Real-time Performance Analysis for Linear Token Passing Bus Networks

Zhou Qiang, Luo Zhiqiang, Xiong Huagang, Li Qiao
Department of Electronic Engineering,
Beijing University of Aeronautics and Astronautics
Beijing, China 100083
Stonezq_2000@yahoo.com

Abstract

This paper provides a study of the use of linear token passing bus (LTPB) networks to support real-time communication in mission-critical system. According to the exact network timing property, an optimal bandwidth allocation scheme (OLA) for LTPB networks and a real-time performance analysis method based on WCAU(the worst available utilization) are proposed. Formal proof that OLA has better performance than any other schemes is given. Finally examples are presented to demonstrate the correctness of the conclusion.

1. Introduction

The LTPB (Linear Token Passing Bus) protocol is a timed token protocol which has been developed by the Society of Automotive Engineers as a LAN standard (SAE AS4074 [1]), which addresses the requirements of advanced systems in 1990s and beyond, principally avionics systems and also ground-based vehicle and naval vessel systems. It has been used in the advanced aircraft by U.S. army [2]. Because of the critical applications, real-time supports by the LTPB networks are requested in the message transmission. The real-time performance is influenced mainly and directly by the implementation of bandwidth allocation among the nodes in LAN. To ensure the transmission of messages before their deadline with relatively high traffic load, bandwidth must be properly allocated to individual nodes, which has been proved to be a very challenging work.

The LTPB protocol is a timed token protocol. The basic concepts of the timed-token passing networks were proposed by Grow in 1982. In the late of 1980s, Johnson, Ross, Sethi, Pang, Ferguson and other experts studied the basic performances of the protocols in a token ring network-- FDDI. In the beginning of 1990s, a research team of A&M Univ. in Texas U.S., including Agrawal, Kamal, Chen, Malcolm especially, promoted the work. Considering the real-time applications in FDDI, they advanced some performance parameters, such as the Achievable Utilization and the Message Real-Time Guaranteeing Probability, to give some guidelines for the real-time analysis. Dissertation [10] was useful for the full-scale analysis of the real-time LTPB systems.

The conventional allocation schemes, with their own limitations, cannot utilize the bandwidth entirely and efficiently. Therefore, the search for both the proper optimized allocation schemes and their performance evaluations has become one of the mainly aspects in research on real-time network performance recently.

In this paper, after analyzing the network and message models, an optimized allocation scheme – Optimal Local Allocation (OLA), which matches workload, is presented based on scheduling principles. A guideline --the Worst Case Achievable Utilization (W.C.A.U) –is under discussion. Then, it is proven that in term of this guideline the OLA is better than any of previously-published allocation schemes. At the end of this paper, comparisons of these allocation schemes using 4 message sets, along with results from message transmission simulation, are demonstrated.

2. The network and message models

LTPB (Linear Token Passing Bus) employs a timed token passing protocol with multi-priority. Nodes connected to LTPB share a broadcasting medium. In the runtime, the nodes link one by one according to the sequence of their physical addresses and form a logical ring. Only one node can hold the token which then has the right to send messages. When a node releases the token, the token is passed directly to the following node in the ring. The time by which a node can hold the token is limited by its *Token Holding Timers* (THTs) related to the message streams. And in each node there are different *Token Rotation Timers* (TRTs) to determine the

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sending sequence of messages with different priorities. But in this paper we only discuss the transmissions with real-time priority messages.

We assume that there are *n* real-time message streams marked S_1, S_2, $\cdots$, S_n in the LTPB network. These streams form a message set *M*, i.e.:

$$M = \{S_1, S_2, \cdots, S_n\} \qquad (1)$$

We describe the message streams S_i as follows:

- Message inter-arrival time P_i: which is the message S_i generating period, for non periodic message, which represents the minimum inter-arrival of the message.
- Message steam length C_i: which denotes the time for the transmission of steam S_i, including the total length of the protocol-specified fields – information field, check field and preamble.
- We assume that the maximum allowed message delay for S_i is equal to the P_i.

Each message steam S_i may be represented as:

$$S_i = (C_i, P_i) \qquad (2)$$

The utilization factor U_i, representing the load requirement of S_i to the network, is defined as:

$$U_i = C_i / P_i \qquad (3)$$

Hence, the *utilization*, *U*, of a message set M is defined as the sum of the utilization factors of all the streams:

$$U = \sum_{i=1}^{n} U_i \qquad (4)$$

3. The bandwidth allocation schemes and the requirements of real-time transmission

3.1. The general bandwidth allocation scheme

The bandwidth allocation algorithm plays a very important role to meet the real-time constraints of message set. If the message set is under the assumption of formula (1) and (2), in the general sense, we denote by *f* the scheme to decide the THT_i, which can be represented as:

$$\begin{aligned}&(THT_1, THT_2, \cdots, THT_n)\\ &= f(C_1, C_2, \cdots, C_n, P_1, P_2, \cdots, P_n, T_{MR}) \qquad (5)\end{aligned}$$

3.2. The requirements

In order to guarantee message deadlines for the whole message set, the bandwidths allocated to the nodes should satify both *protocol constraint* and *deadline constraint*.

(a) Protocol constraint

T_{MR} is *the maximum expected token rotation time*. The time θ as overhead of propagation delay and empty token rotation considered, the sum of THT_i must meet the following conditions:

$$\sum_{i=1}^{n} THT_i \le T_{MR} - \theta \qquad (6)$$

Where, THT_i denotes the *token holding time* in node *i* and is relevant to the bandwidth assigned for the node.

(b) Deadline constraint

Let $X_i(t)$ be the minimum amount of time available for node *i* to transmit its messages during any time interval of length *t*. It must be ensured that the $X_i(t)$ is long enough for each stream S_i to transmit it during its the maximum allowed message delay P_i. That is:

$$X_i(P_i) \ge C_i \qquad (i=1,2,\ldots,n) \qquad (7)$$

3.3. The conventional bandwidth allocation schemes

Some of the conventional bandwidth allocation schemes are listed below.

- *The full length allocation* (*FLA*) [10] scheme. In this scheme, the node transmits the full length of the message streams that queue in the sending buffer.

$$THT_i = C_i \qquad (8)$$

- *The proportional allocation* (PA) [10] scheme. In this scheme, the usable portion of the token rotation time is divided among the nodes according to the ratio of message lengths C_i to message periods T_i.

$$THT_i = \frac{C_i}{P_i}(T_{MR} - \theta) \qquad (9)$$

- *The normalized proportional allocation* (NPA) [10] schemes. In this scheme, the bandwidths used in the PA scheme are normalized by the total utilization of the synchronous messages:

$$THT_i = \frac{C_i / P_i}{U}(T_{MR} - \theta) \qquad (10)$$

- *The local allocation* (LA) [10] scheme.

$$THT_i = \frac{C_i}{[P_i / T_{MR}] - 1} \qquad (11)$$

4. An optimal bandwidth allocation scheme in LTPB and performance analysis

4.1. An Optimal Local Allocation Scheme

During any time interval of length *t*, the minimum amount of time available for node *i* in LTPB can be represented as :

$$X_i(t) = \begin{cases} 0 & 0 \le t < T_{MR} \\ (m_i - 1)THT_i + \min(THT_i, t - m_i * T_{MR}) & T_{MR} \le t \end{cases} \qquad (12)$$

in the expr. $m_i = [t / T_{MR}]$; $m_i \ge 1$; [•] denotes the operation to get the integer part of a real number [3].

During the period P_i, node *i* must transmit messages which length sum is C_i, while the minimum amount of time available for node *i* is calculated as $X_i(P_i)$. According to the guideline making the transmitting time match the workload C_i, let $X_i(P_i)$ equal to C_i, and then the value of THT_i can be calculated. This algorithm for THT_i is an optimal bandwidth allocation scheme (*OLA*) and its only uses information local to node *i*. See (13):

$$THT_i = \begin{cases} C_i & 0 \le P_i - T_{MR} < THT_i \\ C_i / m_i & P_i - m_i T_{MR} \ge THT_i \\ \dfrac{C_i - (P_i - m_i T_{MR})}{m_i - 1} & P_i - m_i T_{MR} < THT_i \end{cases} \qquad (13)$$

- **Worst case achievable utilization**

If a bandwidth allocation scheme can guarantee the deadlines for the whole message set which utilization factor is no more than U_A, we say that U_A is an achievable utilization of the scheme. The worst case achievable utilization U_A^* of a scheme is the least upper bound of its achievable utilization factors. The *WCAU* is used to evaluate the performance of the schemes. Intuitively, it is preferable to select a scheme with a high U_A^*.

4.2. The real-time performance analysis

We denote by f^* the given allocation scheme *. All kinds of f^* form the set F. For a common bandwidth allocation scheme f^*, the corresponding token holding time is denoted as $THT^*{}_i$ and the minimum amount of sending time available during P_i is $X^*{}_i(P_i)$ (see (12)).

Theorem 1: $\forall f^* \in F$, if f^*'s WCAU is U^*, then for f^{OLA}, the following inequation holds:

$$U^{OLA} \ge U^*.$$

Lemma1: For $\forall M$, we have $X^{LA}{}_i(P_i) \ge C_i$.

Lemma2: For f^{LA}, when $U \le \dfrac{\lfloor P_{\min} / T_{MR} \rfloor - 1}{\lfloor P_{\min} / T_{MR} \rfloor + 1}(1-\alpha), \alpha = \theta / T_{MR}$, the protocol constraint is satisfied.

Theorem 2:If bandwidths are allocated by f^{LA}, the following equation hold $U^{LA} = \dfrac{\lfloor P_{\min} / T_{MR} \rfloor - 1}{\lfloor P_{\min} / T_{MR} \rfloor + 1}(1-\alpha)$, where P_{min} is a lower bound on message period.

Proof: This theorem can be proved by showing that both of the following statements are true.

1) For any message set, $\dfrac{\lfloor P_{\min} / T_{MR} \rfloor - 1}{\lfloor P_{\min} / T_{MR} \rfloor + 1}(1-\alpha)$ is a value of an achievable utilization under the *LA* scheme. This has been proved by Lemma 1 and Lemma 2.
2) For any given real number $\varepsilon > 0$, there at least exists a message set with utilization U, where $U \le \dfrac{\lfloor P_{\min} / T_{MR} \rfloor - 1}{\lfloor P_{\min} / T_{MR} \rfloor + 1}(1-\alpha) + \varepsilon$, and the protocol constraint is violated.

This implies that $\dfrac{\lfloor P_{\min} / T_{MR} \rfloor - 1}{\lfloor P_{\min} / T_{MR} \rfloor + 1}(1+\alpha)$ is the least upper bound of the achievable utilizations[4]. ☐

Corollary:

For f^{OLA},

$$U^{OLA} \ge \frac{\lfloor P_{\min} / T_{MR} \rfloor - 1}{\lfloor P_{\min} / T_{MR} \rfloor + 1}(1-\alpha) \approx \frac{1}{3}(1-\alpha).^{1}$$

Proof: Directly, we can deduce it from Theorem 1 and 2.

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[1] In order to make practical discussions, another presumption $P_i \ge 2T_{MR}$ is added.

For complete proofs of all Theorems and Lemmas, see Appendix.

Theorem 1 proves that the *OLA* scheme is better than any other one under WCAU criterion. Theorem 2 and its Corollary bring out a result of the lower limit of its WCAU. Table 1 is a summary of the bandwidth allocation schemes and shows their performance by comparing their WACUs.

Table 1. Bandwidth allocation

Bandwidth Allocation Scheme	THT_i Allocated By Scheme	$WCAU$
FLA	$THT_i = C_i$	0
PA	$THT_i = \frac{C_i}{P_i}(T_{MR} - \theta)$	0
NPA	$THT_i = \frac{C_i / P_i}{U}(T_{MR} - \theta)$	$\frac{1-\alpha}{3}$ *
LA	$THT_i = \frac{C_i}{\left[P_i / T_{MR}\right] - 1}$	$\frac{1-\alpha}{3}$
OLA	equation（13）	$\geq \frac{1-\alpha}{3}$

* $\alpha = \theta / T_{MR}$

Table 2. Bandwidth allocations for message set M_1

Message Parameters			Bandwidth(THT_i) allocated by				
i	C_i	P_i	PA	FLA	LA	NPA	OLA
1	30	135	11.1	30	30	22.7	15
2	36	135	13.3	36	36	27.2	18
Protocol constraint met?			Y	N	N	Y	Y
Deadline constraint met?			N	Y	Y	Y	Y
Real-time transmission?			N	N	N	Y	Y

Table 3. Bandwidth allocations for message set M_2

Message Parameters			Bandwidth(THT_i) allocated by				
i	C_i	P_i	PA	FLA	LA	NPA	OLA
1	15	85	8.8	15	N/A	22.2	15
2	25	95	13.2	25	N/A	27.7	25
Protocol constraint met?			Y	Y	N/A	Y	Y
Deadline constraint met?			N	Y	N/A	Y	Y
Real-time transmission?			N	Y	N	Y	Y

Table 4. Bandwidth allocations for message set M_3

Message Parameters			Bandwidth(THT_i) allocated by				
i	C_i	P_i	PA	FLA	LA	NPA	OLA
1	46	165	13.9	46	23	23.2	15.5
2	53	165	16.1	53	26.5	26.7	19
Protocol constraint met?			Y	N	Y	Y	Y
Deadline constraint met?			N	Y	Y	Y	Y
Real-time transmission?			N	N	Y	Y	Y

Table 5. Bandwidth allocations for message set M_4

Message Parameters			Bandwidth(THT_i) allocated by				
i	C_i	P_i	PA	FLA	LA	NPA	OLA
1	70	152	23.0	70	35	33.98	34
2	33	152	10.9	33	16.5	16.02	15.5
Protocol constraint met？			Y	N	N	Y	Y
Deadline constraint met？			N	Y	Y	N	Y
Real-time transmission？			N	N	N	N	Y

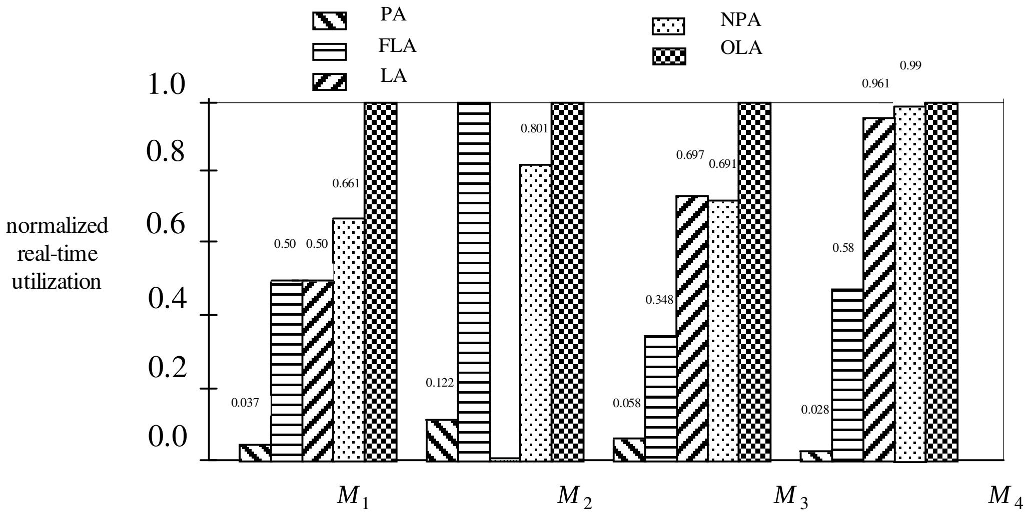

Figure 1：Simulation comparation of five bandwidth allocation schemes

5. Examples and simulation

Four message sets (denoted by M_1, M_2, M_3, M_4) are considered and listed respectively from Table 2 to Table 5. We assume that T_{MR}=50, and $\theta = 0$.The *PA*'s real-time performance is worst, since no real-time transmission can be realized for all four given message sets. Generally speaking, scheme *LA* performs better than either of schemes *FLA* and *PA*. However, exception could happen for some specific message sets. So we find that scheme *FLA* is better than *LA* in Table 3. Among all the 4 tables, only the *OLA* scheme can meet the real-time requirements (protocol constraint and deadline constraint), and is superior to the other schemes , which is consistent with the before-mentioned analysis under WCAU criterion.

Finally, the results of a simulation under these typical massage sets demonstrated the real-time performance comparing among the 5 schemes mentioned above.The goal we pursuit is to utility the real-time bandwidth efficiently and properly. In the simulation, the bandwidth utilization attained by real-time messages (the real-time utilization) is introduced to measure the performance of the schemes. The real-time utilization is defined as the number of the messages that meets the real-time constraints within a time unit. See Figure 1. For analytic convenience, the real-time utilization has been normalized by the value of scheme *OLA*'s . That is, the columns shown in Figure 1 represented the ratio to the value of utilization under scheme *OLA*.

The parameter for simulation has been appointed as : average token rotation time is 50μs. There are 2 nodes in the LTPB; the propagation delay between nodes is zero; the bit rate is 50Mbit/s. The simulation executed for 0.01 seconds.

We can get the conclusion for the diagram consistent with the analysis by theorems.

6. Conclusion

In this paper , an optimal bandwidth allocation scheme, which derived from the principle of matching workload, is addressed. A valid guideline the worst case achievable utilization is employed to evaluate the real-time performance of different schemes. It is notable that this guideline can only used to present the global performance of the schemes where exceptions may occurred for some particular message sets. In addition, it has been shown that the scheme *OLA* performs better than all the others proposed so far. The lower limit of its *WACU* is deduced, while the upper need to research further.

7. Appendix

Theorem 1: $\forall f^* \in F$, if f^*'s WCAU is U^*, then for f^{OLA} , the following inequation holds:

$$U^{OLA} \geq U^*.$$

Proof: according to the definition of U^* , when the utilization $U_1 \leq U^*$, for every message stream set *M*, real-time constraints (see (6)and (7), protocol constraint and deadline constraint) will be satisfied， i.e., $\sum_{i=1}^{n} THT^*{}_i \leq T_{MR} - \theta$ and $X^*{}_i(P_i) \geq C_i$.

Refer to the definition of OLA, we have $X^{OLA}{}_i(P_i) = C_i$ ((7) is satified). So $X^*{}_i(P_i) \geq C_i = X^{OLA}{}_i(P_i)$. Note that $X_i(P_i)$ is a monotone increasing function for THT_i , so there is $THT^*{}_i \geq THT^{OLA}{}_i$.

Further: $\sum_{i=1}^{n} THT^{OLA}{}_i \leq \sum_{i=1}^{n} THT^*{}_i \leq T_{MR} - \theta$ ((6) is satisfied.)We can see that OLA scheme satisfied both protocol constraint and deadline constraint. So U_1 is also OLA's achievable utilization.And according to the definition of U^{OLA}, we can derive the inequality $U^{OLA} \geq U^*$. □

Lemma1: For $\forall M$, we have $X^{LA}{}_i(P_i) \geq C_i$.

Proof: Referring to the definition of LA (see (11)) and (12), we can deduced that

$$X^{LA}{}_i(P_i) = (m_i - 1)THT_i + \min(THT_i, P_i - m_i * T_{MR})$$
$$. \quad \geq (m_i - 1)THT_i = C_i \qquad \square$$

Lemma 2: For f^{LA} , when $U \leq \frac{\lfloor P_{\min}/T_{MR} \rfloor - 1}{\lfloor P_{\min}/T_{MR} \rfloor + 1}(1-\alpha), \alpha = \theta / T_{MR}$, the protocol constraint is satisfied.

Proof: Note that $\frac{[P_i/T_{MR}]-1}{P_i/T_{MR}} > \frac{[P_i/T_{MR}]-1}{[P_i/T_{MR}]+1} \geq \frac{[P_{\min}/T_{MR}]-1}{[P_{\min}/T_{MR}]+1}$ must always hold.

This implies:

$$U \leq \frac{[P_{\min}/T_{MR}]-1}{[P_{\min}/T_{MR}]+1}(1-\alpha) < \frac{[P_i/T_{MR}]-1}{P_i/T_{MR}}(1-\alpha) \tag{14}$$

Let P_j be a period in *M* that minimizes $\frac{\lfloor P_i/T_{MR} \rfloor - 1}{P_i/T_{MR}}$. Clearly, the above inequality (14) still holds for P_j . Substituting $U = \sum_{i=1}^{n} U_i$ and rearranging yields

$$\sum_{i=1}^{n} U_i \frac{P_j/T_{MR}}{[P_j/T_{MR}]-1} < (1-\alpha)$$

And then: $U < \frac{\lfloor P_j/T_{MR} \rfloor - 1}{P_j/T_{MR}}(1-\alpha)$

$$\Rightarrow \quad \sum_{i=1}^{n} U_i < \frac{\lfloor P_j/T_{MR} \rfloor - 1}{P_j/T_{MR}}(1-\alpha)$$

$$\Rightarrow \quad \sum_{i=1}^{n} U_i \frac{P_j/T_{MR}}{[P_j/T_{MR}]-1} < (1-\alpha)$$

$$\Rightarrow \quad \sum_{i=1}^{n} U_i \frac{P_i/T_{MR}}{[P_i/T_{MR}]-1} < (1-\alpha)$$

$$\Rightarrow \quad \sum_{i=1}^{n} \frac{C_i}{[P_i/T_{MR}]-1} < T_{MR} - \theta \ .$$

$$\Rightarrow \quad \sum_{i=1}^{n} THT_i \leq T_{MR} - \theta \ . \square$$

Theorem 2:If bandwidths are allocated by f^{LA} , the following equation hold $U^{LA} = \frac{\lfloor P_{\min}/T_{MR} \rfloor - 1}{\lfloor P_{\min}/T_{MR} \rfloor + 1}(1-\alpha)$, where P_{min} is a lower bound on message period.

Proof: This theorem can be proved by showing that both of the following statements are true. □

3) For any message set, $\frac{\lfloor P_{\min}/T_{MR}\rfloor - 1}{\lfloor P_{\min}/T_{MR}\rfloor + 1}(1-\alpha)$ is a value of an achievable utilization under the *LA* scheme. This has been proved by Lemma 1 and Lemma 2.
4) For any given real number $\varepsilon > 0$, there at least exists a message set with utilization U, where $U \le \frac{\lfloor P_{\min}/T_{MR}\rfloor - 1}{\lfloor P_{\min}/T_{MR}\rfloor + 1}(1-\alpha)+\varepsilon$, and the protocol constraint is violated.

This implies that $\frac{\lfloor P_{\min}/T_{MR}\rfloor - 1}{\lfloor P_{\min}/T_{MR}\rfloor + 1}(1+\alpha)$ is the least upper bound of the achievable utilizations[4]. $\square$

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Author biographies

Zhou Qiang received the B.Sc. in electronic engineering department from Zhengzhou University in 1996.He is directly working towards the Ph.D degree in electronic engineering department at Beijing University of Aeronautics and Astronautics, Beijing, China.

Luo Zhiqiang is a professor in electronic engineering department at
Beijing University of Aeronautics and Astronautics, Beijing, China.

Xiong Huagang is a professor in electronic engineering department at
Beijing University of Aeronautics and Astronautics, Beijing, China.

Li Qiao received the B.Sc. in electronic engineering department from Beijing University of Aeronautics and Astronautics in 1997.He is directly working towards the Ph.D degree in electronic engineering department at Beijing University of Aeronautics and Astronautics, Beijing, China.