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ORIGINAL PAPER

RC performance analysis based on model optimization with the aid of network calculus

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Abstract
Time-Triggered Ethernet (TTE) Network is a communication network which combines the time-triggered traffic and event-triggered traffic. Based on network calculation, the adopted model in TTE considers the worst case which assumes a number of traffic simultaneously arrive at a node and each virtual link work is fully loaded. Such assumptions lead to the analysis of a certain RC data flow's delay performance obsessing too much pessimism. In this paper, based on the partition scheduling model, we introduced the loss packet period of the time-triggered data flow p and the correction parameter of rate-constrained (RC) data flow μ and then optimized the model of service curve and arrival curve of a certain RC data flow. The delay performance of RC data flow is analyzed under proposed optimized model. Simulation results verify that our optimized model relieves the pessimism on delay analysis. The smaller the p value is and the larger the μ value is, the stricter delay bound can be obtained by our optimized model than by the traditional model. According to the optimized delay analysis model, the scheduling table can be better rearranged and the system resources can be used reasonably.

Keywords Time-Triggered Ethernet · Model optimization · Network calculation · Delay performance analysis · Virtual link

1 Introduction

Compared with traditional event triggered which means the transmission of data flows happens only when a certain event emerges, time triggered (TT) means the transmission of data flows is according to the schedule table which is designed at the initial stage. Time-Triggered Ethernet (TTE), which combines the features of real time, determinism and error tolerance with flexible and dynamic of traditional Ethernet, aims to support different traffics and become a norm among distinctive industrial areas. Based on the protocol 802.3 of Ethernet, TTE is not only compatible with the existed traditional Ethernet and but also adds time control in each node and thus ensures the data in a network are transmitted according to a schedule table in a system which separates the different traffics and guarantees the timeliness and certainty.

TTE has attracted considerable attention both in academia and in industry with its ability to ensure the time of data transmission and the safety of aerospace. In order to support the requirement about real time and security of different applications, the traffic flow is divided into three different traffics based on the TTE network architecture, which are TT traffic, RC (rate constraint) traffic and BE (best effort) traffic. TT traffic with the highest priority requires high certainty due to delay and jitter. BE traffic is the lowest priority traffic, and it does not have any requirement regarding to delay. RC traffic is delay sensitive, which has some requirements for delay in generally. In a practical system, the delay of RC traffic is affected by the mutual interference between the TT traffic and the RC traffic, so it is always uncertain. However, RC traffic delay is very important to ensure the safety of the aerospace system. Therefore, it is necessary to analyze the time delay of the RC traffic and network calculus is a mathematical method we can resort to.

Network calculus is a mathematical tool used to analyze the real time of the end-to-end network. By considering the worst case of a certain data flow on each network node, the

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deterministic upper and lower bounds can be calculated which contain all the possible maximum delay jitters on all the nodes that have been previously visited. Therefore, the values of the upper and lower bounds obtained by the above method are conservative in a part. Network calculus method was initially proposed by Cruz [1] and then gradually improved with the joint efforts of scholars [2–5]. Because the traditional network calculus is too pessimistic in the analysis of RC traffic delay, the optimization of RC traffic delay analysis has aroused great concern in industry and academy. In the literature [6], by considering the impact of a virtual link on the network, the jitter factor is introduced into the arrival curve and then optimizes the arrival curve, so as to improve the analysis of worst time delay. By integrating the arrival deviation of the data into the arrival curve, the literature [7] takes the arrival curves of the different flows after passing through the same switch into account and then makes up the pessimism analysis of the worst time delay. A composable method for getting the end-to-end delay bound is proposed in the literature [8]. This method uses the aggregated local arrival curve to get the local delay bound first and then calculates the end-to-end bound by summing up local bounds. By this method, the computation complexity can be largely decreased. By adding the concept of pore to the network which is called pore network modeling, the document [9] optimizes the arrival curve of TT traffic and optimizes the time delay analysis of RC traffic. The literature [10] proposed the utilization stochastic network calculus by which the authors obtain the upper bound of the delay with the probability guarantee of RC traffic and improve the time delay analysis of RC traffic. In the literature [11], TT traffic is regarded as the highest priority RC traffic, and then, the RC delay in preemption mode is studied. In [6–11], however, all authors neglect the impacts which are the loss of TT data and the arriving delay of RC data brought by the ARINC653 partition operation system.

Nowadays, since the superiority of the ARINC653 [12] partition operation system, it has been used extensively in the aerospace system. In order to satisfy the requirement of highly integrated and modular of modern avionics systems, the operating system defines criteria for multi-partition operating system interface to effectively separate upper application and operating system core and actualize the separation of applications based on time and space partition. The time and space partition proposed by ARINC653 becomes the core of the norm of ARINC653. As a design technology, partition management can be used to control the different functions of different applications in certain region, which ensures the dependence of each application and then ensures the security of the system. Partition, in other words, actually is notion of system design in minimal coupling. The smaller the coupling between components, the less likely the system will encounter unexpected risks.

By using time partition, ARINC653 partition operation system is able to divide the host processing time and perform the corresponding task which is the TT traffic during the determined time window. In a practical system, the TT traffic is not always produced in a specified time window according to the scheduling table; that is to say, not all the TT traffics will arrive exactly according to the designed schedule table. Besides, under the partition mode, the missing of the certain TT data has an effect on the system service to the RC traffic. At the same time, the arrival period of RC traffic in actual system can be variable because ARINC653 adopts a two-level scheduling model. The traditional RC traffic delay analysis in papers [6–11] neglects the real arrival of data flows in the actual system. The disadvantages of traditional methods can lead to a great pessimism of the delay analysis, which will result in a large waste of system resources such as time and bandwidth.

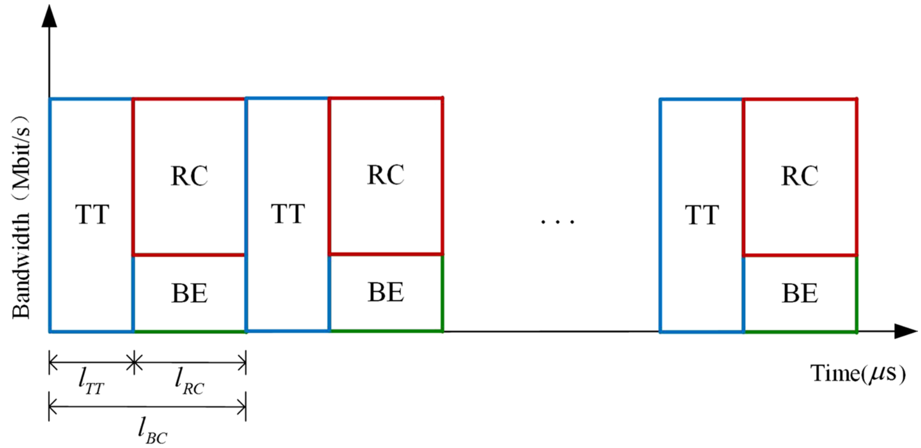
In this paper, the service curve model and the arrival curve model of RC traffic are optimized, respectively, by introducing the TT traffic shortage cycle and the RC traffic arrival adjustment factor. On the one hand, our proposed optimization model considers the interference of TT data packets loss to RC traffic and the variable of the arrival period of RC traffic due to two-level scheduling, which makes our model more realistic and reduces the pessimism of the deterministic network calculus analysis in a certain way. On the other hand, the optimized model can be adopted in the literatures that analyze the RC delay, which can help to improve the accuracy of delay analysis of RC traffic and can further be used to guide the rearranging of scheduling table and reduce the waste of system resources.

2 System model

In the TTE network, the scheduling model of TT is designed by designers, which greatly meets the needs of different designers. As shown in Fig. 1, it is a partition scheduling model [13]. In this partition mode, the transmission of TT traffic, RC traffic and BE traffic occupies the different time domains, respectively. At the same time, the RC traffic and BE traffic are isolated by the bandwidth, so that the three traffics are not interfered with each other which ensures the security of the system. Suppose that the TT traffic and the RC traffic are allocated with the time length l_{TT} and l_{RC} in a basic cycle l_{BC} and the time lengths satisfy the equation $l_{TT} + l_{RC} = l_{BC}$.

As shown in Fig. 2, there are three transmission modes of TT traffic and RC traffic, which are preemption mode, timely blocking mode and shuffle mode [7], respectively. The preemption mode indicates that when a TT data packet is arriving while a certain RC data packet is served by the system at the same time, the transmission of RC data packet

Fig. 1 TTE network partition scheduling model



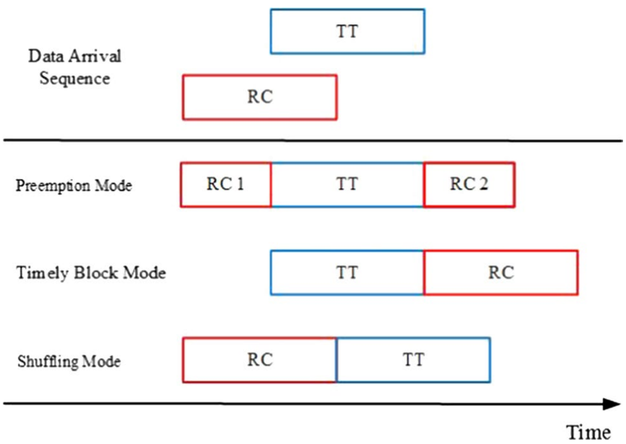
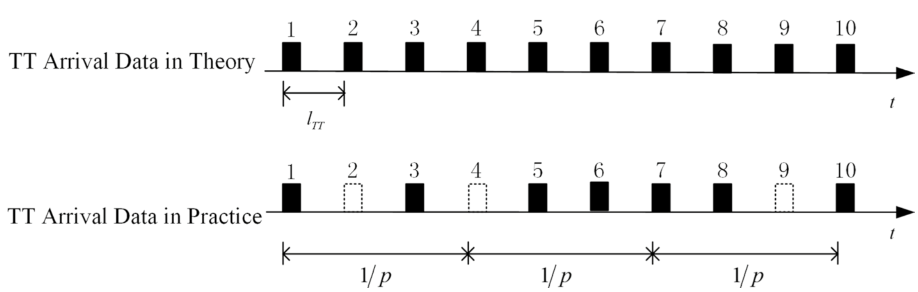


Fig. 2 Traffic transfer model of TT and RC

will be terminated and the system will turn to transmit the arriving TT data. After all the TT data are served, the system then continues the transmission of RC traffic. Under the timely blocking mode, the system will query the time length that is the duration between present time and the time of arriving of the next TT data packet before a RC data packet is transmitted. If the time length is large enough for a RC data packet to be transmitted completely, then the RC packet will be transmitted; otherwise, the transmission of RC data packets will be delayed. The shuffling mode refers to that when TT packet abruptly arrives in the process of RC packet transmission, in this case, TT packet will be sent after RC packet transmission is completed. In a practical TTE network, the preemption mode is extensively applied, so the delay performance of RC traffic is analyzed in the preemption mode.

In an actual TTE network, there will be some TT data packets which are not arrived at the previously designed time and RC data packets will put off the emergence at a switch node. These two kinds of data packets will affect the arrival curve and service curve of the RC data flow. In the previous literatures [6–11], the delay analysis of RC traffic did not take the actual system, i.e., the loss of TT data packets and the putting off RC data packets arrival, into account, so the analysis results would be too pessimistic and unrealistic. As shown in Fig. 3, we consider the actual arrival of TT traffic when the loss of TT data packets happens in a fixed period. Supposing that for a certain TT traffic, there will be a TT data packet missing in every p consistent TT packets, and we define the p as a packet loss period. According to the TTE network partition scheduling model we are adopting, the service time for a certain TT traffic is reduced when the TT traffic is reduced. When all TT traffics have been served by a node and if RC data packets exist in the node cache, then the node will serve the RC data packets. In this case, the time that the system ought to have served the TT traffic will turn to be used to transmit RC traffic; thus, the service curve of the RC traffic will be affected. For a certain RC data flow, due to the adoption of the two-level scheduling

Fig. 3 TT traffic shortage case



model, the actual period of RC traffic at a switch will extend with respect to the schedule table and thus affects the arrival curve of the RC traffic. Based on the changing of service curve and the arrival curve of a certain RC data flow, we will then optimize the two curve models and analyze the delay performance of a certain RC flow.

3 Performance analysis

In this section, we will optimize the service curve model and the arrival curve model of a certain RC data flow and analyze the delay performance of the RC data flow with the aid of network calculus.

3.1 Network calculus

Traditional network performance analysis theories adopt stochastic queueing method to analyze the statistical characteristics of the network, for example, the average time delay, throughput and so on. However, predictability or delay upper bounds for end-to-end delay of traffics to real-time networks are more important than statistical characteristics. In order to analyze the real-time service, a specific method called network calculus was proposed. Network calculus is a mature mathematical tool, which is a new QoS theory, mainly based on the mathematical theory of independent and complementary theory. By using the minimum addition algebra (Min-Plus Algebra) and maximum addition algebra (Max-Plus Algebra) which belong to idempotent mathematic and combining modeling network, network calculus has solved the problem of the delay of the network model and the upper and lower bounds of the queue backlog performance parameters.

There are two branches of network calculus: One is deterministic network calculus and the other one is stochastic network calculus. In deterministic network calculus, the upper and lower bounds of network performance can be accurately obtained with the help of arrival curve and serve curve, such as finding the maximum delay of a certain traffic when it passes through a network, solving the cache size and cache backlog data length of communication nodes in the specified network, etc. In stochastic network calculus, a probability envelope is proposed to represent a random process. Implementing effective bandwidth theory and statistical reuse analysis of arrival and service processes on the probability envelope, issues such as the statistical boundary of network parameters for specified networks and network resource utilization can be figured out. Since network calculus can quickly and effectively obtain the network parameters and performance boundaries of the specified network through network modeling, now it has been widely applied in Ethernet, sensor network, TTE and other network areas for performance analysis.

In terms of the worst case of calculation of end-to-end delay in a network, deterministic network calculus takes the worst case in each node which is passed by a certain traffic into consideration and contains all the possible maximum delays on all the previously visited nodes. A deterministic performance bound can be obtained consequently, which can be attained by calculating the horizontal distance and vertical distance between the traffic's arrival curve and service curve.

For a given data flow, the accumulative function of its packet arrival time $(0, t)$ is set as $A(t)$. $\forall t \geq 0$, if $\alpha(t)$ satisfies formula (1); we call $\alpha(t)$ the arrival curve of the data flow.

$$A(t) \leq \inf_{0 \leq s \leq t} \{A(s) + \alpha(t-s)\} = (A \otimes \alpha)(t) \tag{1}$$

In formula (1), $\otimes$ is the minimum convolution. There are two common arrival curves: affine arrival curve and step function arrival curve.

If $\alpha(t)=\rho t$ in which the constraints of the data flow mean the given arbitrary time length τ, the upper bound of bits of this data flow is ρt, that is, this data flow's peak rate is constrained by the system's link rate which is ρ bit/s. The data flow whose peak rate is constrained is called constant bit ratio (CBR) or deterministic bit ratio (DBR). On the other hand, if the arrival curve can be represented by $\alpha(t)=\sigma$ in which σ is a constant number, this means the received bits of one node cannot exceed σ bits. In a more general case, according to the relationship between leaky bucket and arrival curve, we can express the arrival curve by the following formulation:

$$\alpha(t) = \begin{cases} \sigma + \rho t & t \geq 0 \\ 0 & t \geq 0 \end{cases} \tag{2}$$

in which ρ is the packet arrival rate and σ is burst tolerance. This formula indicates that the packet of σ bits can be sent suddenly by the source, but in the long run, the packet arrival rate cannot exceed ρ bit/s. This is the affine arrival curve. For step-function arrival curve, it can be represented by the following formulation,

$$\alpha(t) = \begin{cases} \left\lceil \frac{t+\tau}{T} \right\rceil & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{3}$$

in which the parameter T represents time interval and the parameter τ represents delay tolerance. According to the feature of data flow in TTE network, we select the affine arrival curve as arrival curve to analyze system's performance.

For a certain data flow served by a network, we assume that the arrival cumulative function of the data flow is $A(t)$ and the output cumulative function is $A^*(t)$. If there is any

$\beta(t)$ satisfying formula (4), then we call $\beta(t)$ as the service curve of the arrival flow.

$$A^*(t) \geq \inf_{0 \leq s \leq t} \{A(t) + \beta(t-s)\} = (A \otimes \beta)(t) \tag{4}$$

A typical service curve is the rate delay service curve as formula (5), in which R represents the service rate of the system data flow and T is the service delay, $[x]^+ = \max\{x, 0\}$.

$$\beta(t) = R[t-T]^+ \tag{5}$$

In network calculus, what we focus on is the bound of delay and backlog for a given arrival traffic. Backlog means the number of data which are stored in system' storage and wait to be served or be calculated. In general, we refer backlog to the queue length in a system cache, that is, the queue length is equal to the size of backlog. In a system, the delay of a certain data flow means the time length between the arriving time of the data and the leaving time of the data. Specifically, we can obtain a certain data flow's delay by calculating the time the data waiting to be served and the time the data are being processed. Based on the arrival curve and service curve, we obtained from formulation (6) and formulation (7); then, we can calculate the delay and backlog of a certain data flow. According to the theory of network calculus, the biggest delay $h(\alpha, \beta)$ refers to the maximum horizontal distance between arrival curve $\alpha(t)$ and service curve $\beta(t)$ and the biggest backlog $q(\alpha, \beta)$ can be derived by calculating the maximum vertical distance between arrival curve $\alpha(t)$ and service curve $\beta(t)$. Then, we have the following formulations to calculate the biggest delay and the biggest backlog for a certain data flow:

$$h(\alpha, \beta) = \sup_{s \geq 0} \{\inf\{\tau \geq 0 | \alpha(s) \leq \beta(s+\tau)\}\} \tag{6}$$

$$q(\alpha, \beta) = \sup\{s \geq 0 | \alpha(s) \leq \beta(s)\} \tag{7}$$

3.2 Performance analysis of RC traffic delay

The service rate offered by a system to RC traffic depends on the link physical transmission rate R and the duty ratio of the scheduling table. Under the timely preemption mode and considering the worst case, we can obtain the delay of RC traffic in a basic cycle according to formula (8), in which $S_{\max}$ represents the maximum packet length of a RC data packet.

$$l_1 = l_{\mathrm{TT}} + \frac{S_{\max}}{R} \tag{8}$$

As shown in Fig. 4, if we assume that the aggregation TT data flow has a packet loss period of 4, there are four cases in terms to lose a packet, that is, the loss of the first packet, the second packet, the third packet and the fourth packet, and the occurrence probability of loss a certain

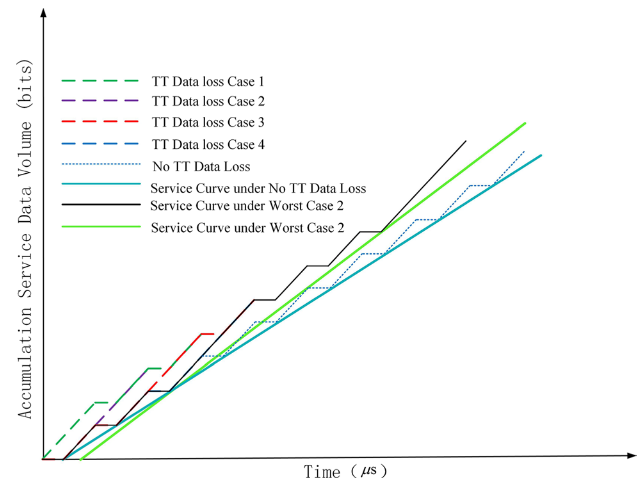


Fig. 4 RC data flow service curve

packet is equal. According to the method of induction, we can find the worst case, that is, the system offers worst service to RC data flows, happens when a certain TT traffic loses its last packet in a packet loss period. Then, we can attain the slope of the optimal service curve of RC traffic as formula (9) under the situation of TT data flows will lose one packet in its packet loss period. And then we can obtain the service curve of the RC traffic which can be expressed as formula (10).

$$k = R \cdot \frac{p \cdot l_{\mathrm{BC}} - (p-1) \cdot l_1}{p \cdot l_{\mathrm{BC}}} \tag{9}$$

$$\beta_1(t) = \frac{R}{p \cdot l_{\mathrm{BC}}} \left\{ \left\{ p l_{\mathrm{BC}} - (p-1) \cdot l_1 \right\} t + (p-1) l_1 (l_1 - 2 l_{\mathrm{BC}}) \right\} \tag{10}$$

Since we adopt the partition scheduling model in network system, the period of actual RC data flows is longer than that in the predesigned schedule table. Thus, we introduce the conception of correction factor to correct the period of RC data flows. Considering the worst case, we assume that the RC data flow will be transmitted with the maximum packet length $S_{\max}$ at a certain node (source terminal or switch), and we assume the minimum packet interval between the adjacent RC data packets is τ_{BAG} and the correction factor is μ; then, we can obtain the RC data flow arrival curve at a certain node according to formulation (11).

$$\alpha(t) = \sigma + \rho t = S_{\max} + \mu \cdot \frac{S_{\max}}{\tau_{\mathrm{BAG}}} t \tag{11}$$

The modified optimization RC data flow's arrival curve model and service curve of RC data flow's model are shown in Fig. 5. According to the delay definition in network calculus, by analyzing the maximum horizontal distance between the arrival curve and the service curve of a RC data flow, we

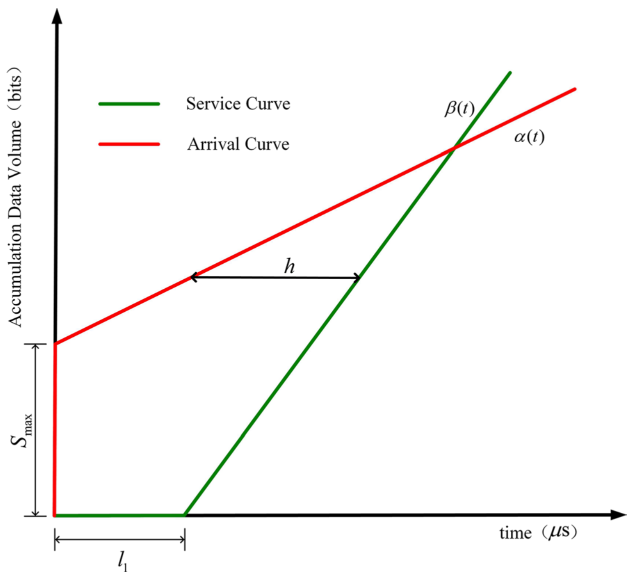


Fig. 5 RC data flow service curve

can get the worst delay of a certain RC data flow at a certain node as the following formulation.

flow is served by port ES1, ES2 and ES3, and we assume that the maximum burst degree of the RC aggregate flow is constrained by 12 packets, which is the longest, that is, $S_{\max} = 1518$ bytes, and we assume the packet arrival period is 2 ms. Besides, the aggregated RC flow is transmitted only through the switch SW1 to port ES5 in the network. Supposing the physical link rate in the network is 100 Mbits/s. According to the partition policy [13], for a basic period in the TT schedule table, we set the length of TT period as $l_{\mathrm{TT}} = 485.76\,\mu\mathrm{s}$.

In Fig. 7, we study the effect of RC traffic correction factor on RC traffic delay performance analysis. The abscissa 0 is defined as the time when the first RC traffic reaches the node, and considering the worst case, the RC traffic is assumed to arrive instantaneously in a maximum length at this point. As shown in Fig. 7, we can find that the initial delay of the RC data flow is equal regardless of which value the μ adopts. The reason is that no matter which value of μ is chosen, once the maximum burst length is determined, the worst time delay of the RC traffic becomes certainty. However, with time going on, the system is beginning to serve the RC data flow, and we can find the waiting time delay of the subsequent RC data will become smaller and smaller.

$$\begin{aligned} h(\alpha,\ \beta) &= \sup_{t\geq 0}\{\inf\{\tau \geq 0 | \alpha(t) \leq \beta(t+\tau)\}\} \\ &= \sup_{t\geq 0}\left\{\inf\left\{\tau \geq 0 | S_{\max} + \mu\cdot\frac{S_{\max}}{\tau_{\mathrm{BAG}}}t \leq \frac{R}{p\cdot l_{\mathrm{BC}}}\cdot\left\{\left\{pl_{\mathrm{BC}} - (p-1)\cdot l_1\right\}(t+\tau) + (p-1)l_1(l_1 - 2l_{\mathrm{BC}})\right\}\right\}\right\} \end{aligned} \tag{12}$$

4 Simulation results

In this section, in order to validate the outperformance of our optimization model to the traditional model, we simulated and analyzed the network delay performance of RC data flows. Since the main research interest of this paper is to optimize the arrival curve and service curve model of RC data flows, we do not consider situations such as flow aggregation, cross-flow, data flow diversion and so on. We assume that there is a known TT aggregate flow and a known RC aggregate flow in the system which are waiting for serving. As shown in Fig. 6, supposing an aggregated RC

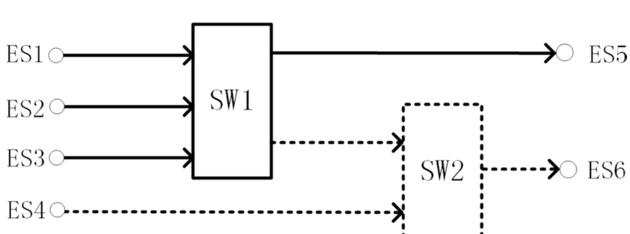


Fig. 6 Switch model

At the same time, we can also find that the RC data delay is also decreasing with the decrease in μ value. This is because when the total number of incoming RC data is reducing,

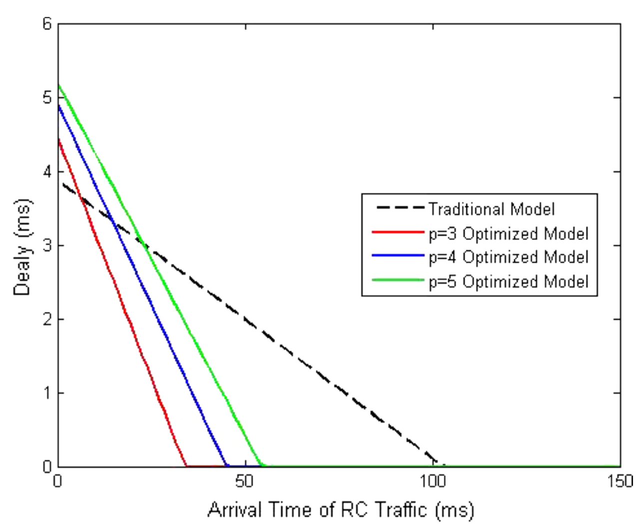


Fig. 7 Analysis of RC traffic delay under the change of RC traffic arrival cycle

the waiting time of subsequent data will also decrease, thus reducing the waiting delay of RC data which arrive at a later time. Compared with the original model, that is, when $\mu = 1$, the waiting time delay of later arrival data in our proposed optimization model is smaller. And thus, we avoid the pessimistic performance analysis to a certain extent. At the same time, we can optimize the scheduling table of the system and rearrange a more practical and efficient schedule according to the results of the analysis.

As time goes on, we can find the time delay of RC data flow which is arrived later is approaching zero. This is because we merely consider one switch node and one aggregation flow in our simulation model, that is, there is no any other cross-flow's interference the flow which we have interest on. Therefore, the RC aggregation flow that arrives after a certain time will not have a waiting delay in such situation. The assumption we proposed will also lead to the same situation, that is, the delay would be zero, happens in the following simulation results. But according to the analysis method used in the article [7], by adjusting the expression of the aggregate flow, our model can be applied to the multi-level switches scene to get a more precise time delay analysis model. In this paper, what we focus on is just the optimization of system model by taking TT data packet loss and RC data arrival period expanded into consideration, so we no longer simulate the multi-level switch model.

As shown in Fig. 8, we simulated the delay of RC traffic with different packet loss periods. As we can see, the RC traffic delay of our proposed optimization analysis model is larger than the original model, that is, $\mu = 1$ before time $(p-2)l_{\mathrm{BC}} + l_1$. The reason is that in order to simplify the analysis of a certain RC data flow delay performance, we used a simplified mathematical model. However, as the system time goes on, after the time $(p-2)l_{\mathrm{BC}} + l_1$, the RC data flow delay of our proposed optimization analysis model is smaller compared with the original analysis model. The smaller the packet loss period of an aggregation TT data flow, the stricter and more practical the delay results of RC flow data in our optimization model compared with the traditional model. According to the results obtained from our proposed optimization model, it is more conducive to adjust the original scheduling table of the system and rearrange the scheduling rules of TT data flows and RC data flows more reasonably.

Combining Figs. 7 and 8, if we ignore that TT data flows have the probability of not emerging in an actual network as the designed schedule and the arrival of a certain RC traffic defers at a certain node due to the partition scheduling, we will find the result would be too pessimistic. When the data obtained from the traditional performance analysis are used to design a scheduling table, it will lead to waste system resources such as time and virtual link bandwidth, which do not meet the requirements of the theme of efficient transmission. Based on the actual system, we optimize the arrival curve and the service curve for a certain RC data flow, which avoids the pessimism of the RC data flow delay performance analysis and is more practical to some extent. The optimization curve model can also be used to guide the rearrangement of scheduling tables, so as to more rationally and more efficiently make use of system resources.

In Fig. 9, we compare a RC data flow delay performance under the proposed optimization model and the simulation model. From the diagram, we can see that the time delay of the optimized model is no less than the time delay of the simulation model which is because we consider the worst case in the system. And thus, we obtain the upper bound of

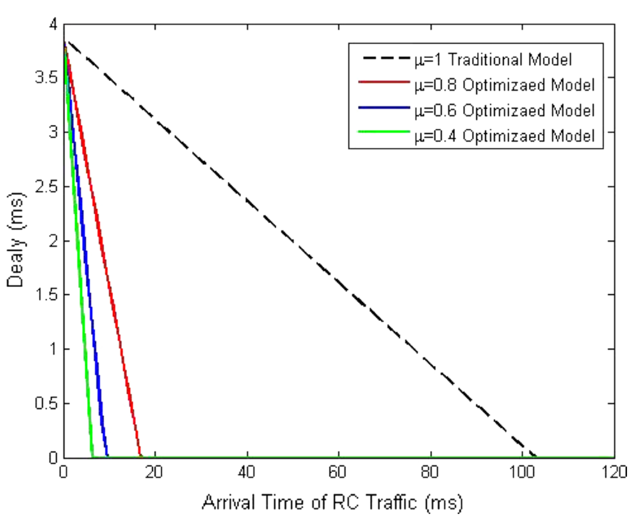


Fig. 8 Time delay analysis of RC traffic under TT traffic packet dropout situation

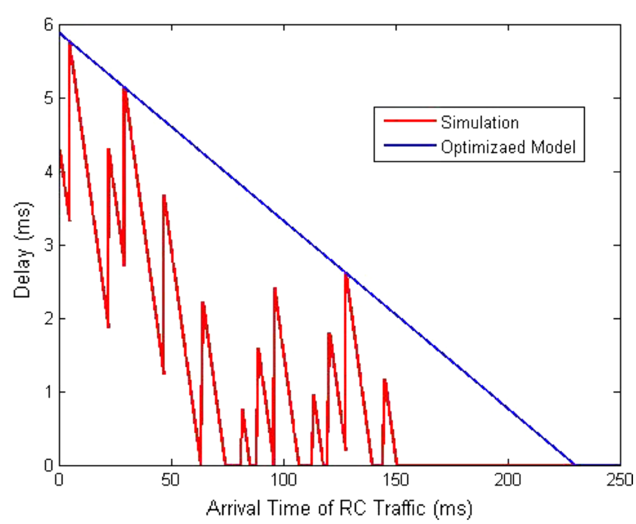


Fig. 9 Analysis of RC traffic delay based on the proposed model and simulation model

a certain RC data flow. It shows that the delay obtained by our analysis is reasonable and can be used to represent the worst time delay in the actual system. The result verifies the correctness of our RC traffic optimization model.

5 Conclusion

In this paper, we optimize the arrival curve model and the service curve model of a RC data flow by considering the non-full load generation of TT data flows and the change of the RC data flow's arrival period which always happen in an actual system. According to our optimization system model, we then analyze the delay performance of a certain RC data flow. The simulation results show that our proposed optimization model outperforms the traditional model in avoiding the pessimism of RC data flows. By adjusting the loss packet period p of the TT data flow and the arrival period correction factor μ of the RC data flow, our proposed optimization model can describe the service curve model and arrival model of the RC data flow more precisely compared with traditional model. At the same time, our proposed RC arrival curve model and the service curve model reduce the pessimism of delay analysis in deterministic network calculus. Based on the optimization model and the analysis results, we can rearrange the system's scheduling table more reasonably and make full use of resources more efficiently.

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