Time Delay Oriented Reliability Analysis of Avionics Full Duplex Switched Ethernet

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Abstract—**Besides the hardware/software failure of switched Ethernet, the capability of data transmission affects its performance and reliability. After summarizing the influence factors of Ethernet service capability, this paper focuses on the time delay oriented reliability model and analysis method. Based on the operational mechanism analysis of Avionics Full Duplex Switched Ethernet (AFDX), this paper emphasizes on the main factors that affect the data transmission capability, viz. the traffic shaping delay and scheduling delay. With the token bucket principle, this paper carries out the traffic shaping to decrease the sudden traffic disturbance. Based on First Come First Service (FCFS) strategy, this paper provides the appropriate service and controls the multiple virtual links in real time. Combining the traffic shaping delay and adjustment delay to traditional reliability model, this paper establishes the integrated reliability model to evaluate the reliability of AFDX.**

Keywords—traffic shaping; traffic adjustment; time delay oriented reliability; integrated reliability evaluation

I. INTRODUCTION

In order to keep the reliable communication among the avionic sub-systems and realize the real time control, Avionics Full Duplex Switched Ethernet (AFDX) is widely used to guarantee the reliable operation even in some failure occurring. With the redundant switchboards, buses and terminals, the avionic system could carry out data transmission reliable even in some failure happening through detecting the failures, carrying out the active switching and adjusting the information resources. Directing to the absolutely reliable data transmission requirement, the most important issue is the data transmission reliability when hardware and software are reliable enough.

The earliest researcher on network reliability is based on topology structure [1], in which only the hardware and software failures could affect the reliability. With the increasing of component reliability, Beaudry [2] and Meyer [3] discovered that the communication capability also influences the performance-related network reliability with data integrity and real-time function. In 1982, the classical Poisson model was used to describe the network traffic and capture its short range dependent [4]-[6] while it was not easy to depict system actual traffic characteristic accurately. In 1993, S. Patra and P. B. Misra utilized the maximum traffic and minimum cut theory to calculate the traffic reliability of network [7]. Over past decades, the Poisson distribution is a popular traffic distribution while Leland discovered that the traffic distribution submitted to the self similarity, which leads to the more heavy time delay of data transmission [8]. Although increasing the bandwidth and cache size could improve the data transmission performance, it also can accumulate the maximum cluster. With the network calculus, we could get the exact the data transmission requirement and service regulation with time delay parameters. In order to keep high quality of service, Ashok Erramilli discovered the network traffic is variable in 2007 [9] and the performance-related reliability model is not suitable to the reliability evaluation for AFDX.

In the design of AFDX, the enough bandwidth and scale buffer ensure never lose the data packet, but the service waiting due to data transmission delay also can influence the network capability. Directing to the bottlenecks of time delay of AFDX, this paper analyzes the influence factors that cause time delay from node to node under limited bandwidth and special dispatching strategy. Then establish its reliability model and realize the reliability evaluation for AFTDX.

The rest of this paper is organized as follows. The time delay analysis is illustrated in section II. The reliability model is established in section III. Section V gives the integrated reliability evaluation considering the component failures and data transmission time delay. The application indicates that the proposed model and method is content.

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II. TIME DELAY ANALYSIS OF AFDX

A. *Structure of AFDX*

Fig.1 shows the structure of AFDX, in which sub-system failure, switchboard failure, link failure and service performance degradation (throughput, time delay etc.) could lead to the AFDX unsafe. It is necessary to analyze the failure mechanism and its sensitive factors that influence the reliability and safety.

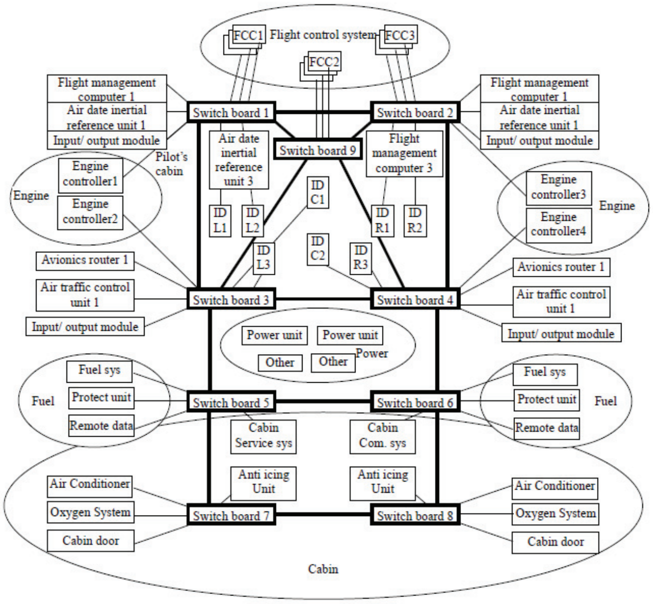

Fig. 1. The typical structure of AFDX

Fig. 1 shows the strong region management and high fault tolerant capability with redundant switch boards and subsystems in AFDX. For example, the engine control command could be transmitted to engine through switch board 3 to switch board 9 when engine controller 1 fails. Once one switcher fails, the other switchers will take charge of this subsystem's data transmission requirement by AFDX fault reconstruction strategy. Meanwhile, the protocol can perform frame filtering, traffic control and data routing. In order to control the data transmission delay, AFDX adopts the credit token bucket control method in every virtual link to assure skew time of the data controlled in special range. So AFDX can realize the real-time failure tolerance and reconfiguration management.

B. *Time Delay Analysis of AFDX*

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The time delay between nodes to nodes plays an important role in AFDX, which influence the real-time performance directly. Although AFDX adopts full duplex and virtual link technology can improve the Ethernet performance with good real time, its switched strategy of single node transmission while other nodes waiting will make time delay.

There are many factors that lead to time delay. Define the time delay between nodes to nodes as

$$T_{delay} = T_{dest} - T_{src} \tag{1}$$

Where T_{src} is the time of sending data at source node; T_{dest} is the time of receiving data at destination node.

According to the data transmission process, there are three kinds of time delay shown in Fig.2, viz. channel delay, traffic shaping delay and traffic adjustment delay.

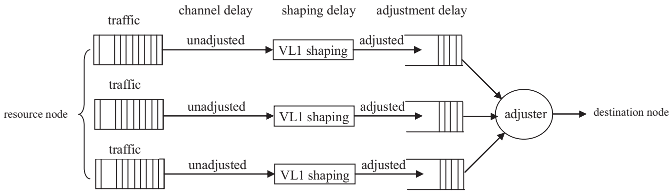

Fig. 2. Time delay composition of multiple virtual link

In Fig.2, the channel delay includes the frame transmission delay and link transmission delay. The frame transmission delay expresses the time from the first type to the last type. The link transmission delay means the time form resource node to switcher link or form switcher to destination node, which depends on the link length and data transmission rate.

The delay of switchboard transmitting data frame consists of exchanging delay, transmitting delay, traffic shaping delay and traffic adjustment delay, in which the first two delays depend on the network composition. Due to access traffic of switchboard is full of sudden traffic, how to shape the sudden traffic and stable traffic appropriately could influence the time delay of network. The token bucket principle is a popular method to shape the traffic, which can be considered as a G/M/1 queuing model. With queuing model, we could calculate the traffic shaping delay T_Z .

The traffic adjustment delay is the maximum delay in real-time control. When the data flow after shaping is entered into the adjuster, no service requirement lines up and is waiting for service when multiple data packet visit same port. The network calculus will be used to calculate the maximum traffic adjustment delay T_D .

Compare with the other factors, the traffic shaping delay is related to the switchboard characteristics and traffic shaping strategy, while the real time adjustment depends on the access traffic, service capability and traffic control method, so the T_Z and T_D are the main factors that can be modified through appropriate design and compensation.

Base on the fixed AFDX, the time delay from node to node can be described as

$$T_{delay} = T_{dest} - T_{src} = T_Z + T_D \quad (2)$$

C. Influence factor Analysis of Time Delay

Because the time delay of AFDX consists of T_Z and T_D, it is necessary to analyze their influence factors shown in Fig.3.

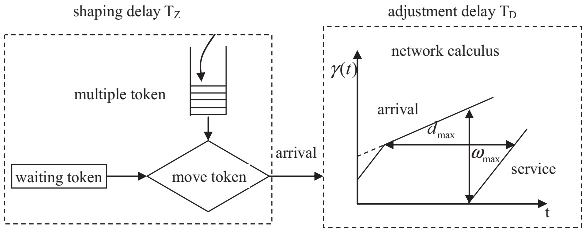

Fig. 3. The influence factors of time delay for AFDX

- The influence of T_Z

Different data traffic characteristic causes different time delay. Suppose the access traffic of switchboard includes sudden traffic s_u and stable traffic s_s, the traffic model can described as

$$f(t) = \begin{cases} a \times e^{-b \times t} + c, 0 < M \le R \\ \frac{1}{\pi}\left[\frac{\gamma}{(t-t_0)^2 + \gamma^2}\right], M > R \end{cases} \quad (3)$$

where sudden traffic s_u submit to the modified exponential distribution, in which a, b, c are parameters; stable traffic s_s obey to the Cauchy distribution, in which t_0 is the location parameter, γ is the scale parameters; M is network traffic; R is optimal threshold that can separate the sudden traffic s_u and stable traffic s_s.The selection of a, b, c, γ, t_0 can influence the T_Z.

- The influence of T_D

In AFDX, the multiple data packets visit same port at the same time, so it is difficult to avoid the queuing after the data flow shaping. In order to guarantee the real time capability, it is necessary to adjust the data in limit buffer. The influence factors of traffic adjustment include:

1) Arrival curve

Different data transmission requirement arrival influence service response, so the arrival curve leads to the time delay.

2) Service curve

The service curve affects the network input and output, the maximum service delay is related to the distance between input and output.

3) Adjustment strategy

To the switchboard, there are three kinds of types: First Come First Service (FCFS), General multiplexer and Local First Come First Service. Different strategy has different time delay.

Besides the above factors, the average length of data frame, the number of workstation, the bandwidth of Ethernet and topology structure of AFDX.

III. QUEUING MODEL OF T_Z BASED ON G/M/1

A. Time Delay Mechanism Based on G/M/1

From the point of queuing theory, data transmission process can be described as a customer-service model with fixed capacity shown in Fig.4.

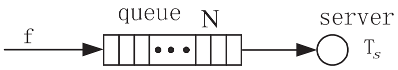

Fig. 4. Queuing model of network

The network traffic arrives service station with transmission rate f, then waits for transmission. Suppose the average transmission time is T_S and the capacity is N, the data will stay at buffer waiting for transmission when the service unit is not enough. The later data will be thrown away when the number is larger than fixed capability. At this time, the network congestion happens. This process can be described with four factors as follows:

1) Network service application arrival

Generally, the service application arrives one by one or group by group, whose arrival distribution submits to the Poisson distribution and its arrival time interval obeys to the exponential distribution.

2) Service rules of queuing

The common service rules of queuing consist of First Come First Served (FCFS), Last Come First Served (LCFS) and Random Selecting Service (RSS). If we don't consider the Quality of Service (QoS), the normal service regulation tacitly agrees to FCFS.

3) Service law

The node provides the service one by one. Since the service time is totally different with the different service requirement. Define the service time as a random variable, the service law often submit to the exponential distribution.

4) Queuing length

The buffer of node is limit, so the data transmission congestion will occur when the queuing is too long.

B. T_Z Calculation Based on Token Bucket Algorithm

Suppose the arrival time interval submit to the normal distribution $P(t), (t \ge 0)$:

$$p(t) = p(s_u) \times p(t \mid s_u) + p(s_s) \times p(t \mid s_s) \quad (4)$$

where $P(t)$ is the probability distribution when the average arrival time interval is less than t, which considers the sudden traffic s_u and stable traffic s_s. $p(t \mid s_u)$ expresses the conditional probability under sudden traffic s_u, which leads to the s_u at next time interval or the s_s at next time interval. $p(t \mid s_s)$ is similar.

Suppose the s_u submits Cauchy distribution and traffic s_s obeys to the exponential distribution, the traffic distribution of network can be described as

$$p(s_s \le t) = \int_0^t (a \times e^{-b \times x} + c)dx = -\frac{a}{b}e^{-bt} + ct + \frac{a}{b} \tag{5}$$

$$p(s_u \le t) = \int_0^t (\frac{1}{\pi}\left[\frac{\gamma}{(x-t_0)^2+\gamma^2}\right])dx = \frac{1}{\pi}\arctan(\frac{t-t_0}{\gamma}) + \frac{1}{2} \tag{6}$$

If the average service rate of link submits to the exponential distribution with parameter μ as follows:

$$G(t) = 1 - e^{-\mu t}, t \ge 0 \tag{7}$$

To G/M/1 queuing, the customer waiting time distribution when the system achieve balance can be described as:

$$F_{T_Z^i}(t) = P(T_Z^i < t) = \begin{cases} 0, t < 0 \\ 1 - \sigma e^{-\mu(1-\sigma)t}, t \ge 0 \end{cases} \tag{8}$$

where:

$$\sigma = \int_0^\infty e^{-(\mu - \sigma\mu)t} dP(t) = \int_0^\infty e^{-(\mu-\sigma\mu)t} p(t)dt \tag{9}$$

Combine above equation, the distribution of network can be described as

$$\begin{aligned} p(t) &= (-\frac{a}{b}e^{-bt} + ct + \frac{a}{b}) \times (\frac{1}{2} - \frac{1}{\pi}\arctan(\frac{t-t_0}{\gamma})) \\ &\quad + (\frac{1}{\pi}\arctan(\frac{t-t_0}{\gamma}) + \frac{1}{2}) \times (1 + \frac{a}{b}e^{-bt} - ct - \frac{a}{b}) \\ &= \frac{1}{2} \times (-\frac{a}{b}e^{-bt} + ct + \frac{a}{b}) - \frac{1}{\pi}\arctan(\frac{t-t_0}{\gamma}) \times (-\frac{a}{b}e^{-bt} + ct + \frac{a}{b}) \\ &\quad + \frac{1}{\pi}\arctan(\frac{t-t_0}{\gamma}) \times (1 + \frac{a}{b}e^{-bt} - ct - \frac{a}{b}) + \frac{1}{2} \times (1 + \frac{a}{b}e^{-bt} - ct - \frac{a}{b}) \\ &= \frac{1}{\pi}\arctan(\frac{t-t_0}{\gamma}) \times (1 + \frac{2a}{b}e^{-bt} - 2ct - \frac{2a}{b}) + \frac{1}{2} \end{aligned} \tag{10}$$

So the σ can be described as

$$\begin{aligned} \sigma &= \int_0^\infty e^{-(\mu-\sigma\mu)t} dP(t) = \int_0^\infty e^{-(\mu-\sigma\mu)t} p(t)dt \\ &= \int_0^\infty e^{-(\mu-\sigma\mu)t} \times (\frac{1}{\pi}\arctan(\frac{t-t_0}{\gamma}) \times (1 + \frac{2a}{b}e^{-bt} - 2ct - \frac{2a}{b}) + \frac{1}{2})dt \end{aligned} \tag{11}$$

Based on the collected data, we can get the parameters of Cauchy distribution with the least squares method, viz. t_0=1.12, γ=0.31, a=1.0772, b=0.2852, c=0.1496.

According to the configuration of AFDX, the average service rate is $\mu = \omega / 8\ell$, in which ω is the bandwidth of link and ℓ is the service requirement length. If AFDX consists of N_0 virtual links, the service rate of the i*th* link can be described as

$$\mu_i = \frac{\mu}{N_0} = \frac{\omega}{8 \times \ell \times N_0} \tag{12}$$

Select ℓ=512byte, ω=10 $Mbps$ and N_0=30, then we could get $\sigma = 0.7135$, then

$$F_{T_Z^i}(t) = P(T_Z^i < t) = \begin{cases} 0, t < 0 \\ 1 - \sigma e^{-\frac{C}{8 \times \ell \times N_0} \times (1-\sigma)t}, t \ge 0 \end{cases} \tag{13}$$

C. T_D Calculation Based on Network Calculus

In AFDX, an important issue is how to calculate the network time delay. Cruz presented a network calculus algorithm based on Min-Plus Algebra to analyze the time delay [10].

- The traffic access curve $\alpha(t)$

Define the access curve as

$$\{x(t) - x(s)\} \le \alpha(t - s) \tag{14}$$

where α is the access curve when time $s \le t$, $x(t)$ is the input of data traffic. Generally, the AFDX utilizes the virtual link to mark the data flow, in which the bandwidth BAG and the maximum frame length $L_{\max}$ can describe the arrival curve as

$$\alpha(t) = \frac{L_{\max}}{BAG}t + L_{\max} \tag{15}$$

- The service curve $\beta(t)$

Define the service curve as

$$y(t) - x(t_0) \ge \beta(t - t_0) \tag{16}$$

Where $y(t)$ is the output of data traffic, $x(t_0)$ is the input of data traffic at time t_0. Suppose the total service capability is R, the total service curve provided for the data flow is

$$\beta(t) = R(t-0)^+ \tag{17}$$

where:

$$(t-0)^+ = \begin{cases} t - 0, t > 0 \\ 0, t \le 0 \end{cases} \tag{18}$$

- Amount of hysteresis $\omega_{\max}$

The backlog of data traffic is determined by the vertical distance between arrival cure and service curve.

- The maximum time delay $d_{\max}$

The maximum time delay can be calculated by the horizontal distance between arrival curve and service curve.

Suppose there are N(t) data traffic into the adjuster that are VL_1, VL_2, …, VL_{N}, the total arrival curve can be described as

$$A(t) = \sum_{i=1}^{N} a_i(t) = \sum_{i=1}^{N} (\frac{L_{\max}^i}{BAG}t + L_{\max}^i) \tag{19}$$

The network time delay under the N-1 data traffic can be described as

$$\begin{aligned} A(t)-a_i(t) &= \sum_{i=1}^{N} a_i(t)-a_i(t) \\ &= (\sum_{i=1}^{N}\frac{L_{\max}^i}{BAG}-\frac{L_{\max}^i}{BAG})t+(\sum_{i=1}^{N}L_{\max}^i-L_{\max}^i) \end{aligned} \tag{20}$$

With First-In-First-Out (FIFO) transmission strategy, the service curve can be described as

$$\begin{aligned} \beta_i(t) &= \left[Rt-\left(\sum_{i=1}^{N}\frac{L_{\max}^i}{BAG}-\frac{L_{\max}^i}{BAG}\right)\left(t-\frac{\sum_{i=1}^{N}\left(L_{\max}^i\right)-L_{\max}^i}{R}\right)-\left(\sum_{i=1}^{N}L_{\max}^i-L_{\max}^i\right) \right]^+ \\ &= \left[R-\left(\sum_{i=1}^{N}\frac{L_{\max}^i}{BAG}-\frac{L_{\max}^i}{BAG}\right)\right]\left(t-\frac{\sum_{i=1}^{N}\left(L_{\max}^i\right)-L_{\max}^i}{R}\right) \end{aligned} \tag{21}$$

The service rate and service delay that the switchboard provide the i^{th} data traffic can be shown as

$$R_i = R-\left(\sum_{i=1}^{N}\frac{L_{\max}^i}{BAG}-\frac{L_{\max}^i}{BAG}\right) \tag{22}$$

$$T_D^i = \frac{\sum_{i=1}^{N}\left(L_{\max}^i\right)-L_{\max}^i}{R} \tag{23}$$

IV. RELIABILITY EVALUATION OF AFDX

A. *Reliability Modeling of Apparatus*

With the traditional reliability theory, the reliability model of switchboard and subsystem can be expressed as

$$P_0(t) = e^{-\lambda_W t} \tag{24}$$

where λ_W is the failure rate of individual apparatus. Define the random variable $W(t)=\{0,1,2,\ldots,N_0\}$ is the number of workstations, then

$$P\left(W(t)=n\right) = C_{N_0}^n P_0^n(t)\left(1-P_0(t)\right)^{N_0-n}, n=0,1,2,\ldots,N_0 \tag{25}$$

where N_0 is the number of normal workstations, whose mathematical expectation can be described as

$$N(t) = \sum_{n=0}^{N_0} nP\left(W(t)=n\right) \tag{26}$$

Let $n-1=k$, then

$$\begin{aligned} N(t) &= N_0P_0(t)\left[\sum_{n=1}^{N_0} C_{N_0-1}^{n-1}P_0^{n-1}(t)\left(1-P_0(t)\right)^{N_0-n}\right] \\ &= N_0P_0(t)\left[\sum_{k=0}^{N_0-1} C_{N_0-1}^{k}P_0^{k}(t)\left(1-P_0(t)\right)^{N_0-1-k}\right] \\ &= N_0P_0(t)\left[P_0(t)+(1-P_0(t)\right]^{N_0-1} \\ &= N_0P_0(t) \\ &= N_0e^{-\lambda_W t} \end{aligned} \tag{27}$$

It is obvious that the probability of network apparatus $P_\lambda(t) = f(\lambda_w, N(t)) = f(\lambda_w, N_0)$ is related to the average failure rate λ_W of workstation and the number of normal workstations under initial state N_0.

B. *Reliability Modeling of Service Performance*

With the traffic shaping and real time adjustment, the network can realize the reliable transmission at limit time delay. So the traffic shaping and adjustment are key factors that influence the time delay. After effective traffic shaping with token bucket, the arrival customer waiting distribution at the i^{th} link can be described as

$$F_{T_Z^i}(\tau) = P(T_Z^i < \tau) = \begin{cases} 0, \tau < 0 \\ 1-\sigma e^{-\mu(1-\sigma)\tau}, \tau \ge 0 \end{cases} \tag{28}$$

With $\frac{L_{\max}}{BAG}t+L_{\max}$ as adjuster, the service time delay at the i^{th} switchboard is

$$T_D^i = \frac{\sum_{i=1}^{N}\left(L_{\max}^i\right)-L_{\max}^i}{R} \tag{29}$$

where N is the number of normal operation workstations at time t

C. *Integrated Reliability Modeling of AFDX*

After establishing the reliability model of apparatus and service performance, it is necessary to combine them to obtain the integrated reliability model as

$$R(t) = P(T_{delay} < \tau \mid M > t) \times P(M > t) \tag{30}$$

where $P(M > t) = e^{-\lambda_W t}$ is the reliability of apparatus and $P(T_{delay} < \tau \mid M > t)$ expresses the probability of time delay T_{delay} is less than fixed delay upper limit τ under normal apparatus. Then the integrated reliability can be described as

$$\begin{aligned} R(t) &= P(T_{delay}^i < \tau \mid M > t) \times P(M > t) \\ &= P(T_Z^i + T_D^i < \tau \mid M > t) \times P(M > t) \\ &= P(T_Z^i < (\tau - T_D^i) \mid M > t) \times P(M > t) \\ &= (1-\sigma e^{-\mu(1-\sigma)(\tau-T_D^i)}) \times e^{-\lambda_w t} \\ &= (1-\sigma e^{-\mu(1-\sigma)(\tau-\frac{\sum_{i=1}^{N}\left(L_{\max}^i\right)-L_{\max}^i}{R})}) \times e^{-\lambda_w t} \end{aligned} \tag{31}$$

Due to $N(t) = N_0e^{-\lambda_W t}$, then

$$\begin{aligned} R(t) &= P(T_{delay}^i < \tau \mid M > t) \times P(M > t) \\ &= (1-\sigma e^{-\mu(1-\sigma)(\tau-\frac{\sum_{i=1}^{N}\left(L_{\max}^i\right)-L_{\max}^i}{R})}) \times e^{-\lambda_w t} \\ &= (1-\sigma e^{-\mu(1-\sigma)(\tau-\frac{\sum_{i=1}^{N_0e^{-\lambda_W t}}\left(L_{\max}^i\right)-L_{\max}^i}{R})}) \times e^{-\lambda_w t} \end{aligned} \tag{32}$$

Suppose R =10Mbps, $N_0 = 30$, $L_{\max}^{i}$ =1518byte/s , μ =8.131/s) , τ =0.5s, we can get the reliability under different failure rate shown in Fig.5 and upper limit of time delay shown in Fig.6.

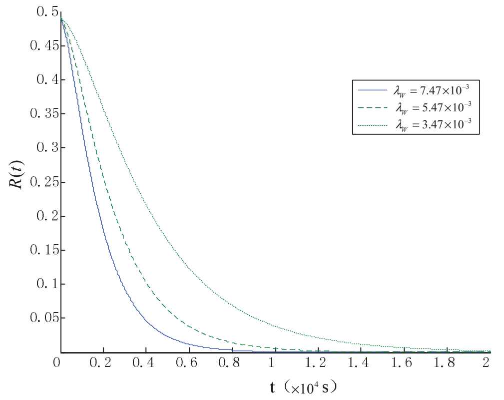

Fig. 5. Integrated reliability under different λ_W

It is obvious that the integrated reliability $R(t)$ decreases with the failure rate λ_W increases under same time t.

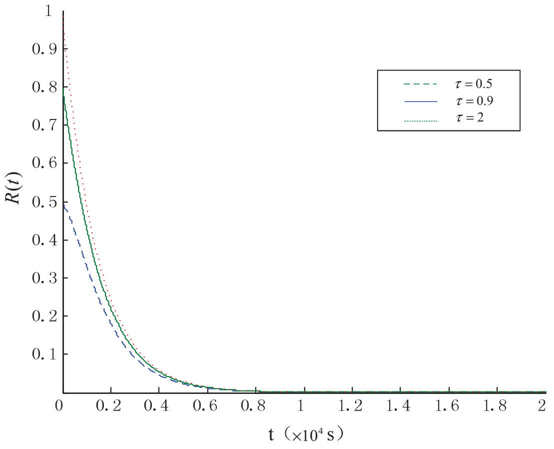

Fig. 6. Integrated reliability under different τ

Fig.6 shows that the integrated reliability $R(t)$ increases with the upper limit of time delay τ increases under same time t.

V. CONCLUSIONS

This paper focuses on the failure mechanism of AFDX and analyzes the influence factors of time delay, then summarizes the two key factors, that is the traffic shaping delay and traffic adjustment delay. In order to decrease the sudden traffic, the token bucket theory and the queuing theory G/M/1 are used to realize the traffic shaping and FCFS is utilized to adjust the maximum time delay T_D .

With the number of normal operational workstation $N(t)$, we can combine the inherent reliability of apparatus and service performance to realize the integrated reliability evaluation. Application indicates that optimal parameters in reliabilit1y model could improve the network reliability effectively.

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