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A DUAL TRANSMITTER DISTRIBUTED CONTROL MULTICHANNEL MAP (D^2M^2AP) NETWORK

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Abstract—Increasing the number of channels is one of the solutions to expand the bandwidth of the Manufacturing Automation Protocol (MAP) network. However, increasing transmitters in the implementation of the multichannel MAP network raises costs, system design complication, Electromagnetic Interference (EMI), and power consumption. This paper proposes a scheme that uses only two transmitters to avoid these problems. Moreover, we also derive the expressions to study the average token cycle time and the overhead caused by the reduction of transmitters. Analytic derivation together with simulation results is also presented. Copyright © 1997 Elsevier Science Ltd

Key words: Manufacturing Automation Protocol, token cycle time, Frequency Division Multiplexing.

1. INTRODUCTION

The Manufacturing Automation Protocol (MAP) network is a Local Area Network (LAN), and its lower layer services are defined by IEEE 802.4 standard [1]. Because of the deterministic response and the compatibility with the CATV cable, MAP is usually applied in industrial and real-time systems. In addition, many industrial programmable devices are already token bus-based, and many factories have broadband capabilities installed [2].

The rapid advance of Computer Aided Manufacturing (CAM) has produced bandwidth scarcity for MAP networks, whereas some surplus bandwidth may remain in the cable. Since the bandwidth allocated for a MAP network is only a small fraction of the cable bandwidth, many MAP networks can be simultaneously put into the same cable to expand the system bandwidth. In fact, IEEE 802.4 standard has recommended the frequency channels [1] as shown in Fig. 1, and also suggested the multiple channel assignments for multiple LANs on a single shared broadband medium.

One of the solutions to increase the system bandwidth is to split up all stations into many independent groups, and assign them to different MAP channels. This is not a good solution because it provides no communication between groups. Another solution is the Multichannel MAP (M^2AP) network. In this network, every station is connected to all available channels, and communication between stations through any channel is possible. The physical and logical topologies of M^2AP are shown as in Fig. 2.

There are two mechanisms to implement an M^2AP network. The first one is made of a set of M parallel broadcast channels to which N stations are connected, each one by means of M separate interfaces, one for each channel [3]. Wong and Benny adopts this mechanism in their Multichannel Token Bus Local Area Network [4]. Obviously, the implementation of this mechanism is very simple, but it is not efficient for the interface duplication. In addition, a large number of interface cards may go beyond the station's interface capability. To overcome this shortcoming, a second mechanism proposed in this paper integrates these interfaces into one. Without causing too much loss in performance, it reduces the number of transmitters and minimizes the token-handling circuits. Evidently, M transmitters are needed for every station in the M^2AP network, because there are M tokens simultaneously in circulation. However, transmitters without tokens are idle, hence transmitters can be shared. In addition, the reduction in the number of transmitters also means a reduction in cost, in system design complication, in Electromagnetic Interference (EMI), and in power consumption. Therefore, reducing the number of transmitters in a station of the M^2AP network is a worthy study topic.

Using a Frequency Division Multiplexing (FDM) scheme [5], a stable and correct carrier frequency can be obtained from a Programmable Frequency Synthesizer (PFS). The PFS is

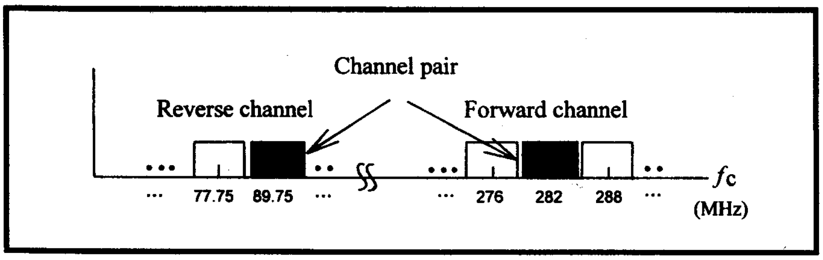

Fig. 1. Channel pairs recommended by IEEE standard 802.4.

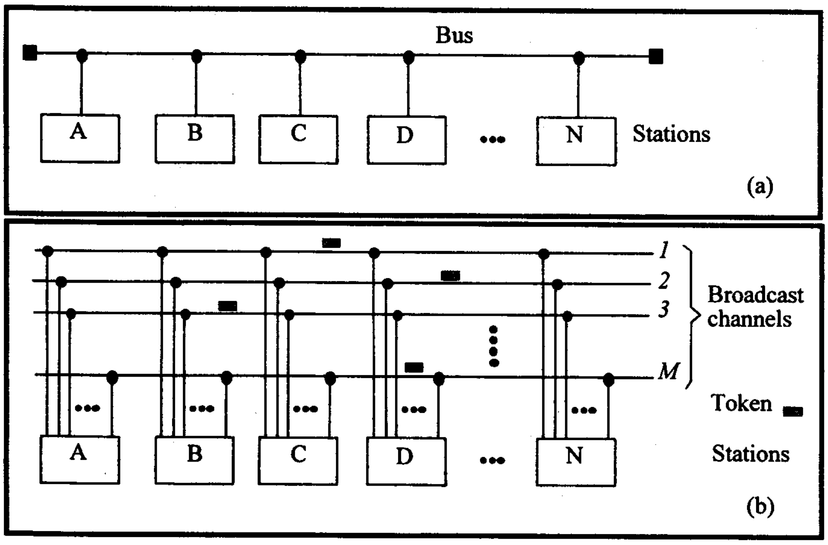

Fig. 2. (a) The physical topology of M^2AP network. (b) The logical topology of M^2AP network.

composed of a Phase-locked Loop (PLL) and a precise *crystal oscillator* as shown in Fig. 3. Presently, a PFS is generally produced as a single chip device, and its output frequency can be precisely controlled by a program.

Theoretically, the minimum number of transmitters needed to operate in an M^2AP station is one. However, it might not work in a multichannel system. Because in the M^2AP network, there are several kinds of MAC frames used for channel maintenance, and most of them have a time constraint. In addition, the size of data frame for this network can be as long as 8191 octets; it is much bigger than the MAC frame size of 14 octets. Therefore, MAC frames in a one transmitter station will possibly lose their validity when they are queued behind a data frame. Having this consideration in mind, we use a dedicated transmitter to handle MAC frames and a transmitter for data frames, so the minimum number of transmitters in a station is two. An M^2AP network

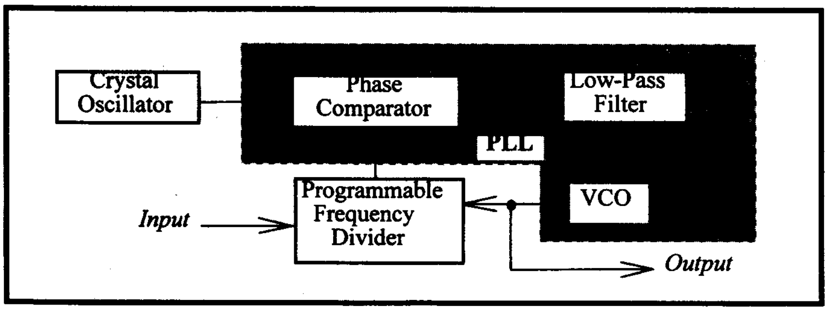

Fig. 3. The programmable frequency synthesizer (PFS).

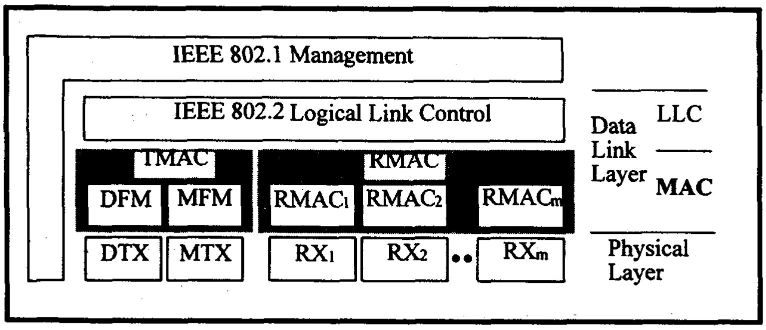

Fig. 4. The model of D^2M^2AP network.

that uses two transmitters in a station is called a Dual transmitter Distributed control Multichannel Manufacturing Automation Protocol (D^2M^2AP) network. In this paper, we will study its architecture, operation, and performance.

Section 2 discusses the model of D^2M^2AP network. Afterward, the architecture, that is built according to this model, and its operations are described. The network performance is analyzed in Section 3. For validating the analysis, the simulation results are also presented in this section. Finally, the conclusions are given in the same section.

2. D^2M^2AP NETWORK

The D^2M^2AP network is one of M^2AP networks. Therefore, its physical topology and logical topology are the same as in Fig. 2. Those channels can be obtained by dividing the bandwidth of a single physical bus, and they consequently provide a high total bandwidth for this network.

The IEEE 802.4 model is designed only for a single channel network. To make it operate correctly in the D^2M^2AP network, the MAC layer is broken into one *Transmitting MAC* (TMAC) sublayer and several *Received MAC* (RMAC) sublayers as shown in Fig. 4. The task of RMAC sublayers is to identify the Frame Kind (FK), and to insert the received data frame into one of Received Queues (RQ) according to its frame priority. The duty of the TMAC sublayer is to manage all contentions produced by the RMAC sublayers, and to carry out the original MAC protocol. TMAC consists of a Data Frame Manager (DFM) and a MAC Frame Manager (MFM). The responsibility of DFM is to remove data frames from Transmitting Queue (TQ) when the DFM has a token, and send them out through the Data Transmitter (DTX). The task of MFM is to arbitrate the contention from the RMACs, to accomplish the protocol for channel maintenance and to assign one of tokens to DFM. However, these modifications are transparent to the Logical Link Control (LLC) layer. In other words, the upper layer of D^2M^2AP network is the same as the upper layer of the MAP network.

The function block diagram of D^2M^2AP station designed according to the model of Fig. 4 is shown in Fig. 5. When a frame arrives from channel i, Receiver (RX) i passes it to the RMAC i, then the RMAC i will identify the frame kind. This frame will be inserted into one of the RQs according to its priority if it is a data frame; otherwise, it will be inserted to the MFM queue.

There are many independent channels in the D^2M^2AP network, so it is possible that many MAC frames from different RMAC are in the same MFM queue. Since MAC frame has a time constrain, its queued delay should be taken into account. According to IEEE 802.4 standard, certain MAC frames that require an immediate response should be answered within a response window. The response window is one slot time long; it is approximately equal to two transmission path delays plus two station delays. Because of the MFM queue time, the station delay may be lengthened in the D^2M^2AP network, and the response window should be consequently increased in this network. However, the response window is only used in channel maintenance, hence its effect on the performance of network is negligible.

Only one token is permitted to enter the DFM at a time. Therefore, contention may happen when many tokens arrive simultaneously at a station, and this is called the 'Token-overlap'. The Token Assignment Strategy (TAS) for solving this contention has been discussed in [6]. It showed that the Limit-1 strategy and the Reject Later Token (RLT) scheme are the best among the TAS's for this network. In the RLT scheme, if the number of tokens possessed by a station reaches a value that the system permits, then all following tokens will be rejected and will be bypassed to the next station immediately. With Limit-1 strategy, no token is permitted to stay in the token queue. Hence, the station picks up the first arrived token, and bypass all other tokens to increase the network throughput.

In order to increase system performance, MFM will first process the token frame from DFM, if any. Then, the MFM picks up a MAC frame from the head of the MFM queue and identifies its FK. If it is a token frame, then it is inserted into the token queue according to the token assignment strategy. Other frames will be processed by the MFM in conformance to the IEEE 802.4 standard. The response of MAC frame will be passed to the MAC Transmitter (MTX); in the same time, the channel ID is also sent to the PFS for selecting carrier frequency. The operation of DFM is similar to the data transmission manager in the MAP network. DFM retrieves the data frame from one of the TQs, and passes it to the DTX; in the same time DFM also sends the channel ID to the PFS. The channel ID is determined from the token ID.

3. PERFORMANCE

Because of the reduction in TMAC and in the number of transmitters, the performance of a D^2M^2AP network should be affected. In a MAP network, only stations that hold tokens are permitted to use the channel, hence the message delay is proportional to the Token Cycle Time (TCT). Their relation can be found in (2) and (4) of [2]. Moreover, the message delay is generally regarded as an index for measuring the network performance, hence the network performance can be evaluated by studying the TCT. In order to analyze the TCT in detail, an analytical model of this network is created as shown in Fig. 6. Here are some assumptions and notations:

3.1. *Assumptions*

1. There are M channels in the network, and every channel has its own independent token.
2. All channels possess the same characteristics, and they use a protocol that conforms to the IEEE 802.4 standard.

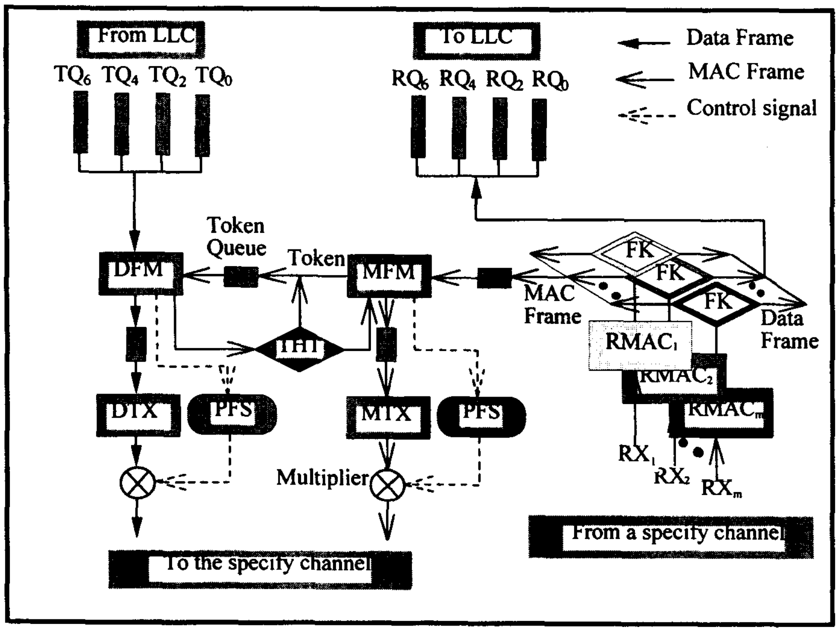

Fig. 5. The flow chart of different kind frames operating in a D^2M^2AP station.

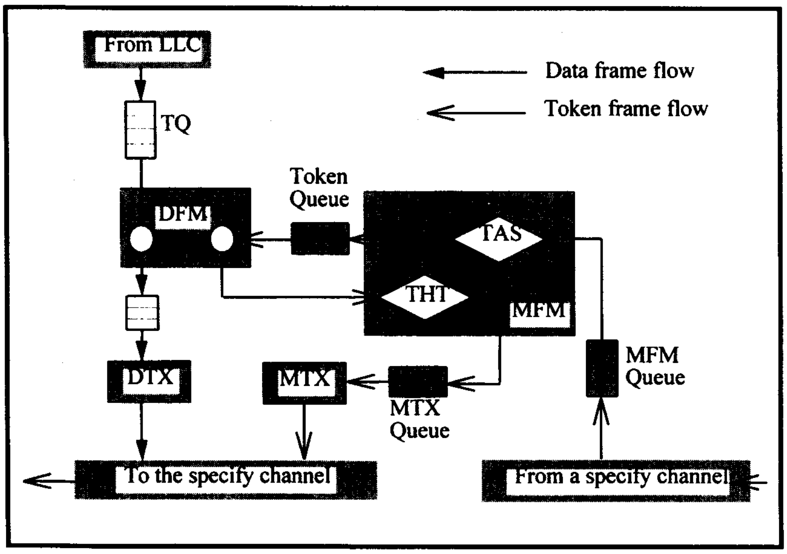

Fig. 6. The analytical model of the D^{2}M^{2}AP network.

3. There are N permanent stations in the network, and every station uses the same operation model as shown in Fig. 2.
4. The arrival of messages at each station is an independent Poisson process with the same mean.
5. The message serving time or the token passing time is an exponentially distributed random variable.
6. All stations set their Token-holding Time (THT) to 200 μs. THT is a limit that a token is allowed to stay in a station.
7. The network is robust, hence the overhead of protocol management is negligible.
8. The delay in MFM for processing a token is 0.66 μs that is shorter than the delay in the MTX for passing a token.
9. The mean delay time in MTX for passing token is 10 μs and has an exponential distribution.

4. NOTATIONS

λ ≡ Message arrival rate of the network.
$\bar{c}$ ≡ Average token cycle time.
$\bar{w}$ ≡ Average token-passing time.
$\bar{q}_{\mathrm{TK}}$ ≡ Average number of tokens in the token queue.
$\bar{q}_{\mathrm{FM}}$ ≡ Average number of tokens in the MFM and in the MFM queue.
$\bar{q}_{\mathrm{MT}}$ ≡ Average number of tokens in the MTX and in the MTX queue.
$\bar{x}_{\mathrm{dt}}$ ≡ Average message service time in the DFM.
$\bar{x}_{\mathrm{FM}}$ ≡ Average token processing time in the MFM.
$\bar{x}_{\mathrm{MT}}$ ≡ Average token processing time in the MTX.
$\bar{t}_{\mathrm{q}}$ ≡ Average total token queueing time in a station.
ρ ≡ Utilization factor of each channel $\equiv (\lambda\bar{x}_{\mathrm{dt}})/M$.
l ≡ Average number of message arrivals to a station per channel in a token cycle.
$E(W)$ ≡ Average message delay.

4.1. *Analysis*

The token cycle time is defined as the time interval between a token's departure from a particular station and the same token's next departure from that station. In the D^{2}M^{2}AP network, the TCT is the total time that token is in passing, in service, and waiting in queue. There are three kinds of token queueing time in the D^{2}M^{2}AP network as shown in Fig. 6. They are the time spent in the MFM queue, in the token queue, and in the MTX queue. A tandem queue is consequently made up. Therefore, the token cycle time $\bar{c}$ can be expressed as:

$$\bar{c} = \sum_{i=1}^{N} \text{average passing time} + \sum_{i=1}^{N} \text{average service time} + \sum_{i=1}^{N} \text{average queueing time} . \qquad (1)$$

The first term is the sum of all average token-passing time $\bar{w}$ in a token cycle. The second term is the sum of average service time in all stations. The third component is the sum of average token queueing time in all stations.

While the network approaches to saturation, the sum of average service time and average queueing time in a station is almost equal to the THT. In this case, there are few contentions because all tokens are operating almost in synchronization, hence the token queueing time is approaching zero. In addition, the service discipline of token bus network is nonpreemptive, hence the message transmission is not interrupted when its THT expires. Taking this into consideration, the average excess token holding time is equal to $\text{THT} + \bar{y}(\text{THT})$; and $\bar{y}(\text{THT}) = \bar{x}_{\text{dt}}\ [1 + M(\text{THT})] - \text{THT}$ has been derived by Yue and Brooks in [2], where $M(\text{THT})$ is a renewal function. In this case, (1) becomes

$$\bar{c} = N\bar{w} + N \cdot [\text{THT} + \bar{y}(\text{THT})] . \qquad (2)$$

From Fig. 6, a token in MFM may be rejected because of the TAS. Here we use $(1 - p_\lambda)$ to indicate the rejection probability under the arrival rate λ. Therefore, (1) becomes

$$\begin{aligned}\bar{c} = p_\lambda[\sum_{i=1}^{N} \bar{w}_i + \sum_{i=1}^{N} (l \cdot \bar{x}_{\text{dt}})_i + \sum_{i=1}^{N} (\bar{q}_{\text{FM}}\bar{x}_{\text{FM}} + \bar{q}_{\text{TK}}\bar{x}_{\text{dt}} + \bar{q}_{\text{MT}}\bar{x}_{\text{MT}})_i] + (1 - p_\lambda)[\sum_{i=1}^{N} \bar{w}_i + \sum_{i=1}^{N} \\ \times (\bar{q}_{\text{FM}}\bar{x}_{\text{FM}} + \bar{q}_{\text{MT}}\bar{x}_{\text{MT}})_i] = p_\lambda[N\bar{w} + N(l \cdot \bar{x}_{\text{dt}}) + N(\bar{q}_{\text{FM}}\bar{x}_{\text{FM}} + \bar{q}_{\text{TK}}\bar{x}_{\text{dt}} + \bar{q}_{\text{MT}}\bar{x}_{\text{MT}})] \\ + (1 - p_\lambda)[N\bar{w} + N(\bar{q}_{\text{FM}}\bar{x}_{\text{FM}} + \bar{q}_{\text{MT}}\bar{x}_{\text{MT}})] = N[\bar{w} + p_\lambda(l \cdot \bar{x}_{\text{dt}} + \bar{q}_{\text{TK}}\bar{x}_{\text{dt}}) + \bar{q}_{\text{FM}}\bar{x}_{\text{FM}} + \bar{q}_{\text{MT}}\bar{x}_{\text{MT}}] . \qquad (3)\end{aligned}$$

Before saturation, the arrival rate of a station is λ/ N, and the average number of arrivals to a station during a token cycle is

$$l = \frac{\lambda\bar{c}}{N} . \qquad (4)$$

These arrivals will be served by $p_\lambda \cdot M$ tokens in a token cycle. In other words, an accepted token should serve $\lambda\bar{c} \ / \ p_\lambda\ MN$ arrivals. Substituting it to (3), we have

$$\begin{aligned}\bar{c} &= N(\bar{w} + p_\lambda \cdot (\lambda\bar{c}/p_\lambda MN) \cdot \bar{x}_{\text{dt}} + \bar{q}_{\text{FM}} \cdot \bar{x}_{\text{FM}} + p_\lambda \cdot q_{\text{TK}} \cdot \bar{x}_{\text{dt}} + \bar{q}_{\text{MT}} \cdot \bar{x}_{\text{MT}}) \\ &= N(\bar{w} + \lambda\bar{x}_{\text{dt}}\bar{c}/MN + \bar{q}_{\text{FM}} \cdot \bar{x}_{\text{FM}} + p_\lambda \cdot \bar{q}_{\text{TK}} \cdot \bar{x}_{\text{dt}} + \bar{q}_{\text{MT}} \cdot \bar{x}_{\text{MT}}) . \qquad (5)\end{aligned}$$

In addition $\rho = \lambda\bar{x}_{\text{dt}}$, then the $\bar{c}$ can be expressed as

$$\begin{aligned}\bar{c} &= p_\lambda \cdot (\rho/M) \cdot \bar{c} + N(\bar{w} + \bar{q}_{\text{FM}} \cdot \bar{x}_{\text{FM}} + p_\lambda \cdot \bar{q}_{\text{TK}} \cdot \bar{x}_{\text{dt}} + \bar{q}_{\text{MT}} \cdot \bar{x}_{\text{MT}}) \\ &= \frac{N(\bar{w} + \bar{q}_{\text{FM}} \cdot \bar{x}_{\text{FM}} + p_\lambda \cdot \bar{q}_{\text{TK}} \cdot \bar{x}_{\text{dt}} + \bar{q}_{\text{MT}} \cdot \bar{x}_{\text{MT}}}{1 - p_\lambda \cdot (\rho/M)} . \qquad (6)\end{aligned}$$

By assumption 7, there are no MAC frames in the D^2M^2AP network besides token frame. Therefore, the maximum number of the MAC frames in a station is M. In addition, since the Limit-1 strategy and the RLT scheme are used in this study, there is no token in the token queue, i.e. $\bar{q}_{\text{TK}} = 0$. Substituting it to (6) yields

$$\bar{c} = \frac{N(\bar{w} + \bar{q}_{\text{FM}} \cdot \bar{x}_{\text{FM}} + \bar{q}_{\text{MT}}\bar{x}_{\text{MT}})}{1 - p_\lambda \cdot (\rho/M)} . \qquad (7)$$

Because the token processing in MFM and in MTX can be done concurrently, the time that a token queued in a station can be reduced. Their relations are shown in Fig. 7. For the case of $\bar{x}_{\text{FM}} < \bar{x}_{\text{MT}}$, tokens should wait not only in the MFM queue, but also in the MTX queue. Since tokens in MFM and in MTX are concurrently processed, the equivalent processing time that a token spends in the

MTX queue is $(\bar{x}_{\mathrm{MT}} - \bar{x}_{\mathrm{FM}})$ for each token ahead of it. The average token queueing time can be expressed as

$$\begin{aligned}\bar{t}_{\mathrm{q}} &= (\text{queueing time } + \text{ processing time})_{\mathrm{MFM}} + (\text{queueing time } + \text{ processing time})_{\mathrm{MTX}} \\ &= [(\bar{q}_{\mathrm{FM}} - 1)\cdot\bar{x}_{\mathrm{FM}} + \bar{x}_{\mathrm{FM}}] + [(\bar{q}_{\mathrm{MT}} - 1)\cdot(\bar{x}_{\mathrm{MT}} - \bar{x}_{\mathrm{FM}}) + \bar{x}_{\mathrm{MT}}] = (\bar{q}_{\mathrm{FM}} - \bar{q}_{\mathrm{MT}} + 1)\cdot\bar{x}_{\mathrm{FM}} + \bar{q}_{\mathrm{MT}}\cdot\bar{x}_{\mathrm{MT}},\end{aligned}$$

when $\bar{x}_{\mathrm{FM}} < \bar{x}_{\mathrm{MT}}$. (8)

In the case of $\bar{x}_{\mathrm{FM}} \geq \bar{x}_{\mathrm{MT}}$, every token from the MFM will be immediately processed by the MTX, hence there is no token waiting in the MTX queue. The average queueing time of a token in a station can be expressed as

$$\begin{aligned}\bar{t}_{\mathrm{q}} &= (\text{queueing time} + \text{processing time})_{\mathrm{MFM}} + (\text{queueing time} + \text{processing time})_{\mathrm{MTX}} \\ &= [(\bar{q}_{\mathrm{FM}} - 1)\cdot\bar{x}_{\mathrm{FM}} + \bar{x}_{\mathrm{FM}}] + [0 + \bar{x}_{\mathrm{MT}}] = \bar{q}_{\mathrm{FM}}\cdot\bar{x}_{\mathrm{FM}} + \bar{x}_{\mathrm{MT}}, \text{ when } \bar{x}_{\mathrm{FM}} \geq \bar{x}_{\mathrm{MT}}. \qquad (9)\end{aligned}$$

Therefore, the average token cycle time can be rewritten as

$$\bar{c} = \frac{N(\bar{w} + \bar{t}_{\mathrm{q}})}{1 - \rho/M}, \quad \text{where } \bar{t}_{\mathrm{q}} = \begin{cases} \bar{q}_{\mathrm{FM}} - \bar{q}_{\mathrm{MT}} + 1)\cdot\bar{x}_{\mathrm{FM}} + \bar{q}_{\mathrm{MT}}\cdot\bar{x}_{\mathrm{MT}}, & \text{when } \bar{x}_{\mathrm{FM}} < \bar{x}_{\mathrm{MT}} \\ \bar{q}_{\mathrm{FM}}\cdot\bar{x}_{\mathrm{FM}} + \bar{x}_{\mathrm{MT}}, & \text{when } \bar{x}_{\mathrm{FM}} \geq \bar{x}_{\mathrm{MT}} \end{cases} \qquad (10)$$

A similar result was presented in [2].

To verify the above derivation, a CACI SIMSCRIPT II.5 program was written to simulate token operations in the D^{2}M^{2}AP network. To validate this program, we follow the simulation parameters used in [2] as below and set $M = 1$ and $\bar{x}_{\mathrm{FM}} = 0$. The $\bar{x}_{\mathrm{FM}}$, is set to zero because the delay of MFM is ignored in [2].

- Bus capacity $= 10$ Mbits/s
- Number of network nodes $N = 10$
- Number of network channels $M = 1$–5
- Token holding time THT $= 200$ μs
- Average message service time of DFM $\bar{x}_{\mathrm{dt}} = 0.1$ ms
- Average token-passing time $\bar{w} = 10$ μs

The results are then compared with the values published in [2]; they show good agreement. Afterward, we reset $\bar{x}_{\mathrm{FM}}$ to 660 ns and run this program for $M = 2$–5. Statistics of each simulation

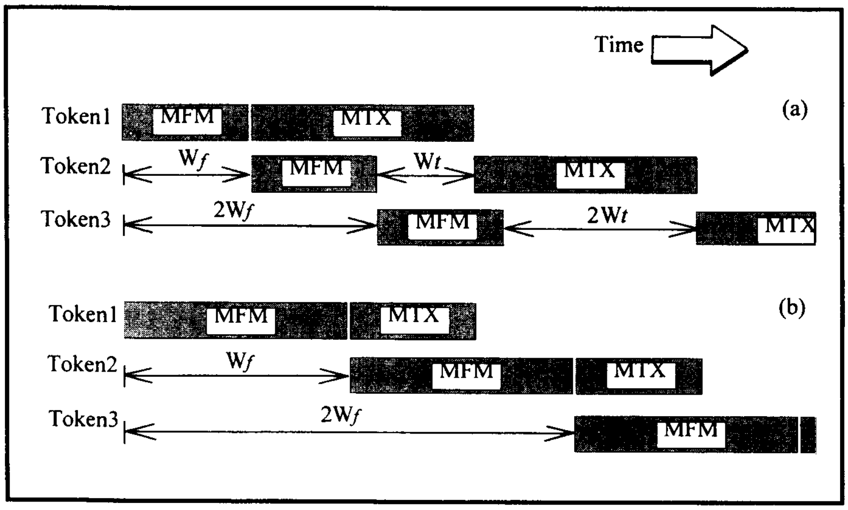

Fig. 7. The processing time and the waiting time of three tokens in MFM and MTX in a D^{2}M^{2}AP station with (a) $\bar{x}_{\mathrm{FM}} < \bar{x}_{\mathrm{MT}}$ and (b) $\bar{x}_{\mathrm{FM}} \geq \bar{x}_{\mathrm{MT}}$. ($Wf = \bar{x}_{\mathrm{FM}}$, $Wt = \bar{x}_{\mathrm{MT}} - \bar{x}_{\mathrm{FM}}$.)

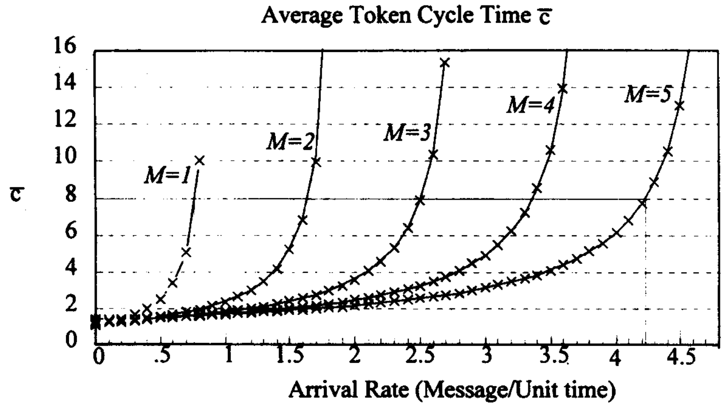

Fig. 8. The average token cycle time vs. arrival rate for the D^2M^2AP network.

are obtained from at least 20,000 transmitted messages, and they fall in 95% confidence interval. The values of $\bar{q}_{FM}$ and $\bar{q}_{MT}$ obtained from simulation are substituted into (10). The simulation result and the values calculated from (10) are shown in Fig. 8. All time values are normalized to $\bar{x}_{dt}$. In this figure, the simulation results are represented by the symbols, and the calculated values are represented by solid lines. As we can see, their differences are small. From Fig. 8, it is not difficult to see that the D^2M^2AP network does expand the processing capacity by increasing the number of channels. For example, the network maintains $\bar{c}$ at 0.8 ms when the λ is increased from 0.75 to 4.21 by increasing the M from 1 to 5.

For reducing the number of transmitters in a D^2M^2AP station, how many overheads should be paid? From (8) and (9), it can be predicted that the overhead is lighter when $\bar{x}_{FM} < \bar{x}_{MT}$ than when $\bar{x}_{FM} \geq \bar{x}_{MT}$. In order to understand this overhead, another simulation program was written for the M^2AP network according to the model shown in Fig. 6 except that the number of MTX is set to M. In this model, tokens from MFM will be immediately processed by their respective MTX without any delay.

By executing these two programs, their average message delay $E(W)$ for $\lambda =$ 0.5, 1.5, 2.5, 3.5, and 4.5 are obtained and are shown in Table 1 and in Fig. 9. At $\lambda = 0.5$, the $E(W)$ in $M = 5$ divides that in $M = 1$ is 8.192 for M^2AP and 6.210 for D^2M^2AP. Therefore, the overhead for reducing the number of transmitters from five to two is 24.2% for $\lambda = 0.5$, 17.1% for $\lambda = 1.5$, 11.4% for $\lambda = 2.5$, 7.4% for $\lambda = 3.5$, and 5.2% for $\lambda = 4.5$. Though the relative overhead in the D^2M^2AP network is higher when the network load (or λ) is light, however, the heavy load performance is more important in general applications. In addition, D^2M^2AP makes the network expansion easier because it only requires the addition of receivers.

5. CONCLUSION

D^2M^2AP is a multichannel MAP network that uses only two transmitters regardless of the number of channels. The reduction in the number of transmitters will reduce the cost, the Electromagnetic Interference (EMI), the system design complication, and the power consumption. By deriving the expression of token cycle time, we have proved that the network performance does grow with the number of channels. Since only two transmitters are used in this network, some

Table 1. The average message delay of two networks

			M^2AP					D^2M^2AP		
	$M = 1$	$M = 2$	$M = 3$	$M = 4$	$M = 5$	$M = 1$	$M = 2$	$M = 3$	$M = 4$	$M = 5$
$\lambda = 0.5$	2.130	0.613	0.390	0.305	0.260	2.130	0.657	0.461	0.389	0.343
$\lambda = 1.5$	∞	3.427	0.941	0.593	0.475	∞	3.481	1.004	0.682	0.573
$\lambda = 2.5$	∞	∞	4.677	1.283	0.837	∞	∞	4.803	1.384	0.945
$\lambda = 3.5$	∞	∞	∞	6.382	1.730	∞	∞	∞	6.683	1.869
$\lambda = 4.5$	∞	∞	∞	∞	9.640	∞	∞	∞	∞	10.172

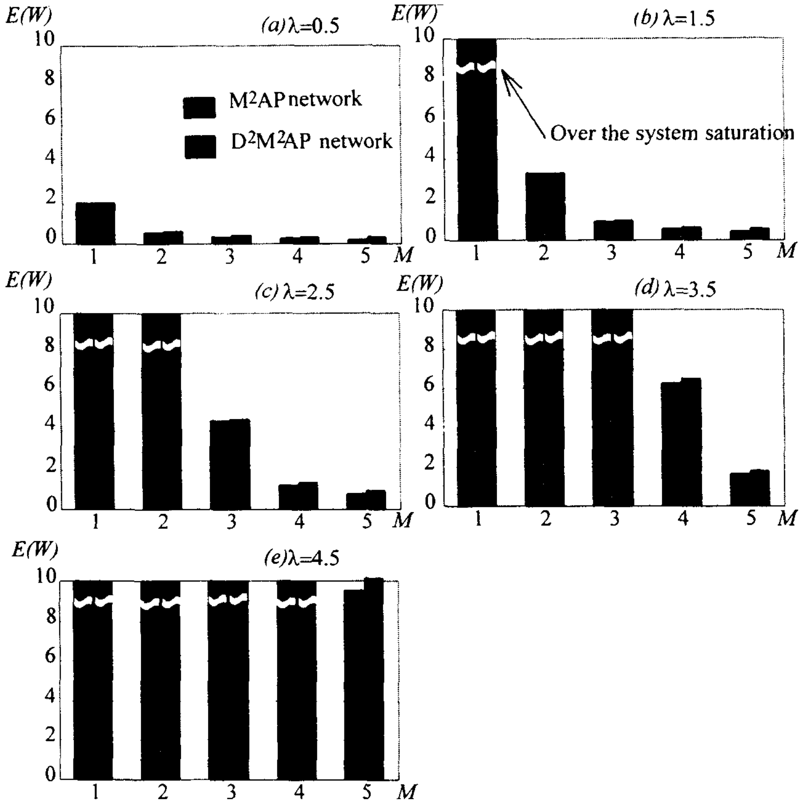

Fig. 9. The average message delay of two networks in $M = 1$–5 for (a)$\lambda = 0.5$, (b)$\lambda = 1.5$, (c)$\lambda = 2.5$, (d)$\lambda = 3.5$ and (e)$\lambda = 4.5$.

overheads are produced. However, the overhead is less than 10% in our study when the network load is heavy. Therefore, the D^2M^2AP network is a practical solution for the multichannel MAP network.

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