Article citation info:
WU Z, HUANG N, LI R, ZHANG Y. A delay reliability estimation method for Avionics Full Duplex Switched Ethernet based on stochastic network calculus. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2015; 17 (2): 288–296, http://dx.doi.org/10.17531/ein.2015.2.17.

Zhitao WU
Ning HUANG
Ruiying LI
Yue ZHANG

A DELAY RELIABILITY ESTIMATION METHOD FOR AVIONICS FULL DUPLEX SWITCHED ETHERNET BASED ON STOCHASTIC NETWORK CALCULUS

OPARTA NA STOCHASTYCZNYM RACHUNKU SIECIOWYM METODA ESTYMACJI NIEZAWODNOŚCI CZASU TRANSMISJI DLA PRZEŁĄCZANEJ POKŁADOWEJ SIECI ETHERNETOWEJ TYPU AFDX UMOŻLIWIAJĄCEJ RÓWNOCZESNĄ TRANSMISJĘ DWUKIERUNKOWĄ

The delay reliability estimation is required in order to guarantee the real-time communication for avionics full duplex switched Ethernet (AFDX). Stochastic network calculus (SNC) can be applied to estimate the reliability with a delay upper bound. However, only linear deterministic traffic envelope function is used to bound its traffic, which cannot represent the traffic randomness and is far from practice. In this paper, a stochastic traffic envelope function, which randomizes the input of SNC, is proposed to solve the problem. A new probabilistic algorithm is derived to estimate the delay reliability based on stochastic envelope functions. A test was conducted to demonstrate our method on an AFDX testbed, and the test results verify that the estimation of delay reliability via our algorithm is much closer to the empirical estimation.

Keywords: *reliability estimation, delay upper bound, stochastic network calculus, traffic envelope function.*

Ocena niezawodności czasu transmisji (czasu opóźnienia) jest niezbędną procedurą gwarantującą komunikację w czasie rzeczywistym za pośrednictwem przełączanej pokładowej sieci ethernetowej typu AFDX (Avionics Full Duplex Switched Ethernet), która umożliwia równoczesną transmisję dwukierunkową. Stochastyczny rachunek sieciowy (SNC) można stosować do oceny niezawodności przy zadanej górnej granicy opóźnienia. Do tej pory jednak, do ograniczania ruchu telekomunikacyjnego stosowano tylko liniową deterministyczną funkcję obwiedni (traffic envelope), która nie oddaje losowości ruchu telekomunikacyjnego i odbiega dalece od rzeczywistości. W niniejszej pracy zaproponowano rozwiązanie tego problemu wykorzystujące stochastyczną funkcję obwiedni ruchu telekomunikacyjnego. Wyprowadzono nowy algorytm probabilistyczny, który pozwala ocenić niezawodność czasu transmisji na podstawie funkcji obwiedni. Przeprowadzono badanie, w ramach którego testowano zaproponowaną metodę w środowisku testowym AFDX; wyniki testu pokazują, że ocena niezawodności czasu transmisji z wykorzystaniem zaproponowanego przez nas algorytmu jest znacznie bardziej zbliżona do estymacji empirycznej.

Słowa kluczowe: *ocena niezawodności, górna granica opóźnienia, stochastyczny rachunek sieciowy, funkcja obwiedni ruchu telekomunikacyjnego.*

1. Introduction

Airborne network plays a key role in the integration of modern airplanes. Avionics full duplex switched Ethernet (AFDX) [4] was developed by Airbus aiming to provide 100Mbps bandwidth with deterministic quality of service, and has been successfully applied in several advanced aircrafts, such as A380, Boeing 787, etc. For avionics applications, the real-time requirement is essential, so the delay reliability needs to be estimated to ensure that the network configuration satisfies the customer requirement. Customers define maximum allowed frame delay (i.e., delay upper bound) on AFDX. If a frame delay exceeds the upper bound, the frame transmission is considered as a transmission failure. If not, it is regarded as a successful transmission. The occurrence probability of successful transmission is the delay reliability, which is also named as transmission time reliability [22], delay-oriented reliability [34], and reliability with delay [18].

Network delay reliability was first introduced by Asakura and Kashiwadani [5] for road networks where it is named as transportation time reliability, and was then expanded by Li et al. [22] to computer networks. Similar studies are referred to [1, 14, 25, 28, 33], which investigate factors that affect delay reliability, and provide the corresponding estimation methods. However, traffic randomness, which has large effects on delay reliability as Meyer [26] and Ball [6] stated, was neglected in the above research, and traffic with high burst usually causes network performance degradation. Stochastic network calculus (SNC) was proposed to provide an elegant framework that can be used to evaluate the delay reliability with traffic randomness [15, 16, 24]. Traffic envelope and service envelope are used to bound traffic arrivals and the services offered at network nodes, respectively, and the delay reliability can be estimated based on the mathematical foundation of min-plus algebra.

When Ridouard et al. [29] first proposed SNC to evaluate the delay reliability which uses the maximum allowable delay as the delay upper bound in AFDX in 2008, only pessimistic linear traffic envelopes were used to bound AFDX traffic. Moreover, Yao [38] and Liu [23] summarized the current AFDX traffic models used to derive deterministic traffic envelopes, and found that the linear expression is the only form. In [17], Jiang summarized that there were two ways to estimate the delay reliability via SNC: (i) randomize the input of SNC, i.e., traffic and service envelope functions; (ii) randomize the reliability derivation based on deterministic traffic and service envelopes (which are not randomized). The former one is an intrinsic stochastic process, which randomizes the calculation source. However, as it is difficult to build stochastic traffic and service envelope functions, to the best of our knowledge, only the latter idea has been applied in computing the delay reliability in AFDX [32]. However, since Lelend [21] discovered the self-similar property of Ethernet traffic, in which AFDX is a special case, linear traffic models cannot reflect the long range dependence and burstiness (i.e., self-similarity) of AFDX traffic [7, 19]. Therefore, the traffic self-similarity needs to be incorporated into the traffic envelope to improve the accuracy of the delay reliability estimation.

In this paper, we build a stochastic traffic envelope function, which randomizes the input of SNC, to reflect the self-similarity of AFDX traffic, and propose a new probabilistic algorithm to estimate the delay reliability based on the stochastic envelope functions, which gives a better approximation. This remainder of the paper is organized as follows. Section 2 details some basic knowledge about the AFDX. Based on a brief introduction of SNC theory, the stochastic envelope functions are analyzed for AFDX in Section 3. Particularly, the fractional Brownian motion (FBM), which is commonly used to model the self-similar traffic of Ethernet, is introduced to model the non-linear aggregate traffic in AFDX. Section 4 derives the delay reliability according to the SNC theory. Case study is presented in Section 5, and it verifies that our proposed method can provide more accurate delay reliability estimation compared to the previous SNC methods. Finally, concluding remarks are provided in Section 6.

2. AFDX context

AFDX, originating from mature Ethernet technology, is a real-time system. As shown in Fig. 1, an AFDX system comprises avionics subsystems, end systems (ES) and a redundant switched system. Avionics subsystems, such as flight control system, global positioning system, etc., are designed to accomplish multiple avionics tasks. Avionics computer systems are used to provide a computational environment for these avionics subsystems. Each avionics computer system contains an embedded ES that connects the avionics subsystems to an AFDX interconnect. The ES is generally referred to as network interface cards (NIC). The traffic between avionics subsystems is transmitted through ESs and the switched system. All frames copied at the ES are sent on both networks in the redundant switched system, and are finally received by the destination ES. Moreover, a gateway provides interconnection between AFDX and Internet.

In AFDX, the deterministic end-to-end transmission is guaranteed by the virtual link (VL) mechanism [23]. VL can be seen as a unidirectional logical channel from one source ES to one or more destinations, which defines a deterministic communication path. All the data transmission between ESs are accomplished through VLs in the AFDX. To guarantee the deterministic data exchange, each VL is assigned to a maximum allowed frame size (L_m), a maximum allowed jitter (J_m), a bandwidth allocation gap (BAG) and a maximum bandwidth, where BAG is the minimum time interval between the start of consecutive frames. Normally, S_m is denoted as the maximum frame size with interframe gap, i.e., $S_m=L_m+20$ Bytes, where interframe gap is a minimum idle period between transmission of frames.

The end-to-end delay of a certain frame F transmitted on a VL can be described as the sum of transmission delays on links and latencies in switches between source and destination. According to [32], it can be defined as:

$$D_F = LD_F + TD_F + BD_F \tag{1}$$

where LD_F is the transmission delay over the link, TD_F is the technical processing delay, and BD_F is the delay in switch buffer. In particular, LD_F is determined by $LD_F = m_L \times S_m(F)/R$, where m_L is the number of links in the VL, $S_m(F)$ is the frame size with interframe gap, and R is the link bandwidth; TD_F is caused by the protocol process in switches, such as frame policing and filtering. According to AFDX specification [4], the processing delay at one switch does not exceed 16 µs. As the number of swithes in the AFDX is not large, hence TD_F can be regarded as a fixed value, i.e., $TD_F = m_s \times 16$ µs, where m_s is the number of switches in the VL; BD_F is determined by the frame queuing process, which highly depends on the traffic load of each switch port [32]. As LD_F and TD_F are fixed values for a deterministic AFDX configuration, we focus on how to model delay reliability with BD_F consideration in our study.

3. Envelope functions for stochastic network calculus

Section 3.1 introduces the basic knowledge of the SNC theory, and the envelope functions for AFDX, i.e., STP and SSP, are derived based on the characteristics of AFDX traffic in Section 3.2 and 3.3, respectively.

3.1. Stochastic network calculus

SNC provides an analytical framework of the probabilistic upper bound estimation for BD (i.e., the delay in the switch buffer) [16], and its analytical expression is as follows:

$$\Pr(BD \ge BD_U) \le f(BD_U)\ , \tag{2}$$

where BD_U is the delay upper bound requirement of BD, and f is the violable function.

Eq. (2) can be used to calculate the conservative end-to-end delay reliability as:

$$\begin{aligned} R_D &= \Pr(\mathrm{D} \le \mathrm{D}_U) \\ &= 1 - \Pr(\mathrm{D} \ge \mathrm{D}_U) \\ &= 1 - \Pr(LD + TD + BD \ge \mathrm{D}_U) \\ &\ge 1 - f(\mathrm{D}_U - LD - TD), \end{aligned} \tag{3}$$

where R_D is delay reliability with the end-to-end delay upper bound D_U.

In the SNC algorithm, left-continuous stochastic processes $A(t)$ and $A^*(t)$ are used to quantify cumulative arrivals and departures of a traffic flow in the time period

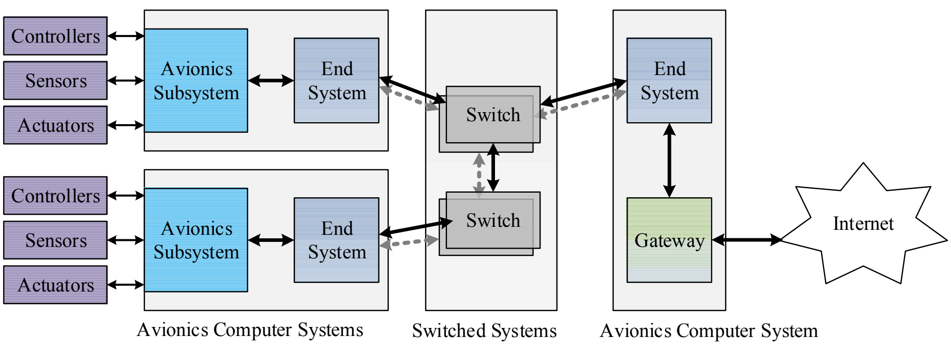

Fig. 1. AFDX context

[0,t). Intuitively, we use $A(s,t):=A(t)-A(s)$ to denote the accumulative arriving traffic in the time period [s,t).

***Definition* 1:** A non-random function $\alpha(t)$ is a *stochastic traffic envelope* (STP) for an arrival process A if it bounds arrivals over a time interval by the following equation, for all $t \geq s \geq 0$ and for all $\sigma \geq 0$,

$$\Pr(A(s,t) > \alpha(t-s)+\sigma) \leq f_A(\sigma), \quad (4)$$

where $f_A(\sigma)$ is a non-negative, non-increasing function known as the violable probability function of $\alpha(t)$, and satisfies $f_A(\sigma) \to 0$ as $\sigma \to \infty$.

***Definition* 2:** A *stochastic service envelope*(SSP) for a network system with arrival traffic A is a function $\beta(t)$, if for all δ>0,

$$\Pr(A \otimes \beta(t) - A^*(t) > \delta) \leq g_A(\delta), \quad (5)$$

where symbol $\otimes$ is the min-plus convolution: $a \otimes b(x) = \inf_{0\leq y\leq x}[a(y)+b(x-y)]$, $g_A(\delta)$ is the violable function of $\beta(t)$.

The delay in the network switch buffer at time t can be defined as:

$$BD(t) = \inf_{0\leq\tau\leq t}\{\tau, A(t-\tau) \leq A^*(t)\}. \quad (6)$$

As is shown in Fig. 2, the delay at time t_1 in the network switch buffer actually is the horizontal distance of STP and SSP. With STP and SSP, SNC can be applied to derive the delay reliability via Eq. (6). Note that $f(\cdot)$ in Eq. (6) is a compound function of $f_A(\sigma)$ and $g_A(\delta)$.

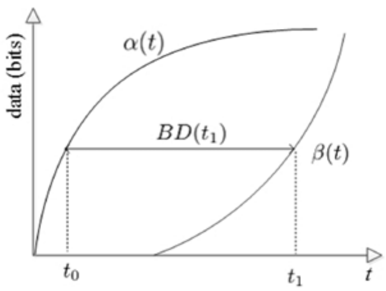

Fig. 2. Transmission delay bound

When there are multiple flows competing for service resources in a system, the following theorem presented in [16] provides a useful technique to construct SSP for a single flow.

Theorem 1 (*Left-over service characterization*): Consider the case where two traffic flows A_1 and A_2 compete for resources in a switch system under the scheduling policy. Assume the SSP of the network system is $\beta(t)$, the STP of A_i is $\alpha_i(t)$, and the SSP $\beta(t)$ provided by the system for A_i can be expressed as $\beta_i(t) = \max\{\beta(t) - \alpha_{A_j}(t), 0\}$ (i=1,2, and j=3−i), and its violable function can be calculated as $g_{A_i}(x) = g \otimes f_{A_j}(x)$.

3.2. Stochastic traffic envelope

In the switched network of AFDX, the traffic arrival process is determined by its departural process at the source ES, as the frame transmission on link dose not change the frame interval. To guarantee the *BAG* for each VL, the traffic at ES outports are regulated by traffic regulator, and no more than one frame can be sent out in each interval of *BAG*. When multiple VLs exist, the VL scheduler will introduce jitter for the frame if it arrives at a non-empty virtual link queue. The frame transmitting process at the ES outport is illustrated in Fig. 3. Therefore, in the i^{th} VL, the frame intervals are between $BAG_i - J_m^i$ and $BAG_i + J_m^i$, where J_m^i is the jitter of the i^{th} VL.

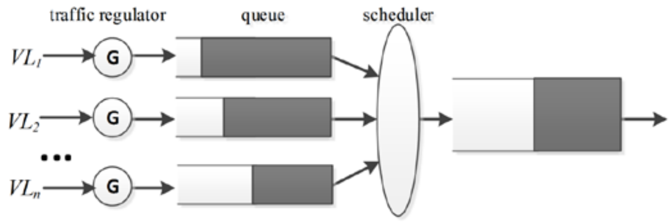

Fig. 3. Frame transmitting process in multiple VLs at an ES outport

In a switch, the queuing is occured at the outport. In one outport (see Fig. 4), except the VL_i traffic under estimation, other traffic of VLs, i.e., background traffic, is also transmitted through the same outport. Note that, background traffic is actually a superposition of frames from all VLs in the outport except the i^{th} VL. Let $A_i(t)$ and $A_B(t)$ be the cumulative arrivals of VL_i and background traffic flow in the time period [0, t), respectively.

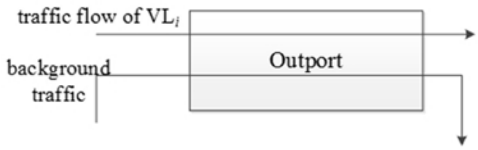

Fig. 4. VL_i traffic under estimation and its background traffic at the switch

3.2.1. The stochastic traffic envelope for VLi

In the previous study [23], as seen in Fig. 5, a series of frames are transmitted through VL_i, and the linear traffic envelope (LTP) is built for the worst-case situation, i.e., transmitting maximum-size frames with the minimum transmission intervals. Hence, LTP $\alpha_i(t)$ (in bits) for A_i can be expressed as:

$$\alpha_i(t) = 8S_m^i + \frac{8S_m^i}{BAG_i}t. \quad (7)$$

From Eq. (4), the STP of VL_i can be written as:

$$\Pr\left(A_i(s,t) > \alpha_i(t-s)+\sigma\right) \leq f_i(\sigma), \quad (8)$$

and the corresponding $f_i(\sigma) = 0$, as the LTP $\alpha_i(t)$ can surely bound the traffic.

3.2.2. The stochastic traffic envelope for the background traffic

When multiple VLs exist in a physical link, the aggregate traffic LTP $\alpha_B(t)$ can be obtained as:

$$\alpha_B(t) = 8\sum_i S_m^i + 8\sum_i \frac{S_m^i}{BAG_i}t. \quad (9)$$

In [23, 32, 38], the above LTP is applied to estimate the delay reliability using SNC. Obviously, Eq. (7) provides a rough bound of the cumulative traffic in a single VL, and Eq. (9) supposes that the traffic statistical characteristics do not change after the traffic is aggregated from different VLs at switches. However, it is not the real situation, as aggregating process in AFDX may lead to a non-linear statistical property, i.e., self-similarity appears.

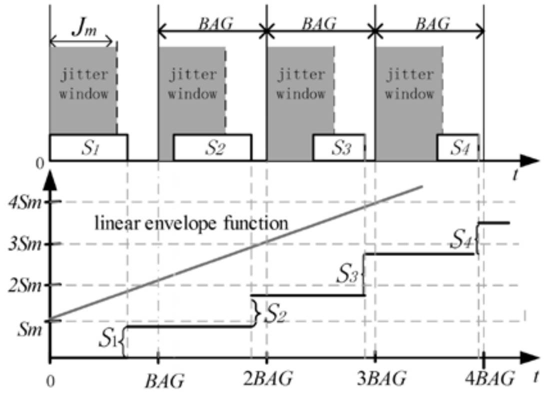

Fig. 5. Cumulative process of frames and linear envelope function in VL_i

In order to illustrate the statistical characteristics of the AFDX aggregate traffic, we collected time intervals between frames from four AFDX traffic, as shown in Fig. 6. One can see that some large traffic occurs with a small probability, which shows the traffic burstiness. Moreover, the traffic self-similarity property can be verified by the Hurst parameter (*H*). Using the absolute value method with the tool designed by Karagiannis [20], the *H* values of the collected data can be calculated as follows: 0.820, 0.763, 0.693 and 0.778, respectively, which show typical self-similar characteristics (Clegg [7] stated that the traffic self-similarity exsits if H>0.5). This is consistent with the traffic feature of Ethernet, in which the self-similarity has been widely recognized [9, 36].

Willinger [35] first applied fractal brown motion(FBM) to model self-similar aggregate traffic in 1998. Nowadays, FBM is widely used to model the aggregate traffic (see [7, 9, 19] for details). Rizk and Fidler [30, 31] analyzed the envelope function of FBM, and their result has been applied to derive performance bound in Internet. Hence, in this paper, we adopt FBM to model AFDX aggregate traffic, i.e., the aggregate traffic $\alpha_B(t)$ can be computed as:

$$\alpha_B(t) = \sum_{i=1}^{n} \alpha_i(t) = \rho t + \sqrt{\rho\omega^2} B_H(t)\,, \tag{10}$$

where n is the number of VLs of the background traffic, ρ is the mean arrival rate, ω^2 is the variance of traffic flow, and $B_H(t)$ is a trace of FBM with the Hurst parameter $H \in (0.5,1)$, which depends on n. FBM is used to model the traffic deviations from its mean value, and the self-similarity is characterized by H in FBM. According to the property of FBM presented by Duffield et al. [8], for $\forall \sigma, c \geq 0$, $\alpha_B(t)$ satisfies:

$$\ln\left\{\Pr\left[A_B(s,t) - \alpha_B(t-s) \geq \sigma\right]\right\} \leq -\sigma^{2(1-H)} \inf_c \left\{c^{-2(1-H)}(c+\rho)^2/2\right\}. \tag{11}$$

In order to simplify Eq. (11), the minimum value of $c^{-2(1-H)}(c+\rho)^2/2$ over c>0 can be obtained at $c=(1-H)\rho/H$ by derivation. Substituting the value of c into Eq. (11) yields:

$$\Pr\left[A_B(s,t) - \alpha_B(t-s) \geq \sigma\right] \leq \min\left\{1, \exp\left\{-0.5\left(\frac{\sigma}{1-H}\right)^{2(1-H)}\left(\frac{\rho}{H}\right)^{2H}\right\}\right\}. \tag{12}$$

Therefore, the right part of Eq. (12) can be viewed as the violable probability function, i.e.,

$$f_B(\sigma) = \min\left\{1, \exp\left\{-0.5\left(\frac{\sigma}{1-H}\right)^{2(1-H)}\left(\frac{\rho}{H}\right)^{2H}\right\}\right\}.$$

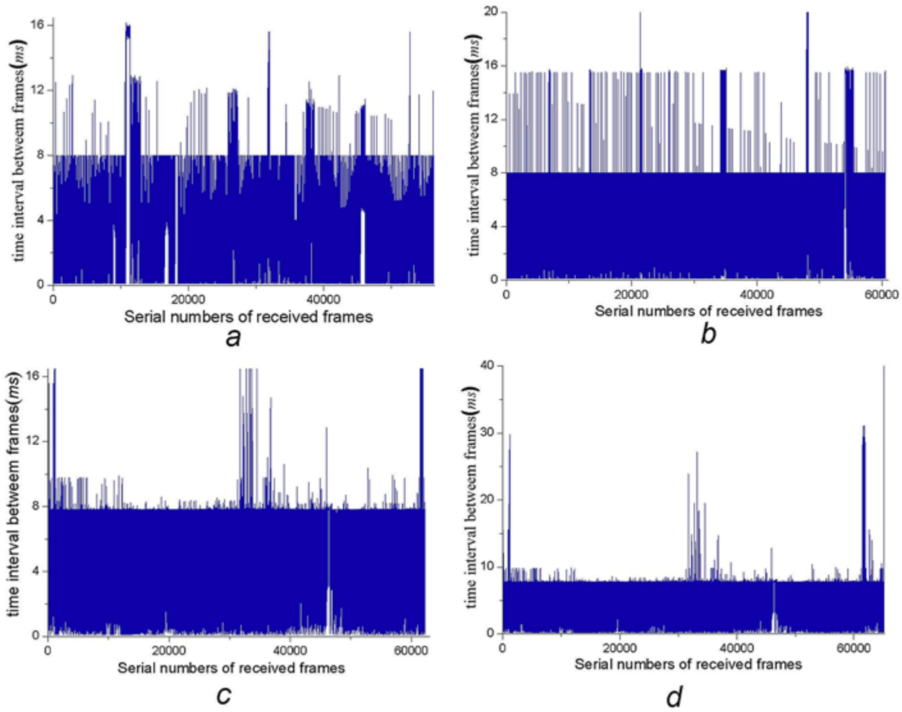

Fig. 6 Time interval between frames

3.3. Stochastic service envelope

As shown in Fig. 4, the service resource competition between traffic in the i^{th} VL and background traffic widely exists at the switch outports. Suppose that the switches are in the work-conserving manner, then the SSP $\beta(t)$ for the aggregate traffic at a switch outport can be obtained as [32]:

$$\Pr(A \otimes \beta(t) - A^*(t) > \delta) \leq g(\delta), \tag{13}$$

where $A(t)$ and $A^*(t)$ are the cumulative arrivals and departures of the aggregate traffic at the switch outport, $\beta(t) = Ct$ and $g(\delta)$=0, C is the bandwidth of the switch outport. According to the left-over service theorem (Theorem 1), we can derive the SSP $\beta_i(t)$ for VL_i as:

$$\Pr(A_i \otimes \beta_i(t) - A_i^*(t) > \delta) \leq g_i(\delta), \tag{14}$$

where $\beta_i(t) = \max\{\beta(t) - \alpha_B(t), 0\}$, and $g_i(\delta) = g \otimes f_B(\delta) = f_B(\delta)$ as $g(\delta)=0$.

4. Reliability estimation with the given delay upper bound

With the basic knowledge of SNC theory, we can derive the following theorem to estimate the end-to-end delay reliability for a VL:

Theorem 2: Assume that a switch k whose SSP $\beta(t)$ satisfies Eq. (13), provides service for multiple VLs in AFDX as shown in Fig. 4. If the STPs for A_i and background traffic follow Eq. (8) and (12), respectively. We have:

$$\Pr(BD_k \ge BD_{U,k}) \le f_B((C - \rho_k)BD_{U,k}), \tag{15}$$

where BD_k is the delay of a frame in the outport buffer at switch k, and $BD_{U,k}$ is the given upper bound requirement of k. For a VL with m_s switches, the end-to-end delay reliability R_D with the given delay upper bound BD_U is given by:

$$R_D \ge 1 - f_B\left(\frac{D_U - LD - TD}{\sum_{k=1}^{m_s} \frac{1}{C - \rho_k}}\right). \tag{16}$$

Proof: According to Eq. (6), the delay in the outpor buffer at switch k can be computed as:

$$BD_k = \inf_{0 \le \tau \le t} \left\{\tau, A_i(t-\tau) \le A_i^*(t)\right\}.$$

Hence, for any t>0, $\Pr(BD_k > d) \le \Pr\left\{A_i(t-d) \le A_i^*(t)\right\}$ holds.

In order to compute the probability, for all $y \in [0,t]$, we have:

$$\begin{aligned}
&A_i(t-y) - A_i^*(t) = A_i(t-y) - \inf_{0\le s\le t-y}\{A_i(s) + \beta_i(t-s)\} + \inf_{0\le s\le t-y}\{A_i(s) + \beta_i(t-s)\} - A_i^*(t) \\
&\le \sup_{0\le s\le t-y} [A_i(t-y) - A_i(s) - \beta_i(t-s)] + A_i \otimes \beta_i(t) - A_i^*(t) \\
&= \sup_{0\le s\le t-y} [A_i(s,t-y) - \alpha_i(t-y-s) + \alpha_i(t-y-s) - \beta_i(t-s)] + A_i \otimes \beta_i(t) - A_i^*(t) \\
&\le \sup_{0\le s\le t-y} [A_i(s,t-y) - \alpha_i(t-y-s)] + \sup_{0\le s\le t-y} [\alpha_i(t-y-s) - \beta_i(t-s)] + A_i \otimes \beta_i(t) - A_i^*(t) \\
&\triangleq \sup_{0\le s\le t-y} [\alpha_i(t-y-s) - \beta_i(t-s)] + A_i \otimes \beta_i(t) - A_i^*(t) \\
&= \sup_{0\le s\le t-y} \left[\frac{8S_m}{BAG}(t-y-s) - (C-\rho_k)(t-s) + \sqrt{\rho_k \omega^2} B_H(t-s)\right] + A_i \otimes \beta_i(t) - A_i^*(t) \\
&\triangleq -(C-\rho_k)y + A_i \otimes \beta_i(t) - A_i^*(t).
\end{aligned}$$

The equation $\triangleq$ of the above inference holds as Eq. (8) shows $\Pr(A_i(s,t) > \alpha_i(t-s) + \sigma) \le 0$ for all σ>0. Since $B_H(t)$ is used as a deviation and has expectation zero, $\sqrt{\rho_k \omega^2} B_H(t-s)$ is assigned to 0 in statistical sense, in addition, the bandwidth C of the outport is larger than $8S_m/BAG+\rho_k$, and hence the maximum value of

$$\left[\frac{8S_m}{BAG}(t-y-s) - (C-\rho_k)(t-s) + \sqrt{\rho_k \omega^2} B_H(t-s)\right]$$

over $s \in [0, t-y]$ is obtained at $s=t-y$, which yields the equation $\triangleq$. Therefore, we have

$$A_i(t-d) - A_i^*(t) \le A_i \otimes \beta_i(t) - A_i^*(t) - (C-\rho_k)d.$$

Based on the above analysis, we can obtain,

$$\begin{aligned}
&\Pr(BD_k \ge d) = \inf_t \Pr\{A_i(t-d) \le A_i^*(t)\} \\
&\le \inf_t \Pr\{A_i \otimes \beta_i(t) - A_i^*(t) \ge (C-\rho_k)d\} \\
&= f_B \otimes g((C-\rho_k)d) = f_B((C-\rho_k)d),
\end{aligned}$$

where f_B is given in Eq. (12).

In a VL (with m_s switches) whose end-to-end delay upper bound is D_U, for each switch, we have $\Pr(BD_k \le BD_{U,k}) \ge 1 - f_B((C-\rho_k)BD_{U,k})$. Solving:

$$\begin{cases} \sum_{k=1}^{m_s} BD_{U,k} = D_U - LD - TD, \\ (C-\rho_1)BD_{U,1} = (C-\rho_2)BD_{U,2} = \cdots = (C-\rho_{m_s})BD_{U,m_s}, \end{cases}$$

where the second equation holds as the traffic of the same VL is identical. We have:

$$\begin{cases} BD_{U,1} = \dfrac{D_U - LD - TD}{(C-\rho_1)\sum_{S=1}^{m_s} \dfrac{1}{C-\rho_S}}, \\ BD_{U,k} = \dfrac{C-\rho_1}{C-\rho_k} BD_{U,1}, \quad k = 1, 2, \ldots, m_S. \end{cases}$$

Hence, the end-to-end delay reliability can be written as:

$$\begin{aligned}
R_D &= \Pr(D \le \mathrm{D}_U) \\
&= 1 - \Pr\left(\sum_{S=1}^{m_s} BD_S \ge D_U - LD - TD\right) \\
&\quad \text{(Accorrding to the min-plus convolution)} \\
&\ge 1 - f_B((C-\rho_1)BD_{U,1}) \otimes \cdots \otimes f_B((C-\rho_{m_S})BD_{U,2}) \\
&= 1 - f_B\left(\frac{D_U - LD - TD}{\sum_{S=1}^{m_s} \frac{1}{C-\rho_S}}\right).
\end{aligned}$$

According to Theorem 2, the delay reliability with a given delay upper bound can be obtained. The proposed method makes a distinct contribution to estimate the delay reliability for a certain VL: (1) the non-linear FBM aggregate traffic envelope is randomized, which represents the self-similarity of the AFDX background traffic; and (2) the compact algrithom for the delay reliability with a given delay upper bound is derived using STP and SSP, which is an intrinsic stochastic process.

5. Case study

In this section, a case study is provided to illustrate the effectiveness of the proposed method. We consider an AFDX with the topology and parameters shown in Fig. 7 and Table 1. Messages are transmitted from ES1, ES2 and ES3 to ES4 through SW1 and SW2. In this case, messages of all VLs are generated according to Pareto and exponential distributions, which form a typical self-similar traffic and is frequently used in network traffic analysis (see Addie et al. [2], Field et al. [10], Nadarajah [27], Yamkhin [37], and Fras et al. [11, 12] for details). Our proposed algorithm is applicable to other heavy-tailed traffic distributions only if its background traffic is self-similar. Moreover, this idea can also be applied in non-heavy-tailed traffic distribution based on similar derivation. In this case study, the delay reliability of VL_{11} is measured with a delay upper bound.

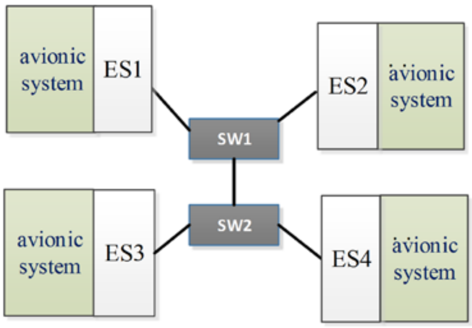

Fig. 7. AFDX Topology

Table 1. AFDX configuration

VL Number	Source ES	Message generation parameters① (λ, α, X_{min})	Destination ES	*BAG* (ms)	L_m (byte)	*R* (Mbps)
VL_{11}-VL_{16}	ES1	0.2,1.1, 3MB	ES4	8,32,2,4,8,16	1518	100
VL_{21}-VL_{27}	ES2	0.4, 1.1, 1MB	ES4	8,1,64,16,16,128,64		
VL_{31}-VL_{38}	ES3	0.6, 1.1, 133KB	ES4	1,32,16,1,128,32,8,2		

① *The size X of avionics message generated by source ES is supposed to follow Pareto distribution:* $F_X(X \le x) = 1 - (X_{min}/x)^{\alpha}$, *and the time interval Y between message generation follows exponential distribution with parameter λ:* $F_Y(Y \le y) = 1 - \exp\{-\lambda y\}$. *All parameters are adopted according to the statistical results presented in [13].*

We conducted a test on an AFDX testbed to compute the empirical estimate of delay reliability, and the estimation results obtained by our method is much closer to the empirical estimate compared a previous method.

5.1. AFDX testbed

Our AFDX testbed is shown in Fig. 8. In the testbed, there are three types of nodes as follows,

(1) Three personal computers (PC) embedded with ES peripheral component interconnect (PCI) cards, which are used as substitutions of avionic subsystems.
(2) Two switches, which are used to forward frames to the destination.
(3) A test equipment, which is served as both test device and destination ES.

Both ES PCI cards and switches, ACTRI-FDX-ES-PMC and ACTRI-FDX-SW-24, are designed and manufactured by an avionics institution in China. The test equipment [3], AFDX/ARINC664P7 (AIM), is an advanced avionics test apparatus designed by AIM GmbH of Germany with nanosecond resolution. As a test device, it can capture transmission data to calculate the delay. As a destination ES, it can receive data transmitted from ES1, ES2 and ES3 via VLs. Traffic can be generated by the software installed in the three source ES, and transmitted to the destination, i.e., the AIM test equipment, via different VLs. Timestamps of each frame can be recorded at the outport of either source ES or switch by the AIM test equipment. The red dotted lines in Fig. 8 show an example of the timestamp capture, and the delay between the time that the frame departures the outports of ES1 and SW2 can be calculated using PBA.pro Databus Analyser & Analysis Software embedded in AIM.

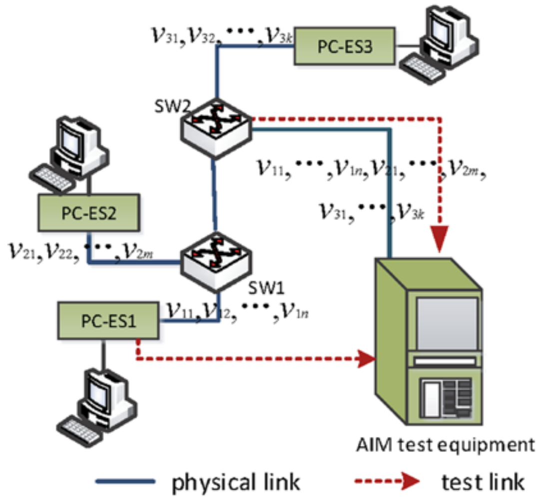

Fig. 8. AFDX testbed

5.2. Test result and discussion

5.2.1. Empirical estimation from test

We conducted a test according to the configuration shown in Table 1, and millions of frames were collected by AIM. According to the data collected from the test, the Hurst parameter was estimated by the absolute value method as 0.778, which well satisfies the typical non-linear self-similar characteristics of the aggregate traffic.

As shown in Fig. 9, the delay obtained by AIM is in a range from 251 μs to 507 μs, and the empirical estimate of the delay reliability can be obtained by:

$$\hat{R}(D_U) = \frac{k_{D_U}}{n}, \tag{17}$$

where k_{D_U} is the number of frames whose delay does not exceed the delay upper bound D_U, and n is the total number collected. The test result is recorded using the green solid curve in Fig. 9.

5.2.2. Estimation by the new method

With the parameter presented in Table 1, we can calculate the transmission delay of frames in VL_{11} as:

$$LD = m_L \times S_m / R = 2 \times 8 \times (1518 + 20) / 100 \times 10^6 \ \mu s = 246 \ \mu s,$$

According to AFDX specification, the processing delay can be calculated as:

$$TD = m_s \times 16\ \mu s = 2 \times 16\ \mu s = 32\ \mu s.$$

From the test, ρ_1 and ρ_2, the mean arrival rate in outport buffer of SW1 and SW2, are measured as ρ_1=1.935 Mbps and ρ_2=2.469 Mbps by AIM. According to Theorem 2, the delay reliability can be estimated under the given delay upper bounds. For example, if D_U=500 µs, then BD_U=D_U–LD–TD=222 µs, and the delay reliability can be calculated as:

$$\begin{aligned} R_{D_U} &= \Pr(BD_{SW1} + BD_{SW2} \le BD_U) \\ &= 1 - f_B\left(\frac{D_U - LD - TD}{\frac{1}{C-\rho_1} + \frac{1}{C-\rho_2}}\right) \\ &= 1 - f_B\left(\frac{222 \times 10^{-6}}{\frac{1}{100-1.935} + \frac{1}{100-2.469}}\right) \\ &\cong 0.8125. \end{aligned}$$

As the sum of LD and TD is deterministic in the new method, i.e., 278µs, the delay reliability keeps 0 when D_U is smaller than 278µs. It is larger than the test result (251 µs), because fixed TD used in this method is actually an upper bound. When D_U varies, the estimation results can be seen in the black dotted line in Fig. 9.

5.2.3. Estimation by SNC proposed by [32]

Similarly, the delay reliability can also be estimated using SNC method from [32] with LTP (Eq. (9)),

$$R_D = 1 - \Pr(D > D_U) \ge 1 - \frac{C}{\rho}\sum_{k=1}^{K-1} \exp(-A(s_k, s_{k+1}, BD_U)),$$

where $A(s_k, s_{k+1}, d)$ can be found in Theorem 1 of [32], and $0 = s_0 \le s_1 \le \cdots \le s_K = \tau$ for any $K \in \mathbb{Z}^+$ and $\tau = \lim_{u \ge 0}\{\alpha_i(u) \le \beta_i(u)\}$.

If d=4 ms, the delay reliability can be calculated as 0.96. When d varies, the estimation results can be seen in the blue dashed line in Fig. 9.

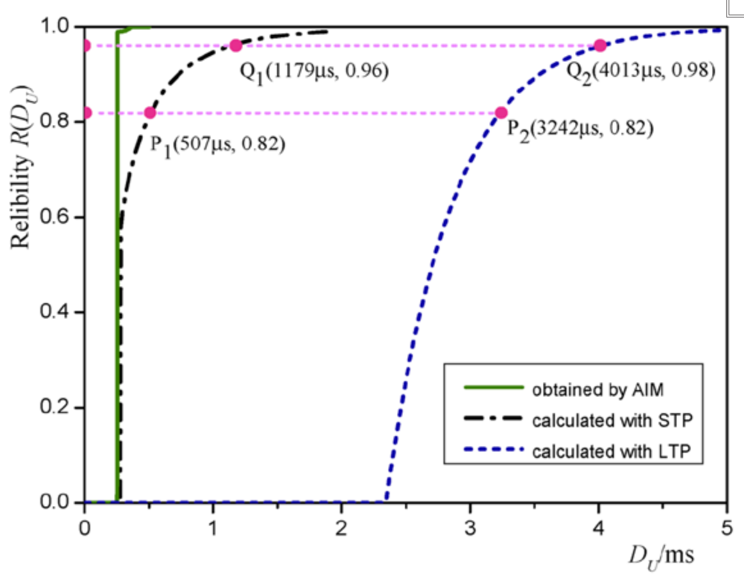

Fig. 9. Reliability with given delay upper bounds

5.2.4. Discussion

From Fig. 9, one can see that both estimates obtained by SNC methods are conservative estimates, as they exceed the empirical estimate from test for any given delay upper bound, as well as the delay upper bounds are larger than the test results for any given delay reliability requirement. It is obvious that the black dotted curve (calculated by our SNC method) is much closer to the blue solid one (the test result) compared to the blue dashed one (calculated by SNC proposed by [32]). The major reason for the error is that LTP analyzes the worst-case situation, i.e., each frame experiences the maximum queue as all frames from different VLs arrive at the switch together. STP captures a more realistic statistical feature of AFDX traffic by considering the traffic randomness, while LTP uses the worst-case situation. It means that the SNC method from [32] with LTP (Eq. (9)) is over conservative which may cause design waste.

Moreover, if the delay reliability is given, one can calculate the delay upper bound. For example, if the given reliability requirement R=0.82, the delay upper bounds for the two SNC methods are 507µs and 3242 µs (see P_1 and P_2 in Fig. 9). If the reliability requirement increases to R=0.96, the delay upper bounds are relaxed to 1179 µs and 4013 µs, respectively. More discussions can be seen in Table 2. The results show our method is more accurate.

Table 2. Delay upper bound of the three methods with different delay reliability

method \ R		0.82	0.88	0.96	0.99
AIM	D_u(ms)	0.253	0.254	0.255	0.279
SNC with STP		0.507	0.660	1.179	1.877
SNC with LTP		3.242	3.450	4.013	4.740

Table 3. Comparison of the three methods

methods	traffic envelope	service envelope	estimation
SNC with STP	statistical multiplexing	statistical multiplexing	Both traffic and service envelope are randomized, and the derivation is not randomized.
SNC with LTP	worst-case	worst-case	The reliability derivation is randomized with deterministic traffic and service envelope.
AIM	--	--	empirical estimation.

Further analysis reveals that: 1) compared to worst-case LTP, STP captures a more realistic statistical feature of AFDX traffic; 2) SNC with STP and SSP randomizes the calculation source, i.e., traffic envelope and service envelope, which derives more accuracy result than the one with LTP. Table 3 is listed to compare the three methods.

6. Conclusion

The current SNC algorithm based on linear deterministic traffic envelop function cannot represent the traffic self-similarity (which has already been verified in the real situation) of AFDX. To solve the problem, a stochastic traffic envelope is proposed based on FBM model, a common analytical model of Ethernet aggregate traffic, to model the background aggregate traffic in AFDX. A closed form expression of reliability with the end-to-end delay considerations is derived according to the framework of SNC theory, in which the traffic randomness is taken into account. The test result from a high-precision testbed verifies that our proposed method can obtain a better estimation result compared to the previous algorithm. To the best of our knowledge, this work is among the first that uses SNC with stochastic FBM envelope to derive the reliability with the given delay upper bound in a deterministic AFDX configuration.

Since different scheduling algorithms are used in the outport buffers at the switch, an exploration of the effect caused by different scheduling algorithms will be studied in our future research.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (61304220) and the Beijing Natural Science Foundation (4143064). (Corresponding author: Li R.)

References

1. Abdrabou A, Liang B, Zhuang W H. Delay Analysis for Sparse Vehicular Sensor Networks with Reliability Considerations. IEEE Transactions on Wireless Communications 2013; 12: 4402-4413, http://dx.doi.org/10.1109/TW.2013.072313.121397.
2. Addie, R G, Neame T D, Zukerman M. Performance evaluation of a queue fed by a Poisson Pareto burst process', Computer Networks-the International Journal Of Computer And Telecommunications Networking 2002; 40(3): 377-397.
3. AIM GmbH. The AIM's AFDX/ ARINC664P7. http://www.aim-online.com/index.aspx (accessed 10 Dec 2013).
4. ARINC. ARINC 664 Part 7:Aircraft Data Network-Deterministic Networks. 2003.
5. Asakura Y, Kashiwadani M. Road network reliability caused by daily fluctuation of traffc flow. in: Proceedings of Seminar G Held at the PTRC Transport, Highways and Planning Summer Annual Meeting, University of Sussex, United Kingdom, 1991:73–84.
6. Ball M O, Colbourn C J, Provan J S. Network reliability. Handbooks in operations research and management science. 1995; 7: 673-762, http://dx.doi.org/10.1016/S0927-0507(05)80128-8.
7. Clegg R G, Di Cairano-Gilfedder C, Zhou S. A critical look at power law modelling of the Internet. Computer Communications 2010; 33: 259-268, http://dx.doi.org/10.1016/j.comcom.2009.09.009.
8. Duffield N G, O'connell N. Large deviations and overflow probabilities for the general single-server queue. Mathematical Proceedings of the Cambridge Philosophical Society with applications, Cambridge Univ Press, 1995:363-374.
9. Erramilli A, Roughan M, Veitch D, Willinger W. Self-similar traffic and network dynamics. Proceedings of the IEEE 2002; 90: 800-819, http://dx.doi.org/10.1109/JPROC.2002.1015008.
10. Field T, Harder U, Harrison P. Network traffic behaviour in switched Ethernet systems. Performance Evaluation 2004; 58(2-3): 243-260, http://dx.doi.org/10.1016/j.peva.2004.07.017.
11. Fras M, Mohorko J, Cucej Z. Modeling of measured self-similar network traffic in OPNET simulation tool. Informacije Midem-Journal Of Microelectronics Electronic Components And Materials 2010; 40(3): 224-231.
12. Fras M, Mohorko J, Cucej Z. Limitations of a Mapping Algorithm with Fragmentation Mimics (MAFM) when modeling statistical data sources based on measured packet network traffic. Computer Networks 2013; 57(17): 3686-3700, http://dx.doi.org/10.1016/j.comnet.2013.07.032.
13. Ha S, Le L, Rhee I, Xu L. Impact of background traffic on performance of high-speed TCP variant protocols. Computer Networks 2007; 51: 1748-1762, http://dx.doi.org/10.1016/j.comnet.2006.11.005.
14. Huang N, Hou D, Chen Y, Xing L D, Kang R. A network reliability evaluation method based on applications and topological structure. Eksploatacja I Niezawodnosc-Maintenance and Reliability 2011; 3: 77-83.
15. Jiang Y M. A basic Stochastic network calculus. Computer Communication Review 2006; 36: 123-134, http://dx.doi.org/10.1145/1151659.1159929.
16. Jiang Y M, Liu Y. Stochastic network calculus, Springer, 2008.
17. Jiang Y M, Yin Q, Liu Y, Jiang S. Fundamental calculus on generalized stochastically bounded bursty traffic for communication networks. Computer Networks 2009; 53: 2011-2021, http://dx.doi.org/10.1016/j.comnet.2009.03.004.
18. Jin P Y, Tanaka S. Reliability Evaluation of a Network with Delay. IEEE Transactions on Reliability 1979; R-28:320-324, http://dx.doi.org/10.1109/TR.1979.5220618.
19. Karagiannis T, Molle M, Faloutsos. Long-range dependence ten years of Internet traffic modeling. IEEE on Internet Computing 2004; 8: 57-64, http://dx.doi.org/10.1109/MIC.2004.46.
20. Karagiannis T. The SELFIS Tool, 2002. http://alumni.cs.ucr.edu/tkarag/Selfis/Selfis.html(accessed10Dec2013).
21. Leland W E, Taqqu M S, Willinger W, Wilson D V. On the self-similar nature of Ethernet traffic. ACM SIGCOMM Computer Communication Review 1993: 183-193, http://dx.doi.org/10.1145/167954.166255.
22. Li R Y, Huang N, Kang R. Modeling and simulation for network transmission time reliability. Reliability and Maintainability Symposium (RAMS) 2010: 1-6.
23. Liu C, Wang T, Zhao C, Xiong H G. Worst-case flow model of VL for worst-case delay analysis of AFDX. Electronics Letters 2012; 48: 327-328, http://dx.doi.org/10.1049/el.2011.4028.
24. Liu Y, Tham C K, Jiang Y M. A calculus for stochastic QoS analysis. Performance Evaluation 2007; 64: 547-572, http://dx.doi.org/10.1016/j.peva.2006.07.003.
25. Ma X M. On the reliability and performance of real-time one-hop broadcast MANETs. Wireless Networks 2011; 17: 1323-1337, http://dx.doi.org/10.1007/s11276-011-0351-x.
26. Meyer J F. Performability evaluation: Where it is and what lies ahead. Computer Performance and Dependability Symposium 1995:334-343.
27. Nadarajah S. Comment on "A general model for long-tailed network traffic approximation". Journal Of Supercomputing 2008; 44(1): 98-101, http://dx.doi.org/10.1007/s11227-007-0150-4.
28. Ramirez-Marquez J E, Coit D W. A Monte-Carlo simulation approach for approximating multi-state two-terminal reliability. Reliability Engineering & System Safety 2005; 87: 253-264, http://dx.doi.org/10.1016/j.ress.2004.05.002.
29. Ridouard F, Scharbarg J L, Fraboul C. Probabilistic upper bounds for heterogeneous flows using a static priority queuing on an AFDX network. IEEE International Conference on Emerging Technologies and Factory Automation(ETFA) 2008: 1220-1227.
30. Rizk A, Fidler M. Non-asymptotic end-to-end performance bounds for networks with long range dependent fBm cross traffic. Computer

Networks 2012; 56: 127-141, http://dx.doi.org/10.1016/j.comnet.2011.07.027.
31. Rizk A, Fidler M. Sample path bounds for long memory FBM traffic. Proceedings IEEE INFOCOM 2010:1-5.
32. Scharbarg J L, Ridouard F, Fraboul C. A probabilistic analysis of end-to-end delays on an AFDX avionic network. IEEE Transactions on Industrial Informatics 2009; 5: 38-49, http://dx.doi.org/10.1109/TII.2009.2016085
33. Vaze R. Throughput-delay-reliability tradeoff in ad hoc networks. Proceedings of the 8th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt) 2010: 459-464.
34. Wang S P, Sun D, Shi J, Tomovic M. Time delay oriented reliability analysis of Avionics Full Duplex Switched Ethernet. 8th IEEE Conference on Industrial Electronics and Applications (ICIEA) 2013: 982-987.
35. Willinger W, Paxson V, Taqqu M S. Self-similarity and heavy tails: Structural modeling of network traffic. A practical guide to heavy tails: statistical techniques and applications 1998; 23: 27-53.
36. Willinger W, Taqqu M S, Sherman R, Wilson D V. Self-similarity through high-variability: statistical analysis of Ethernet LAN traffic at the source level. ACM SIGCOMM Computer Communication Review 1995; 25: 100-113, http://dx.doi.org/10.1145/217391.217418.
37. Yamkhin D, Won Y. Modeling and Analysis of Wireless LAN Traffic. Journal Of Information Science And Engineering 2009; 25(6): 1783-1801.
38. Yao M, Qiu Z, Kwak K. Leaky bucket algorithms in AFDX. Electronics Letters 2009; 45: 543-545, http://dx.doi.org/10.1049/el.2009.1043.
39. Zeng X, Song D. The research on end-to-end delay calculation method for real-time network AFDX. International Conference on Computational Intelligence and Software Engineering(CiSE) 2009:1-4.

Zhitao WU
Ning HUANG
Ruiying LI
Yue ZHANG
School of Reliability and Systems Engineering, Beihang University
No.37, Xueyuan Road, Haidian District, Beijing, 100191, China
Science and Technology on Reliability and Environmental Engineering Laboratory
No. 37, Xueyuan Road, Haidian District
Beijing, 100191, China
E-mails: wuzt2010@gmail.com, hn@buaa.edu.cn, liruiying@buaa.edu.cn, zybuaa2013@163.com