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.
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 Leland [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, $J_m$ 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:

$$D_F = L_D + T_D + B_D + F_D$$  \hspace{1cm} (1)$$

where $L_D$ is the transmission delay over the link, $T_D$ is the technical processing delay, and $B_D$ is the delay in switch buffer. In particular, $L_D$ is determined by $L_D = m_s \times S_m(F) / R$, where $m_s$ is the number of links in the VL, $S_m(F)$ is the frame size with interframe gap, and $R$ is the link bandwidth; $T_D$ 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 switches in the AFDX is not large, hence $T_D$ can be regarded as a fixed value, i.e., $T_D = m_s \times 16$ μs, where $m_s$ is the number of switches in the VL; $B_D$ is determined by the frame queueing process, which highly depends on the traffic load of each switch port [32]. As $L_D$ and $T_D$ are fixed values for a deterministic AFDX configuration, we focus on how to model delay reliability with $B_D$ 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:

$$Pr(BD > BD_U) \leq f(BD_U)$$  \hspace{1cm} (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:

$$R_D = Pr(D \leq D_U) = 1 - Pr(D > D_U)$$  \hspace{1cm} (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.

![Diagram](image-url)
[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 \( \sigma \geq 0 \),

\[
\Pr(A(s,t) > \alpha(t-s) + \sigma) \leq f_A(\sigma), \tag{4}
\]

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 \( \delta > 0 \),

\[
\Pr(A \otimes \beta(t) - A^\ast(t) > \delta) \leq g_A(\delta), \tag{5}
\]

where symbol \( \otimes \) is the min-plus convolution:

\[
a \otimes b(x) = \inf_{y \in \mathbb{R}} \{a(y) + b(x-y)\}, \quad g_A(\delta) \text{ is the violable function of } \beta(t).
\]

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

\[
BD(t) = \inf_{\delta > 0} \{t, A(t) - \beta(t) \leq A^\ast(t)\}. \tag{6}
\]

As is shown in Fig. 2, the delay at time \( t_i \) 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](image)

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 \( \alpha_i(t) \) and \( \alpha_j(t) \) compete for resources in a switch system under the scheduling policy. Assume the SSP of the network system is \( \beta(t) \), the STP of \( \alpha_i(t) \) is \( \alpha_i(t) \), and the SSP \( \beta(t) \) provided by the system for \( \alpha_i \) can be expressed as \( \beta_i(t) = \max\{\beta(t) - \alpha_j(t) > 0\} \) \( (i=1,2, \text{ and } j=3-i) \), and its violable function can be calculated as \( g_{\alpha_i}(x) = g \otimes f_{\alpha_j}(x) \).

### 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 \( BAG - J_m^i \) and \( BAG + J_m^i \), where \( J_m^i \) is the jitter of the \( i \)-th VL.

![Fig. 3. Frame transmitting process in multiple VLs at an ES outport](image)

In a switch, the queuing is occurred at the outport. In one outport (see Fig. 4), except the VL 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 \( J_m(t) \) be the cumulative arrivals of VL and background traffic flow in the time period \([0, t)\), respectively.

![Fig. 4. VL traffic under estimation and its background traffic at the switch](image)

#### 3.2.1. The stochastic traffic envelope for VLs

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

\[
\alpha_i(t) = 8S_m^i + 8S_n/BAG_i t. \tag{7}
\]

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

\[
Pr(A(s,t) > \alpha_i(t-s) + \sigma) \leq f_i(\sigma), \tag{8}
\]

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:

\[
\alpha_B(t) = 8\sum_i S_m^i + 8\sum_i S_n^i/BAG_i t. \tag{9}
\]
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.

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 exists 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:

\[
\alpha_B(t) = \sum_{i=1}^{n} \alpha_i(t) = pt + \sqrt{\rho \omega^2} B_H(t),
\]

(10)

where \( n \) is the number of VLs of the background traffic, \( \rho \) is the mean arrival rate, \( \omega^2 \) 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 \( \forall \geq \sigma, c \geq 0 \), \( \alpha_B(t) \) satisfies:

\[
\ln \Pr \left[ \alpha_B(t) - \alpha_B(t-s) \geq \sigma \right] \leq -\sigma^{2(1-H)} e^{\frac{\sigma}{1-H} \left( c + \rho \right)} \left( 2^H \right) \left( \frac{\rho}{H} \right)^{2H}.
\]

(11)

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

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

(12)

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

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

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]:

\[
\Pr(A \otimes \beta(t) - A'(t) > \delta) \leq g(\delta),
\]

(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:

\[
\Pr(A_i \otimes \beta_i(t) - A_i'(t) > \delta) \leq g_i(\delta),
\]

(14)
where $\beta(t) = \max \{ \beta(t) - \alpha(t), 0 \}$, and $g(t) = g \otimes f_B(t) = f_B(t)$ 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:

$$
Pr(BD_k \geq BD_{U,k}) \leq f_B((C - \rho_k)BD_{U,k}),
$$

(15)

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

$$
R_D \geq 1 - f_B \left( \frac{D_U - L - D - T D}{\sum_{k=1}^{m_s} \frac{1}{C - \rho_k}} \right).
$$

(16)

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

$$
BD_k = \inf_{0 \leq t \leq \tau} \left\{ t, A_i(t - \tau) \leq A_k(t) \right\}.
$$

Hence, for any $t > 0$, $Pr(BD_k \geq d) \leq Pr \left\{ A_i(t - d) \leq A_k(t) \right\}$ holds.

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

$$
A_i(t - y) - A_k(t) = A_i(t - y) - A_i(t - \tau) - \inf_{0 \leq t \leq \tau} \left\{ A_i(t) + \beta_i(t) + s - A_k(t) \right\} \leq \sup_{0 \leq t \leq \tau} \left\{ A_i(t) - A_i(t - \tau) - \beta_i(t) - A_k(t) \right\}.
$$

The equation $\delta$ of the above inference holds as Eq. (8) shows $Pr(\alpha_i(t) > \alpha(t - \tau) + \sigma) \leq 0$ for all $\sigma > 0$. 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 output is larger than $8s_{BAG} + B_i$, and hence the maximum value of $\beta(t)$.

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

$$
A_i(t - d) - A_k(t) \leq A_i(t) + \beta_i(t) - A_k(t) - (C - \rho_k)d.
$$

Based on the above analysis, we can obtain,

$$
Pr(BD_k \geq d) = \inf \Pr[A(t - d) \leq A_k(t)]
$$

$$
\leq \inf \Pr[A_i(t) + \beta_i(t) - A_k(t) \geq (C - \rho_k)d]
$$

$$
= f_B \otimes g((C - \rho_k)d) = f_B((C - \rho_k)d).
$$

(16)

where $f_B$ is given in Eq. (12).

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

Solving:

$$
\sum_{k=1}^{m_s} \frac{BD_{U,k}}{C - \rho_k} \geq D_U - L - D - T D
$$

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

$$
BD_{U,k} = \frac{D_U - L - D - T D}{C - \rho_k},
$$

$$
BD_{U,k} = \sum_{k=1}^{m_s} \frac{1}{C - \rho_k},
$$

(16)

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

$$
R_D = Pr(D \leq D_U)
$$

$$
= 1 - Pr(\sum_{S=1}^{m_s} BD_k \geq D_U - L - T D)
$$

(According to the min-plus convolution

$$
\geq 1 - f_B((C - \rho_k)BD_{U,1}) \otimes \cdots \otimes f_B((C - \rho_{m_S})BD_{U,m_S})
$$

$$
= 1 - f_B \left( \frac{D_U - L - D - T D}{\sum_{S=1}^{m_s} \frac{1}{C - \rho_S}} \right).
$$

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 algorithm for the delay reliability with a given delay upper bound is derived using STP and SSP, which is an intrinsic stochastic process.

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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 VL11 is measured with a delay upper bound.

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 to 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 output 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 departs the outputs of ES1 and SW2 can be calculated using PBA.pro Databus Analyser & Analysis Software embedded in AIM.

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:

\[
\hat{R}(D_U) = \frac{k_{DU}}{n},
\]

where \(k_{DU}\) 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 VL11 as:

\[
LD = m_L \times S_m / R = 2 \times 8 \times (1518 + 20) / 100 \times 10^6 \text{ ms} = 246 \text{ ms},
\]
According to AFDX specification, the processing delay can be calculated as:

\[ TD = m_i \times 16 \mu s = 2 \times 16 \mu s = 32 \mu s. \]

From the test, \( \rho_1 \) and \( \rho_2 \), the mean arrival rate in outport buffer of SW1 and SW2, are measured as \( \rho_1 = 1.935 \text{ Mbps} \) and \( \rho_2 = 2.469 \text{ Mbps} \) by AIM. According to Theorem 2, the delay reliability can be estimated under the given delay upper bounds. For example, if \( D_U = 500 \mu s \), then \( BD_U = D_U - LD - TD = 222 \mu s \), and the delay reliability can be calculated as:

\[
R_{D_U} = \Pr(BD_{SW1} + BD_{SW2} \leq BD_U) = 1 - f_B \left( \frac{D_U - LD - TD}{C - \rho_1} \right) \\
= 1 - f_B \left( \frac{222 \times 10^{-6}}{100 - 1.935} \right) \\
\geq 0.8125.
\]

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)),

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

where \( A(s_k, s_{k+1}, d) \) can be found in Theorem 1 of [32], and

\[ 0 = s_0 \leq s_1 \leq \cdots \leq s_K = \tau \text{ for any } K \in \mathbb{Z}^+ \text{ and } \tau = \lim_{u \to 0^+} x_t(u) \leq \beta_0(u). \]

If \( d = 4 \text{ ms} \), 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.

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.

5.2.4. Discussion

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 envelope 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 output buffers at the switch, an exploration of the effect caused by different scheduling algorithms will be studied in our future research.

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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, zybuua2013@163.com