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Analysis of Several Digital Network Technologies for Hard Real-time Communications in Nuclear Plant

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Abstract

Applying digital network technology for advanced nuclear plant requires deterministic communication for tight safety requirements, timely and reliable data delivery for operation-critical and mission-critical characteristics of nuclear plant. Communication protocols, such as IEEE 802/4 Token Bus, IEEE 802/5 Token Ring, FDDI, and ARCnet, which have deterministic communication capability are partially applied to several nuclear power plants. Although digital communication technologies have many advantages, it is necessary to consider the noise immunity from electromagnetic interference (EMI), electrical interference, impulse noise, and heat noise before selecting specific digital network technology for nuclear plant. In this paper, we consider the token frame loss and data frame loss rate due to the link error event, frame size, and link data rate in different protocols, and evaluate the possibility of failure to meet the hard real-time requirement in nuclear plant.

Key Words : network, protocols, frame loss rate, link error

1. Introduction

Advanced nuclear plant such as SMART is a typical responsive and hard real-time process system fully utilizing advanced digital technology. One of the main features of the future generation nuclear plant is coordinating safety reactor control, balance of plant, subsystem utilities, and plant monitoring functions to improve plant performance and guarantee safety requirements.

Table 1. An Example of Sampling Periods for Safety and Nonsafety System Field Devices

Type	Function	Sampling period
Safety	Control	20ms
	Monitoring	20ms
Nonsafety	Control	100ms
	Information processing	500ms

Thus future generation advanced nuclear plants are envisioned to require communications between various distributed control elements, sensors, data acquisition systems, information processing systems, servo-actuators, on/off actuators and plant display devices[1].

The distributed processing and monitoring characteristic imposes performance and functionality requirements on the implemented network to guarantee the timely and reliable delivery of messages for safety-critical and mission-critical systems. Both mission-critical and safety-critical reactor operational functions are crucial for establishing computer communication system requirements in future generation nuclear plant, of which data rate and induced delays are most important. Dynamics of reactor control and related subsystem are highly sensitive to delays. An example of data rate and sampling intervals for devices in nuclear plant are shown in Table 1.

As shown in Table 1, data rates of safety related signal is 50 samples per second, and a maximum delay of 20*ms* can be considered as representative design criteria for stability and command augmentation functions. On the other hand, messages for nonsafety information processing system may be relatively less sensitive to delays but are generated with high data rate. Some of the possible network protocols for nuclear power plant can be classified as Table 2 according to plant system level.

Table 2. Possible Network Protocols for Nuclear Power Plant

Level	Possible protocol
Plant network	FDDI or Ethernet
Group controller	Ethernet(nonsafety) Token bus(safety)
Local controller	Token bus, Fieldbus

Some documents show that Ethernet can used for nonsafety information transmission[1]. Ethernet has probabilistic communication characteristic and is impossible to predict the network access delay. Therefore, we focus time critical group controller and plant network level with advanced distributed control facilities where deterministic communication is required.

Applying digital network technology may concentrate information flows to limited network facilities and result in network delays such as queuing delay, processing delay, transmission delay and propagation delay. Contrary to the concept of a dedicated bus that serves limited number of reactor control critical functions, distributed control systems (DCSs) in future generation nuclear plant would be subjected to the randomly varying network-induced delays, in addition to the sampling time and data processing delays that are inherent in digital control systems. Futhermore, the DCSs could be subjected to recurrent loss of data due to noise corruption in the communication medium and malfunction of the network protocol. Therefore, timely arrival of transmitted data from the source (eg. sensor terminal) to the destination (eg. controller) is not acquired all times.

To guarantee timely and reliable transmission of messages, the digital network communication

Table 3. Applied Network Protocols for Nuclear Power Plant

	Type of protocol			
	ARCnet	Token Bus	Token Ring	FDDI
MAC protocol	Token passing	Token passing	Token passing	Token passing
Topology	Bus, Star or Mixed Bus and star	Bus	Ring	Ring
Transmission medium	Coaxial cable, STP, Optical fiber	STP	Coaxial cable	Optical fiber Copper
Encoding type	Baseband Phase coherent FSK	Baseband Phase coherent FSK	Differential Manchester	4b/5b, NRZI
Predictability	Deterministic	Deterministic	Deterministic	Deterministic
Applied nuclear power plant	France N4 (NERVIA, CONNET) AP600 (WESTNET II) NUPLEX 80+ (ARCnet)		AP600 (HICS, WESTNET III-FDDI)	

characteristic for nuclear plant is recommended to have deterministic capability[2]. Among several local area communication protocols that provide deterministic communication capability, such as IEEE 802/4 Token Bus, IEEE 802/5 Token Ring, FDDI, ARCnet, SCRAMnet and PERFORMNet are applied to several nuclear and fossil power plants[3, 4]. Also, potentially viable protocols for DCSs networks in advanced nuclear plant include MIL-STD-1553B, FDDI, token bus, token ring, and ARCnet. Some of these protocols are applied to nuclear power plants as shown in Table 3.

As shown in Table 3, most deterministic communication methods use separate token and data frame to arbitrate multiple access nodes for common network transmission medium. Although the arbitration schemes are not same, it is crucial to receive correct token and data frame to provide timely delivery of information with deadline in any protocol.

Although digital communication technologies have many advantages, it is necessary to consider the noise immunity from EMI, electrical interference, impulse noise, thermal noise and crosstalk noise. Unlike data like control communication scheme which usually uses one-to-one or one-to-many data link channels, if multiplexing technology is used for advanced future nuclear power plant, it is very important to consider these noise effects for reliable and hard real-time deadline specific nuclear plant operation. When token or data frame loss event occurs, the network does either retransmit or recover process and this causes further network delays and fails to meet the hard real-time requirement in nuclear plant operation.

Therefore, in this paper we first consider the link error event, frame size, and data rate in several protocols, and then evaluate their effects to the token frame loss and data frame loss. Also, we calculate data and token frame loss rate in several commercial opearting nuclear power plants and give some recommendations to selecting protocols for nuclear plant.

2. Data and Token Frame Loss Rate Evaluation in Deterministic Digital Network Protocols

Errors due to several noise sources can cause receiver to misjudge the received signal level and may be interpreted as opposite to the source information. For example, if a signal level is misinterpreted as "1" instead of "0" which was source' s intended information this may cause to be interpreted as token frame loss or unintended errors in data frame.

With this sequel, token frame loss in token passing protocol occurs when receiver does not recognize a token frame due to some errors in token frame. If a token frame loss occurs, token will be regenerated or sometimes ring initialization mechanism may be invoked according to protocols and thus network delay will be increased in addition to prefixed deterministic access time.

2.1 Token Ring

The encoding scheme of IEEE 802/4 token ring is differential Manchester and coded 1 bit information makes two pluses signal. Thus, either "0" and "1" is determined by comparing adjacent signal' s polarity. When there are errors in there two pulses, the correct determination of each information will be failed. Therefore, it is necessary to consider two times of coded bit for calculating the token or frame error due to link error event.

The token ring frame structure is shown in Figure 1, and has 48 code bits in a token frame. Detailed descriptions of each field of the frame are given in appendix.

If we consider the code bit error probability in a link as p, and link transmission speed as B, then the mean time to link error in a ring is MT(*mean time before error*)=$\frac{1}{pB}$. Also, if we consider the

SD (1)	AC (1)	ED (1)

Fig. 1. Token Ring Frame Structure Modes of *FFC* and *FFS* Sectorial Plates

token ring network has a bypass switch, and N nodes are connected to this bypass switch to compose a ring, then the mean time to failure will be $MT_{ring} = \frac{N}{pB}$ [5].

Token rotates whole ring to provide access for each node, it is necessary no code bit error just before the first bit of starting delimiter (SD). Thus the error probability P^T_{token} for one token rotation time is similar to FDDI as in [6],

$$P^T_{token} = 1-(1-p)^{(F^T_{token}+1)}N \simeq F^T_{token}pN \qquad (1)$$

where, N is the number of nodes to a ring and F^T_{token} is the size of token frame in token ring protocol. If a coaxial cable which has error event probability as 5.0×10^{-9} is used in token ring protocol, the token frame loss rate will be about 6.125×10^{-3}%. If the ring is in idle state, token will rotate continuously and the mean time to token frame loss will be

$$MT^T_{idle\ loss} = \frac{D_{ring}}{F^T_{token}pN} \qquad (2)$$

In Eqn. (2), D_{ring} is the token rotation time without carrying any data frame and can be computer with $D_{ring} = L_{ring} \times T_{prop} + N_{max} \times T_{node}$ where, L_{ring}, T_{prop}, N_{max}, and T_{node} stands for ring length, signal propagation time in a medium, maximum number of node and 1bit delay for processing in each node respectively.

Thus, if 250 nodes compose a ring with evenly distributed in a 10*km* ring and medium propagation speed of 5μsec/*Km* is used for 10*Mbps* token ring, this network has 0.75*ms* D_{ring} time. Therefore, the mean time to token frame loss is 125 seconds, and

SD (1)	AC (1)	FC (1)	DA (6)	SA (6)	Data(5000)	FCS (4)	ED (1)	FS (1)

Fig. 2. Token Ring Data Frame Format

Parameter	Value
Maximum number of nodes	500 stations (Link number is 1,000 for dual ring)
Maximum ring length	200Km (100km for a single ring)

(a) FDDI organization characteristics

SD (2)	FC (2)	ED (2)

(b) FDDI token frame format

SD (2)	FC (2)	DA(12)	SA(12)	Information(<4500)	FCS(8)	ED(1)	FS (1)

Fig. 3. FDDI Parameters

network overhead will be experienced every 2 minutes due to token frame loss.

Meanwhile, the data frame error may be resulted in every code bit error of the data frame and the data frame structure is described in Figure 2.

Let' s define the total size of data frame to be F^T_{data}. It is also required no code bit error just before the first bit of starting delimiter. Then the probability of no error in $F^T_{data}+1$ code bit as shown in [6],

P(*no error* in $F^T_{data}+1$) = $P^T_{data} = (1-p)^{N(F^T_{data}+1)}$
and if $pNF^T_{data} \ll 1$ then, the data frame loss rate is defined as

$$P^T_{data} = 1-(1-p)^{N(F^T_{data}+1)} \simeq pNF^T_{data}. \tag{3}$$

And the mean time to data frame loss is minimized when every nodes in the ring continuously transmit messages. Thus the number of generated frame per second under all nodes send message is B/F^T_{data} and the error frame per second is $(B/F^T_{data})[1-(1-p)^{N(F^T_{data}+1)}]$. Finally, the mean time to data frame loss is

$$MT^T_{data} = \frac{1}{(B/F^T_{data})[1-(1-p)^{N(F^T_{data}+1)}]} \simeq \frac{1}{BpN} \tag{4}$$

Thus, B=10*Mbps*, N=250, $p=5\times10^{-9}$ token ring may experience data frame loss rate of 5.021% with maximum frame size. The mean time to data frame loss is 80*ms*.

2.2. FDDI

Fiber Distributed Data Interface (FDDI) is based on token ring protocol to speed up by several applying several modifications on token ring protocol. Thus, the analysis method is not so different as in a token ring protocol. The token and date frame parameters are described in Figure 3.

The encoding scheme adapted in FDDI is 4b/5b and 4 bit data is encoded into 5bits code bits. That means 100*Mbps* data rate implies that 125*Mbps* code bit data transmission speed with 85% channel efficiency. The fiber optic cable used in FDDI is assumed as its noise event probability to be 2.5×10^{-10} and is specified in the standard[7]. As Jain[6] described, the maximum data frame loss rate is 1.13%, mean time to frame loss is 32*ms*, token frame loss rate is 7.75×10^{-4}%, and mean time to token frame loss is 223.6sec in idle ring condition. These calculations are based on the maximum specification conditions as shown in Fig. 3.

2.3. Token Bus

IEEE 802/4 token bus protocol uses coaxial

SD (1)	FC (1)	DA (6)	SA (6)	FCS (4)	ED (1)

(a) Token frame of IEEE 802/4

SD (1)	FC (1)	DA (6)	SA (6)	Data(<8191)	FCS(4)	ED(1)

(b) Data frame of IEEE 802/4

Fig. 4. EEE 802/4 Token Bus Protocol Frame Structure

cable as a transmission medium and baseband, broadband or carrier band which is a modified baseband digital transmission technique is used[8]. In baseband modulation, digital pulse is transmitted and transmission rate is possible up to 10*Mbps*. In carrier band modulation, binary '1' signal is assigned to a frequency and '0' is assigned to the other frequency that is two times of '1' signal. and these signals are modulated by phase-coherent frequency shift keying (FSK) method. Thus the receiver filters these two frequencies and determines either '1' or '0' according to detected frequency.

In case of baseband, noise can corrupt signals to be misjudge and modulated signals need correct timing for correct recovery of transmitted signals. If modulated signals is affected by noise and different frequency is detected during a bit time, it is impossible to decode modulated signals correctly and thus gives bit error in receiver. Therefore, it is necessary to predict the frame loss in a token bus protocol by assuming these two points.

Token bus protocol passes token to right next descendant node in sequence to hand over the medium access right, it can be assumed as a logical ring in physical bus topology. But, every frame is broadcasted to every other nodes, the error analysis approach is different from that of ring topology.

The token frame error can calculated using token frame structure. Figure 4 shows the token frame structure of IEEE 802/4 protocol. A token has its own address and logical neighbor node address to pass the permission to send data and other field required for token frame integrity. When the token is passed to logically descendant node, all active node should not misjudge to consider itself as a legal receiver of token except logically descendant node. Therefore, error in address field should be prevent and token frame loss must be avoided. Also, the token bus protocol encodes data bit into code bit, we can derive token frame error rate from Equation (1) as in (5).

$$P^B_{\text{token}} = 1-(1-p)^{(F^B_{\text{token}}+1)N_{active}} \simeq F^B_{\text{token}}\, p N_{active} \tag{5}$$

where, N_{active} is the number of active nodes, F^B_{token} is the size of token frame in token bus protocol. Thus, if $N_{active} = 250$ and coaxial cable is used, the token frame loss rate will be about $1.91 \times 10^{-2}\%$. To derive the mean time to token frame loss under no active node transmits any message, only the token are passed by each node there are N_{active} number of token is generated. Thus, similar to Eqn. (2) the mean time to token frame loss is

$$MT^B_{\text{token}} = N_{active} \times \frac{D_{bus\ slot\ time}}{(F^B_{\text{token}}+1)pN_{active}} = \frac{D_{bus\ slot\ time}}{(F^B_{\text{token}}+1)p} \tag{6}$$

where, bus slot time $D_{bus\ slot\ time}$ is defined as

$$D_{bus\ slot\ time} = 2 \times (T_{prop} + MAC_{process}) + \tau_{sm} \tag{7}$$

and T_{prop} is bus propagation time and $MAC_{process}$ medium access control(MAC) layer processing time in each node and τ_{sm} is safety margin of bus protocol. Suppose an 10 *Km* bus topology with 5 repeaters and MC68824 $MAC_{processor}$ is used, then the $MAC_{process}$ is 20.9μsec[9], safety margin is assumed as 100μsec, then the $D_{bus\ slot\ time}$ is 0.24*ms* and mean time to token frame loss becomes as

313.7 sec.

The data frame loss rate, P^B_{data}, can be derived from Eqn. (3) and (5) with token bus data frame size and is given $P^B_{data} \simeq pN_{active}F^B_{data}$. Also the mean time to data frame loss can be computed using Eqn. (4) and resulted in $MT^B_{data} \simeq \frac{1}{BpN_{active}}$. When B=10$Mbps$, N_{active} = 250, p=5×10^{-9} is given parameters for a token bus protocol, the frame error rate is up to 8.21% with frame size of 8,210 octet and mean time to data frame loss is around 80ms.

2.4. ARCnet

ARCnet(Attached Resource Computer NET work) is a token passing LAN architecture and is implemented either bus or start topology and complex distributed star with branched network. Transmission medium of ARCnet is coaxial cable and fiber optic cable and shield twisted pair cable are also used. ARCnet protocol has 5 different frames and the frame consists of an 11 bits sequence:ONE+ONE+ZERO+8bits characters[10]. As a result, the network throughput is actually 1.8$Mbps$ and it's efficiency is 72.7%. The ARCnet frame structures are shown in Figure 5.

With these frames, ARCnet operates as follows:

① When a node receive a token, it can either play by initiating transmit sequence or pass by sending the Invitation to Transmit to another node.

② If transmission is desired, the source issues a FBE to the intended destination to confirm its ability to accept a message. Either ACK or NACK is returned.

③ If an ACK is received from a FBE, a packet is transmitted. Upon reception, the destination node verifies the CRC, and send an ACK if the data passes the CRC.

④ If the data fails the CRC, the destination node is silent, signaling the transmission node that the transmission failed, and that the transmission must be re-attempted the next time that the node holds the token.

We can compute the token and data frame loss rate of ARCnet considering these operation and IEEE 802/4 token bus structure. For simplicity, we assume that the transmission medium is coaxial cable and 255 nodes are evenly distributed in 4Km bus topology and its data rate is 2.5$Mbps$.

To initiate the message transmission, it is necessary not to loss the ITT and FBE frames. Thus, we need to calculate the error probability by this assumption and the token frame loss rate is given as $P^T_{ARCnet} \simeq 2 \times 34pN_{active}$ and is 8.67×10^{-3}%. Also, if we assume the ARCnet bus slot time as 0.105ms[10], the mean time to token frame loss is 35.2 sec from Eqn. (6). The data frame loss rate can be computed from $P^B_{data} \cong pN_{active}F^B_{data}$ as in Token bus with ARCnet data frame size, and resulted error percentage is 0.526% under B=2.5$Mbps$, N_{active} =255, p= 5×10^{-9} condition, the mean time to data frame loss is 313.72ms.

3. Token and Frame Loss Effects to Hard Real-time Requirement

Some of the errors in token and data frame may be detected through physical layer and upper layers. For FDDI, as is in [6], about 34% of data error can be detected in physical layer and 47% is undetected errors and 17% of errors may be detected according to their control symbols.

Therefore, the undetected errors may result in token and frame loss to receiver and retransmission or other recovery mechanism should be invoked and further network delay will be added in turn. With this in mind, we calculate possible token and data frame loss rate in several nuclear power plants using derived equations and the results are given in Table 4.

With 150 octet data field, the N4 data

SD (2)	FC (2)	ED (2)

(a) Invitation To Transmit (ITT)

SD (2)	FC (2)	ED (2)

(b) Free Buffer Enquiry (FBE)

SHO(1)	SID(1)	DID(1)	DID(1)	Count(2)	Data(508)	CRC(1)	CRC(1)

(c) Packet

ACK (1)

(d) ACK and NACK (NACK and ACK have the same formats)

Fig. 5. ARCnet Frame Structure

communication network may loss token and data frame above 2%. From this information, we may expect that large network delay happen to handle these losses and will affect to whole system. As described in section 2, most of the token and data frame loss rate are function of number of active node, link error event probability, token and data frame size, and ring latency. Therefore, we need to limit the number of node to a network and limit data field size to manage token and data frame loss rate under specific requirements.

Frame loss can be prevented with detect mechanism such as CRC, but some undetectable error should be considered to meet the regulatory requirement of bit error probability being less than 10^{-9}[2]. In reliable real-time systems such as safety control system, the timing requirement is set to 20*ms* and possible retransmission due to frame loss may cause to fail periodic update of status data. Thus, one of the resolution is to provide specialized space-redundant architecture for data networks in nuclear plant. Although multiple digital networks are costly and complex this is one of the best solutions.

However, dual networks need complex coincident back up systems and regular test and check-up schedule, it is necessary to design network and protocols to be better fault tolerant and less frame loss scheme. Conventional local area networks have been designed for data communication which time network throughput is emphasized rather than timely delivery and reliable communication, conventional technologies should be modified for high reliable and real-time communication for nuclear plant. Field Bus or miniMAP which only use limited layers of OSI 7 layers scheme could be an example required improvement. These problems are open problems for safety-critical digital network technology application for advanced nuclear plant.

4. Conclusions

Continuity of services and determinism in transmission delay are specially required in fault-tolerant and real-time nuclear plant' s control and monitoring system. Since OSI 7 layer scheme was initially targeted maximum throughputs instead of timely delivery of network traffic and thus, current OSI 7 layer based digital network technologies need to be modified.

Also, it is required to use fiber optic for transmission medium to prevent EMI and minimize other noises effect. As shown in Table 4, frame error rate can be reduced using fiber optic cable, and limiting other factors, such as number of node to a network, frame size, and ring latency. If conventional digital technology is directly applied to nuclear plant without any modification, it is recommendable to use FDDI because of its proven dual ring reliability, and lower data and token frame loss rate. Although ARCnet has lower data frame loss rate than FDDI, its data rate is about 10% of FDDI. Thus, it is not recommendable for backbone network where several systems'

Table 4. Possible Frame Error Rate in Several Operating Nuclear Power Plant

	Nuclear power plant				
	NUPLEX 80+	N4		AP600	
Adopted protocol (Name of network)	ARCnet (Indication and Alarm system)	Token passing (NERVIA)	Token passing (CONNET)	Token passing (WEST NET II)	FDDI (WEST NET III)
Topology	Bus, star/Mixed of bus and star	Bus	Bus	Ring	Ring
Transmission medium	Coaxial cable STP Fiber optic	STP *	Coaxial cable	Fiber optic	Fiber optic
Data rate (Mbps)	10+	2.5	1	10	100
Number of Nodes	<255+	<30	20	254	>300
Token error rate	0.00867%	2.28%	0.01%	0.0015%	0.036%
Data frame error rate	0.2215%†	2.415%†	0.012%†	0.0662%†	0.0996%†

* Link bit error rate=5.0 times 10^{-6}[11], +Assumed as coaxial cable, † Data field size is 150 octets

multiplexed data are concentrated, but could be used for intra-system network where less traffic volume is processed.

Appendix : abbreviations

SD : Starting delimiter
AC : Access control
ED : Ending delimiter
FC : Frame control
DA : Destination address
SA : Source address
FCS : Frame check sequence
FS : Frame status
DID : Destination node ID
SID : Source node ID
CRC : Check redundancy code
ACK : Acknowledgement
NACK : No Acknowledgement

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