Research on train communication network based on switched Ethernet

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Abstract

Recently with the development of high-speed railways, the traditional train communication network (TCN) can barely meet the increasing demand of real-time and high data rate transmission requirements. In this study, a solution based on switched Ethernet is firstly proposed with reconstructed TCN topology and communication protocol stacks. Then, virtual link and flow shaping were introduced in order to realize a strictly real-time communication. By using the network calculus theory, the presented strategies were proven to admit a maximum delay constraint and simulation results also verify our analysis. Finally, a detailed analysis of the vehicle layer and backbone layer are given, where the results show that traditional TCN could be replaced by TCN based on switched Ethernet.
Keywords: switched Ethernet, TCN, network calculus, virtual link.

1 Introduction

The train communication network (TCN) is a real-time system. During the data transmission process, a message has a determined time limit. Failing to complete within the limit will lead to disastrous results. The communication rate of a multifunction vehicle bus (MVB) and wire train bus (WTB) are respectively 1 Mbit/s and 1.5 Mbit/s, in order to meet the strict real-time requirement. The only way of guaranteeing the real-time constraint is to limit the size of

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the message, hence reducing the data frame transmission delay. But with the fast development of high-speed trains in China, the data communicated in TCN are increasing dramatically. So it can be foreseen that MVB and WTB should meet the growth of information, and their capacity would be larger, and the rate would be higher.

Switched Ethernet has the characteristics of good expansibility, a high bandwidth and low cost, etc. Recently, it has been wildly applied in the national defence, communication, aerospace and industrial control fields. Avionics full duplex switched Ethernet [1] (AFDX) is a new generation avionics data bus, which is based on switched Ethernet and has been improved in real-time and reliability according to the needs of aviation electronics. It is now widely recognized by the aircraft manufacturers [2], and it has been successfully used in large commercial aircraft. Therefore, in this paper, our focus is on the design of applying the switched Ethernet in the TCN.

1.1 Traditional and TCN base on switched Ethernet

IEC61375-1 standard was established for the railway on board device data communication in 1999. The TCN standard defines two-level bus structures which share upper real-time protocols (RTP), namely MVB and WTB. Both of them use the periodic master–slave protocol, providing three services of process data, message data and monitoring data.

Switched Ethernet adopts micro collision domain division technology, solving the conflicts of delay uncertainty in the shared Ethernet caused by the carrier sense multiple access with collision detection (CSMA/CD) mechanism. In addition, functions such as 802.1p, the 802.1q, and full-duplex are introduced, which also make the applications of switched Ethernet become possible for strong real-time industrial control fields [3].

AFDX is developed on the basis of switched Ethernet. It makes full use of commercial off-the-shelf (COTS), which has achieved high-cost performance. Moreover, it meets the demand of high bandwidth, reduces channel jams, and improves the transmission rate at the same time. In solving the uncertainty of traditional Ethernet, AFDX uses the measure of limiting the transmission delay of data packets in the terminal nodes, and making the communication operation schedules. Hence, the AFDX transmission performance can be improved and the aviation electronic system needs are met [4].

1.2 TCN topology structure based on switched Ethernet

The development of switched Ethernet can bring new opportunities to solve the problem of Ethernet uncertainty. Moreover, equally applying switched Ethernet to TCN can also improve both the network communication rate and its real-time performance with certainty. Based on this, the following network topology structure combined switched Ethernet with TCN is proposed, as shown in Figure 1.

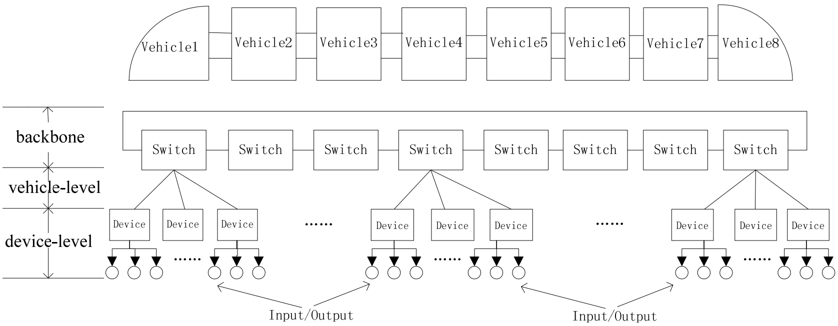

Figure 1: The TCN topology structure based on switched Ethernet.

The scheme divides the basic structure of TCN into three layers.

The first layer is backbone, namely, the train-level layer (corresponding to WTB). Each carriage's switch is connected in a cascade way, realizing the train-level control. Head and tail vehicle switches are also connected forming a ring network structure. In the circuit connection, a redundant double lines scheme is used. For control instruction data that have strict requirements for real-time performance and reliability, the central unit sends information towards two directions of the loop at the same time, so as to avoid immediate failure. This ring network structure improves the reliability of a TCN.

The second layer is the vehicle-level layer (corresponding to MVB), with physical media using a redundant twisted shielded pair. It abandons the traditional topology of TCN, using the star-type topology for connection. Each terminal system has a unique physical access to the switch, and each has an only collision domain, which avoids data conflicts on the transmission path while reducing the data transmission delay.

The third layer is the device-level layer, (corresponding to equipments which are connected to the railway vehicle MVB equipment). In this way, the improved TCN only changes the realization of the bottom layer, rather than a TCN upper protocol.

1.3 TCN communication protocol stack based on switched Ethernet

There are three main improvements to the traditional TCN communication protocol stack, as shown in Figure 2.

Firstly, application tasks are divided into two types, real-time and non real-time. The next thing is to set up the RTP layer and real-time virtual layer. Finally, the bottom uses the transport layer based on the standard TCP and UDP protocol, and the network layer based on the standard IP and switched Ethernet layer.

In order to be well integrated with the existing TCN, the real-time protocol is fully compatible with the traditional RTP protocol. Moreover, in order to meet the requirements of the data transmission mechanism by RTP in TCN standard, as well as the goal that the bottom layer can use TCP and UDP/IP and switched Ethernet, the real-time virtual layer is able to provide an upper RTP with the process data, message data and monitoring data transmission services, which not only conforms to the requirements of RTP, but also shields the RTP from the bottom using TCP and UDP/IP protocols.

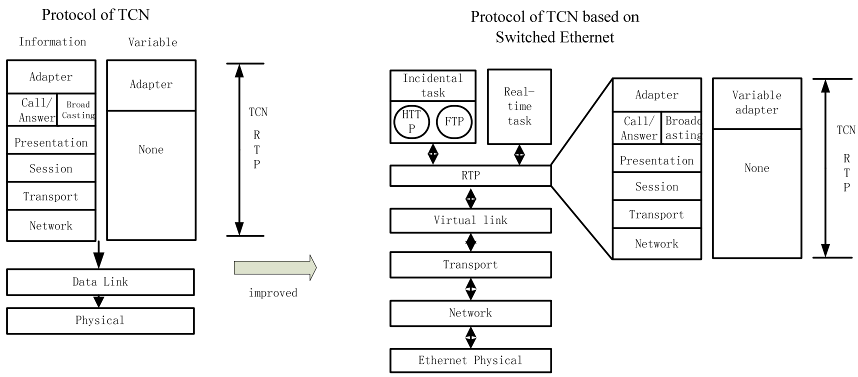

Figure 2: Improvement of communication protocol stack.

2 Real-time virtual layer

2.1 Virtual link (VL)

With reference to the AFDX related concepts in [1], the concept of virtual link (VL) is introduced to the real-time virtual layer. VL provides a one-way logical link from a source terminal to one or more target terminals.

VL connections can be adopted in the RTP layer to guarantee the availability of the RTP layer with the determinate network. Here, we summarize the characteristics of VL as follows:

(1) Data communication in the TCN is realized by VL, each VL has its own VL ID. For the real-time virtual layer packets data, the VL ID is packed. Each VL has its own special VL bandwidth, allocated by the system integration.

(2) The terminal system realizes VL separation in the logic after setting the available bandwidth of each VL. It does not matter whether the VL is utilized to full loads, the available bandwidth of other VLs is not affected.

(3) VL has two important parameters:

- The minimum time interval between a VL internal adjacent Ethernet frames is BAG (Figure 3), whose value is $2n$ times of the TCN fundamental period $(n = 0, 1, 2 \ldots 10)$.
- In VL, the allowed transmission maximum length of the Ethernet frame is $Lmax$. Therefore, each VL's maximum bandwidth [1] allocated is defined as:

$$C= (Lmax *8*1000) /BAG \text{ bps} \tag{1}$$

Then, for a VL whose BAG is 1 ms and frame length is 1518 bytes, its maximum data transmission rate is 12.144 Mbit/s.

(4) VL realizes a flow control function through two of its own parameters including the bandwidth allocation gap and jitter.

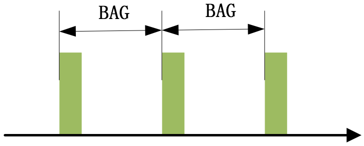

Figure 3: Minimum time interval.

For example, according to Table 1, which shows the number of message source ports and communication period of the first vehicle of CRH3 (a type of China high-speed train), the real-time data are packeted in the real-time virtual layer to meet data transmission requirements. According to the characteristics of the above data, they are packeted into six packets, and separately used for six VLs.

Table 1: Source port and communication period.

First vehicle	Number of polling cycle's source port					
	32 ms	64 ms	128 ms	256 ms	512 ms	1024 ms
No. Source Port	22	5	97	4	12	27

According to the definition of VL, the BAGs of VL are set to 32, 64, 128, 256, 512, 1024 (ms), in order to meet the needs of real-time data transmission.

2.2 Virtual link dispatch mechanism

Flow shaping, VL dispatch and other real-time data transmission guarantee mechanisms are added in the real-time virtual layer, as shown in Figure 4 [5]. Flow shaping is used to distribute communication resources, which means each specific VL is allocated with an available bandwidth interval (BAG) and a maximum sending frame length (*Lmax*) according to its need. The function of flow shaping is to ensure that the message flows sent during each BAG interval do not exceed a frame. So it can prevent transient data flow and determine the max limit of queuing delay flow under the worst conditions. VL dispatch sends an Ethernet frame to the physical link through the FIFO way.

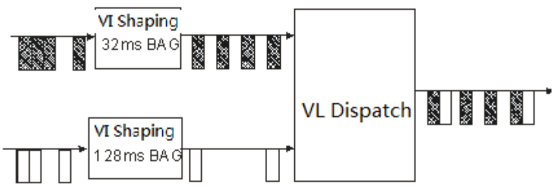

Figure 4: Flow shaping and VL dispatch.

2.3 Process of sending and receiving messages

The application data are divided into real-time data and incidental data. When the train data collector acquires real-time data, data are sent to the real-time protocol layer for packeting (according to the RTP protocol of TCN). In practice, the real-time data are called process data, which are sent periodically and have no change. As a result, the specific process data and specific VL can be connected. In other words, only a few kinds of specific process data are transmitted in a VL. In the real-time virtual layer, according to this corresponding relationship, the process data are sent to the related VL. Then through the VL dispatch, data of multiple VL are added with UDP header, IP header and Ethernet header, and finally packeted into an Ethernet frame. During each basic cycle, the system broadcasts a main frame according to the polling strategy (meeting the TCN polling strategy) in switched Ethernet. All devices receive the main frame and then decode. They determine whether they are required to respond to a slave frame in this basic cycle (more than one device could respond to the slave frame), and then the device sends a slave frame to the switched Ethernet correspondingly. Let us define the time of sending data process in switching Ethernet as:

$$T\_S = T\_SMF + T\_SMS + T\_SAS \tag{2}$$

where T_SMF is the time of sending the main frame, T_SMS is the time interval between a master frame and its slave frame, and T_SAS is the time of sending a slave frame.

For the non-real time data, the operation of real-time protocol layer is consistent with the traditional TCN. In the real-time virtual layer, messages are sent to the related VL; then, the data are packeted into an Ethernet frame, and sent by switched Ethernet.

When the receiver gets the data, it checks integrity according to the protocol of each layer, and removes the header of each layer. Finally, in the real-time layer, data are transferred with the RTP protocol of TCN.

3 Determinacy analysis of TCN network based on switched Ethernet

The delay of the network will be analyzed with the Network Calculation Theory to prove that the network has a maximum end-to-end data delay.

3.1 Network calculation theory

The network calculation theory is based on a series of conclusions of Min-Plus Algebra. It is widely applied in network performance evaluation and resource allocation, etc. The network calculation theory is mainly used for analyzing the determinacy service guarantee offered by the system in the worst cases. Two important concepts of the network calculation theory are arrival curve and service curve [6].

3.2 Determinacy proof

After acquiring real-time data, the train data are separately used for different VLs. Then through VL dispatch, they are packeted into an Ethernet frame, which is sent to switched Ethernet for transmission.

The determinacy of the TCN network based on switched Ethernet will be analyzed in some data flow.

Assume that a system has n lines of VLi $(i = 1\ldots n)$.The data flow from these VLs gets through $S_{0,i}, S_{1,i}, S_{2,i}, S_{3,i} \ldots\ldots S_{m,i}$ from source terminal device to the target terminal device, the terminal device can be regarded as $S_{0,i}$.

Using the induction method in [7]:

(1) After flow shaping, data flow into terminal VL dispatch, from definition [8] and equation (1),the arrival curve of data flow of VL into dispatch is:

$$\alpha_i(t) = L^i_{\max} + \frac{L^i_{\max}}{BAG_i} t, \quad i = 1\ldots n; \tag{3}$$

After summation, the arrival curve is:

$$G(t) = \sum_{i=1}^{n} L^i_{\max} + \sum_{i=1}^{n} \left(\frac{L^i_{\max}}{BAG_i}\right) t \tag{4}$$

Derive from formula *(1)*:

The maximum delay of data flow i in terminal system is $\sum_{i=1}^{n} \frac{L^i_{\max}}{C}$.

(2) Assume that while data flow has a delay maximum bound through S_{n-1}, it also does after going through S_n.

It can be demonstrated as follows.

Define data flow through S_{n-1} by VLi $(i = 1\ldots n)$. According to the assumptions above, the delay of data flow through switch S_{n-1} has its maximum bound, respectively defined as *d1, d2...dn*. So before entering S_n the arrival curve of data flow i is:

$$L^i_{\max} + \frac{L^i_{\max}}{BAG_i} \quad (t + di) \tag{5}$$

By accumulating the arrival curves, we can further deduce that data flow into S_n aggregation arrival curve as:

$$\sum_{i=1}^{n} L^i_{\max} + \frac{L^i_{\max}}{BAG_i} \ (t + di) = \sum_{i=1}^{n} L^i_{\max} \left(1 + \frac{di}{BAG_i}\right) + \frac{L^i_{\max}}{BAG_i} t \tag{6}$$

S_n can supply aggregation data flow with the service curve. According to the theory that the maximum time delay can be determined by horizontal distance, the maximum bound of aggregation data flow's delay in S_n is:

$$\sum_{i=1}^{n} L_{\max}^{i}(1+\frac{di}{BAG_i})/C \tag{7}$$

From equations (5)–(7), we have the maximum bound of delay of data flow i through S_n:

$$Di = di + \sum_{i=1}^{n} L_{\max}^{i}(1+\frac{di}{BAG_i})/C \tag{8}$$

According to the assumption and formula (7), di is a constant value, therefore, Di is a constant value. It can also be proved that data flow i through S_n still has a maximum bound of delay. So all the data flow through switch have the maximum bound of delays, which illustrates that TCN based on switched Ethernet is a determinacy network with maximum delay. However, this cannot illustrate meeting the strong real-time performance of TCN. Then the end-to-end maximum network delay in the worst cases needs to be further analyzed.

3.3 Analysis of switched Ethernet delay

From deduction (9), the service curve of data flow i supplied by switch is:

$$\beta_i(t) = [\beta(t) - (A(t-\theta) - \alpha_i(t-\theta))]^{+} \tag{9}$$

At first time (time is 0), for data flow i, $\beta_i(t) = A(\theta) - \alpha_i$, and $\theta = \frac{\sum_{i=1}^{m}\sigma_i\text{-}\sigma_i}{C}$.

Also from (9):

$$A(t) - \alpha_i(t) = \sum_{i=1}^{m}\alpha_i(t) - \alpha_i(t) = (\sum_{i=1}^{m}\rho_i - \rho_i)t + (\sum_{i=1}^{m}\sigma_i\text{-}\sigma_i) \tag{10}$$

By substituting formula (9) and (10), it gives:

$$\beta_i(t) = [ct - (\sum_{i=1}^{m}\rho_i - \rho_i)(t - \frac{\sum_{i=1}^{m}\sigma_i\text{-}\sigma_i}{C}) - (\sum_{i=1}^{m}\sigma_i\text{-}\sigma_i)]^{+} = [c - (\sum_{i=1}^{m}\rho_i - \rho_i)](t - \frac{\sum_{i=1}^{m}\sigma_i\text{-}\sigma_i}{C}) \tag{11}$$

From formula (11), the service rate and service delay of data flow i supplied by the switch respectively are:

$$R_i = c - (\sum_{i=1}^{m}\rho_i - \rho_i) \tag{12}$$

$$T_i = \frac{\sum_{i=1}^{m} \sigma_i \text{-} \sigma_i}{C} \tag{13}$$

Considering the way of store-and-forward in switch, only after receiving the whole data frame, can the data be processed. This process equals the fact that it adds a packing device to the output terminal of the service node. Data packing adds the time of a data frame transmission to the service delay, thus the maximum bound of delay of vehicle-level layer becomes:

$$D_{\text{vehicle-level}} = T_i + \frac{l_{\max}}{R_i} \tag{14}$$

where $l_{\max}$ is the maximum length of data flow *i*.

When calculating the data delay of a backbone network layer, we consider the worst cases equally. When the control unit of Vehicle 1 and that of Vehicle 8 transfer data to each other, the maximum transmission delay appears in the backbone layer.

The total length of CRH3 is about 210 m, and the length of one vehicle is about 26 m. Hence we can conclude that the cables' lengths between two adjacent switches are 26 m and the transmission delay ι of electrical signal in seven sections of cable are same. So the maximum bound of time delay of backbone layer is:

$$D_{\text{backbone}} = 8* \left(T_i + \frac{l_{\max}}{R_i}\right) + 7*\iota \tag{15}$$

4 Simulation result

As shown in Figure 1, TCN uses a star topology structure, assuming that the rate of all switches is 100 Mb/s and using the store-and-forward mode. In order to simplify the analysis, it is assumed that every switch is associated with m loads and their patterns are the same. For the periodic data in the vehicle-level layer, considering the limiting case that the minimum basic cycle of MVB in TCN protocol is 1 ms, we can assume that loads send the minimum Ethernet frame every 1 ms, whose length is 64 bytes. The frame also needs to mix with 8 bytes synchronization and a 12 bytes interval. The incidental data are assumed that their average sending rate is 0.01 times than periodic real-time data.

According to the assumptions above, the arrival curves of the periodic and incidental data flow *i*, which is sent to the switch by the load *i,* are separately $\alpha_1(t)$ and $\alpha_2(t)$:

$$\alpha_1(t) = 84 + 84000\text{t} \tag{16}$$

$$\alpha_2(t) = 84 + 840\text{t} \tag{17}$$

The aggregation arrival curve of data flow *i* is:

$$\alpha_i(t)=\alpha_1(t)+\alpha_2(t)=168+84840\mathrm{t} \tag{18}$$

4.1 Simulation of vehicle-level layer

From equations (14) and (16)–(18), we have:

$$D_{\text{vehicle-level}}=\frac{(m-1)*1344}{10^8}+\frac{84*8}{10^8-(m-1)*84840*8} \tag{19}$$

Figure 5 shows the simulation curve.

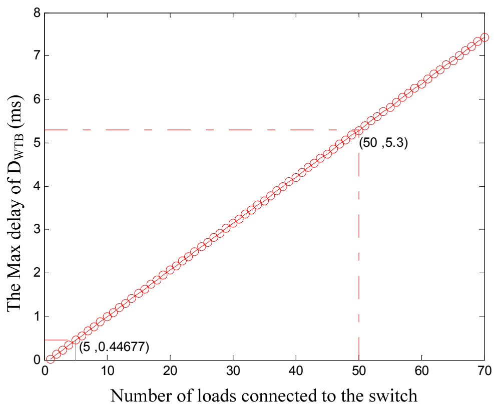

Figure 5: The maximum delay simulation of end-to-end communication in the vehicle layer.

4.2 Simulation of backbone layer

For periodic data in the backbone layer, consider the limiting case that the minimum basic cycle of WTB in TCN protocol is 25 ms and assume that the load sends a minimum Ethernet frame every 2 5 ms, whose length is 64 bytes. The frame also needs to mix with 8 bytes synchronization and 12 bytes interval. The incidental data are assumed that their average sending rate is 0.01 times than periodic real-time data.

According to the assumptions above, the arrival curves of data flow *i* sent to the switch by the load *i* are given below.

The arrival curve periodic data flow is:

$$\alpha_1(t)=84+3360\mathrm{t} \tag{20}$$

The incidental curve is:

$$\alpha_2(t)=84+33.6\mathrm{t} \tag{21}$$

The aggregation arrival curve of data flow i is:

$$\alpha_i(t)=\alpha_1(t)+\alpha_2(t)=168+3393.6t \tag{22}$$

From equations (15) and (20)–(22):

$$D_{\text{backbone}}=8*\frac{(m-1)*1344}{10^8}+\frac{84*8}{10^8-(m-1)*3393.6*8}+7*\frac{213.5}{1.5*10^8} \tag{23}$$

Figure 6 shows the simulation curve.

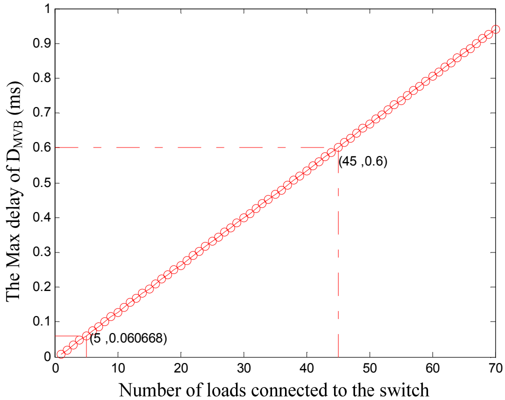

Figure 6: The maximum delay simulation of end-to-end communication in the backbone layer.

4.3 Analysis of simulation results

1) Vehicle layer

The polling basic cycle of MVB is 1 ms. The default value of the incidental phase time in a basic cycle is 350 us, while the periodic cycle phase time is (1 ms–0.35 ms) = 650 us. According to the definition of the MVB data telegram [10], the average time of process data is about 100 us in a basic cycle. Only 6–7 devices (650 us/100 us) can send process data at the same time.

TCN based on switched Ethernet are shown in Figure 5. When there are five devices sending process data at the same time, the end-to-end maximum delay in vehicle-level layer is 60.668 us. It gives:

T_SAS =60.668 us

T_SMF=64 byte*8/(100 Mb/s)=5.12 us

T_SMS=43 us(from the definition of MVB data telegram in [10])

According to the analysis of sending information and receiving periodic data in formula (2),

$$T\_S = T\_SMF + T\_SMS + T\_SAS = 108.788 \text{ us}$$

T_S of five devices only takes up 16.74% of cycle phase time, so the vehicle-level layer can satisfy about 45 devices sending process data simultaneously during a periodic cycle phase of 650 us.

Based on the analysis above, in view of real-time performance, TCN based on switched Ethernet in the vehicle-level layer has more advantages than traditional TCN. Every switch port can exclusively take up the bandwidth of 100 Mb/s, and the data capacity and bandwidth are better than the traditional one as well.

2) Backbone layer

In a traditional TCN, the basic cycle of WTB is 25 ms. During a basic cycle, the incidental phase time takes up 40% of a basic cycle, and the following periodic cycle phase time is 15 ms. According to the rule of WTB message [10], the time to send a process data message during a basic cycle is 2500 us. Accordingly, during a basic cycle, only six (15 ms/2500 us) devices can send process data at the same time.

Figure 6 illustrates the simulation results of a backbone layer of TCN based on switched Ethernet. When there are five devices sending process data at the same time, the end-to-end maximum delay is 0.44677 ms:

T_SAS = 0.44677 ms

T_SMF = 5.12 us

T_SMS = 34 us (From the definition of WTB data telegram in [10])

According to the formula (2), T_S = 0.48589 ms.

T_S of five devices only takes up 3.24% of periodic cycle phase time. so vehicle-level layer can satisfy about 150 devices sending process data simultaneously.From Figure 6, it can also be concluded that when the load number is 50, T_s only equals 5.3 ms. It only takes up 35.3% of periodic cycle phase in a basic cycle.

5 Conclusion

This paper puts forward a pattern of TCN based on switched Ethernet, and its topology and communication protocol stack are reconstructed. The new TCN improves the data communication of TCN with regard to the real-time performance. The novel TCN can effectively solve the contradiction between the bandwidth of train communication and the constantly growing data information capacity. Simulation results show that the traditional TCN can be replaced by our proposed TCN based on switched Ethernet. Future works will focus on the dispatch algorithm based on the network calculation theory.

Acknowledgements

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