \quad (22)$$

Further, we can determine different ISPTCPs according to number of Normal aperiodic messages permitted before promoting PT priority.

$$ISPTCP^{i} = \min\left(D_{U}^{i,j} - \ddot{\zeta}_{U}^{i,x} \middle| i, x \in n, j \in n_{U}^{i}\right) \quad (23)$$

For $M_{U}^{i,j}$, there are different positions where $IAPTCP(c,x)$ or $IAPTCP(c+1,x)$ being larger than SPTCP occurs. Among these positions, $IAPTCP(c,i+1)(c \ne n)$ or $IAPTCP(c+1,1)$ $(c=n)$ is the most effective one preventing transfer of Normal aperiodic message. Under this case, expression (24) is gotten

$$ISPTCP^{i} = \min\left(D_{U}^{i,j} - \ddot{\zeta}_{U}^{i,(i+x) \bmod i} \middle| i, x \in n, j \in n_{U}^{i}\right) \quad (24)$$

since $D_{U}^{i,j} \ge \ddot{R}_{U}^{i,j} = ISPTCP^{i} + \ddot{\xi}_{U}^{i,(i+x) \bmod n}$.

6 Numerical Example

Assume FF network which interconnects 6 nodes, where each owns one urgent and one normal aperiodic message (transaction duration of each urgent aperiodic message is 0.02s and normal aperiodic message is 0.04s) respectively as shown in Fig.9. Both SPTCP and ISPTCP are set as 500ms, the response time of urgent aperiodic message in different node is shown in Fig.9 and Fig.10.

Table.2 Example set of aperiodic messages

Order of node	1	2	3	4	5	6
Arrival rate (urgent) 1/s	1.0	1.0	0.8	0.5	0.8	0.9
Arrival rate (normal) 1/s	1.5	2.0	2.0	2.0	1.8	1.7

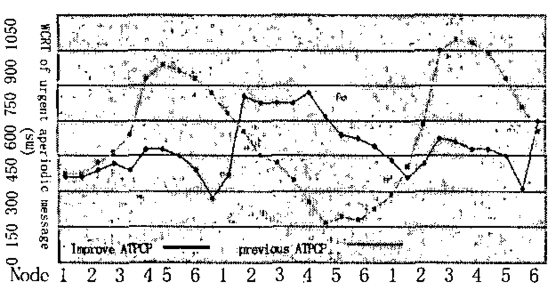

Fig.9 Initial PT priority being Urgent

Table.3 Example set of aperiodic messages

Order of node	1	2	3	4	5	6
Arrival rate (urgent) 1/s	20	30	40	40	30	20
Arrival rate (normal) 1/s	20	30	40	40	30	20

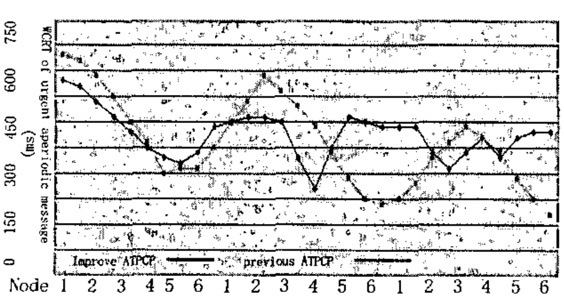

Fig.10 Initial PT priority being Normal

Simulations indicate that IAPTCP can effectively deduce the affect of normal aperiodic message on urgent aperiodic message through early promotion of PT priority. This method prevents simultaneous block of normal aperiodic message on urgent aperiodic message. Besides, these simulations show a powerful result that WCRT of urgent aperiodic message is just fluctuate among a limited region to ISPTCP. That means we truly guarantee requirement of urgent aperiodic message by determining a proper ISPTCP, which can't gotten through initial APTCP.

7 CONCLUSIONS

This paper first synthetically analyzes message transmission procedure and deduces an integrated periodic and aperiodic message model. Then formula of aperiodic message' WCRT is given under four kinds of conditions. Through the formula, the cause of existing mechanism' deficiency is found, that is APTCP counting method. Then an improved counting method and accordingly how to ISPTCP are proposed. At last the improved is validated with simulation.

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