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Modeling and Analysis of the TTE System Based on DSPN

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Abstract: TTE (Time-Triggered Ethernet) expands classical Ethernet in order to meet the requirements of real-time and reliable etc. and has been applied to the safety-critical system. Introducing the DSPN (Deterministic and Stochastic Petri Net), the paper presents the four kinds of TTE component models for modeling the TTE system. Based on these components, the TTE system model can be constructed through the synthesis of Petri Nets and may be used to the system's performance analysis. Finally, the paper also explains on the application of the modeling and analysis method through a case study.

Key words: TTE, DSPN, component model, modeling

INTRODUCTION

Over the past three decade years, Ethernet is used as a universal network solution in office and web applications and production facilities. Engineering, maintenance and training costs for Ethernet-based networks are considerably lower than costs for many proprietary bus (such as CAN, 1553B etc.) systems and Ethernet generally offers higher bandwidths. However, time-relevant, deterministic or safety-critical tasks were not taken into account for Ethernet. Consequently, the technology cannot be used directly in the high real-time, deterministic and safety-critical system.

TTE (Time-Triggered Ethernet) expands classical Ethernet use with powerful services (SAE AS6802) to meet the new requirements of reliable, real-time data delivery in advanced integrated systems (GE Intelligent Platforms, 2011). In addition, TTE switches provide ARINC 664 functionality to meet existing requirements of avionics Ethernet networks. As a new technology, modeling and analysis method of the TTE system is not complete until now. This paper presents a modeling and analysis methodology of the TTE system based on DSPN (Deterministic and Stochastic Petri Net), conducts the TTE system structure and analyzes the behavior by means of DSPN.

The Petri Net is a kind of dynamic graphic modeling tool, which primarily uses cause-and-effect relationship to describe parallel systems. Especially, its specific implementation rules of state and state variety make it describe the dynamic and static behavior of real physical system very well, which leads to the wide application of Petri Net to modeling and performance evaluation in real systems, especially in the real-time embedded systems. DSPN is an extension of Petri Net and introduce the deterministic and stochastic transitions in order to describe the real-time features.

TTE

A TTE system consists of a set of computer nodes that communicate via the TTE protocol (Grillinger *et al*., 2006). A TTE node consists of a host computer and a TTE communication controller that is connected to a switch via a bidirectional point-to-point link, as shown in Fig. 1. User applications are executed on the host computer, whereas the communication controller is in charge of executing the TTE communication protocol.

The TTE protocol distinguishes between two different classes of traffic:

- The event-triggered (ET) traffic that is not required to meet strict temporal requirements regarding the transmission delay. ET traffic can be divided into two different types: Rate-Constrained (RC) traffic and Best-Effort (BE) traffic
- The time-triggered (TT) traffic whose transmission is scheduled based on a conflict-free scheme and which has to meet strict temporal requirements regarding the transmission delay

TT messages are used for time-triggered applications. All TT messages are sent over the network at predefined times and take precedence over all other traffic types. TT messages are optimally suited for communication in distributed real-time systems. TT messages are typically used for brake-by-wire and steer-by-wire systems that close rapid control loops over the network. TT messages

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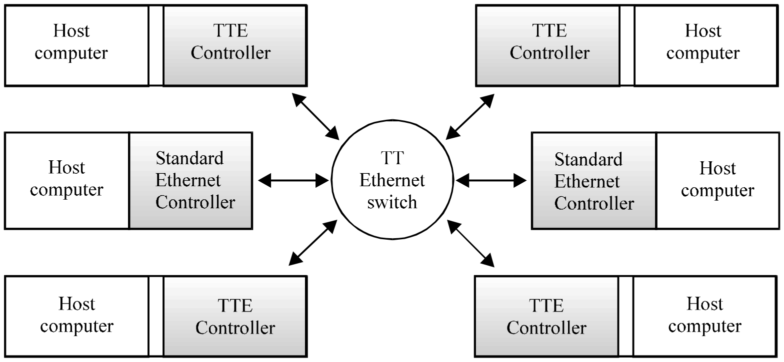

Fig. 1: TTE system

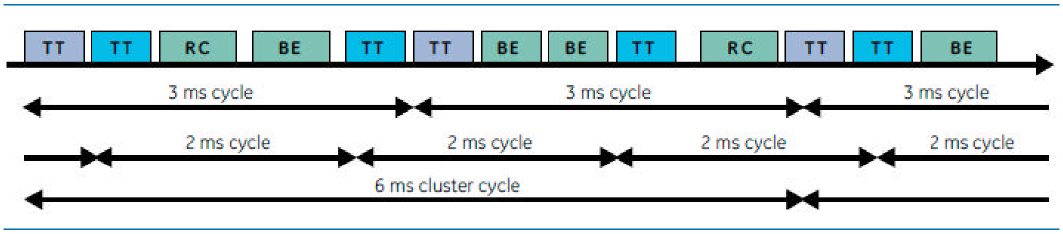

Fig. 2: TTE inlcudes TT, RC and BE messages

allow designing and testing strictly deterministic distributed systems, where the behavior of all system components can be specified, analyzed and tested with sub-micro second precision.

RC messages are used for applications with less stringent determinism and real-time requirements than strictly time-triggered applications. RC messages guarantee that bandwidth is predefined for each application and delays and temporal deviations have defined limits. RC messages are used for safety-critical automotive and aerospace applications that depend on highly reliable communication and have moderate temporal quality requirements.

BE messages follow a method that is well-known in classical Ethernet networks. There is no guarantee whether and when these messages can be transmitted, what delays occur and if BE messages arrive at the recipient. BE messages use the remaining bandwidth of the network and have less priority than TT and RC messages. Typical user of BE messages are web services. All legacy Ethernet traffic (e.g., internet protocols) without any QoS requirement can be mapped to this service class. TTE implements strong partitioning between non-critical BE traffic and all other service classes as shown Fig. 2.

DSPN

Petri Net is one of several mathematical modeling languages for the description of distributed systems. Petri theory allows a system to be modeled by a Petri net, a mathematical representation of the system. Analysis of the Petri Net can then, reveal important information about the structure and dynamic behavior of the modeled system. This information can then be used to evaluate the modeled system and suggest improvements or changes.

Definition: Formally, a Petri net can be defined as follow:

- PN = (P, T, I, O, M0); where
- P = {p1, p2, ..., pm } is a finite set of places,
- $T = \{t_1, t_2, \dots, t_n\}$ is a finite set of transitions and PnT = ϕ and PUT $\neq \phi$
- I: $(P\times T)\rightarrow N$ is an input function that defines directed arcs from places to transitions, where N is a set of nonnegative integers
- O: $(P\times T)\rightarrow N$ is an output function which defines directed arcs from transitions to places and
- M0: $(P\times T)\rightarrow N$ is the initial marking

If I (p, t) = k (O (p, t) = k), then there exist k directed arcs connecting place p to transition f (transition t to place p). If I (p, t) = 0 (O (p, t) = 0), then there exist no directed arcs connecting p to t (t to p). Frequently, in the graphical representation, parallel arcs connecting a place (transition) to a transition (place) are represented by a single directed arc labeled with its multiplicity, or weight k.

DSPN

DSPN (Deterministic and Stochastic Petri Net) is the expansion of Petri net, by introducing the temporal factor into Petri Net. DSPN associates a firing time with each transition. In DSPN, the firing time can be a constant, or an immediate variable (German, 1995). It also may be a stochastic time with exponentially distribution with the parameter λ. λ is the average implementation rate of the transitions, namely, $1/\lambda$ is the average delay time of the transitions.

DSPN represents a graphical method for the modeling of discrete event systems like communication systems, computer architectures and manufacturing systems. The stochastic extensions to the pure Petri Net allow to model and evaluate the performance and dependability of the system. In DSPN transitions may fire either without consuming time *(immediate transitions),* after a deterministic time *(deterministic transitions),* or after a potentially distributed time *(exponential transitions).* Since DSPN allow to mix deterministic and randomly distributed timing, they are well suited for the modeling of systems in which events occur either after constant or unknown durations (e.g., real-time systems with deterministic events and with failures). The elements in DSPN are shown in Fig. 3.

Some methods are used in DSPN for the analysis of the system. For example, Marsan and Chiola (1987) presented a method for the stationary analysis based on the construction of an Embedded Markov Chain (EMC) at memoryless time instants of the underlying stochastic process. Choi *et al.* (1994) presented that state equations were derived by considering an underlying Markov regenerative process. Tan *et al.* (2011) have designed and implemented a DSPN tool based on PIPE2 (Dingle *et al.*, 2009) and the tool can be applied to system modeling and analysis.

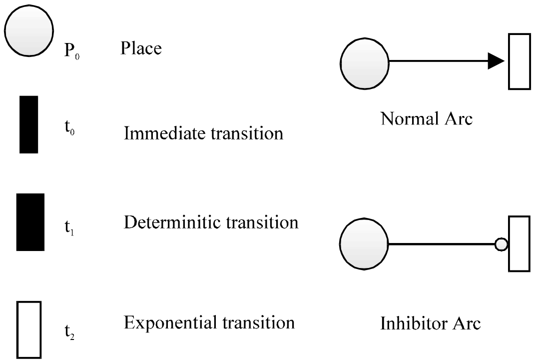

Fig. 3: DSPN Elements

TTE COMPONENT MODEL BASED ON DSPN

Building the DSPN model is a prerequisite for analyzing the TTE system. However, as a typical formal method, learning and using Petri Nets are very difficult for the system's designers. So, it is necessary to provide some auxiliary means to guide the users building the DSPN models.

In fact, there exist many similar features in the different TTE systems, such as basic program structures, end system messages, message scheduling etc. We present the common reusable components modeling those similar features and then inject the parameters used to characterize the system customization behavior into the components. Finally, we assemble these parameterized components to an system integrated model through the synthesis of Petri Nets.

In this study, we present four kinds of DSPN components for the TTE system, such as basic structure components, end system components, message scheduling components and data transmission components and will be discussed as follows.

Basic structure components: This kind of component can model the system's basic control structure independent of the TTE system. Typical structures include sequence, loop, choice and concurrence. The Petri Net components are shown in Fig. 4-7. In these models, there are n

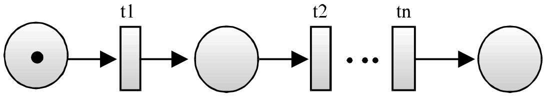

Fig. 4: Sequence component

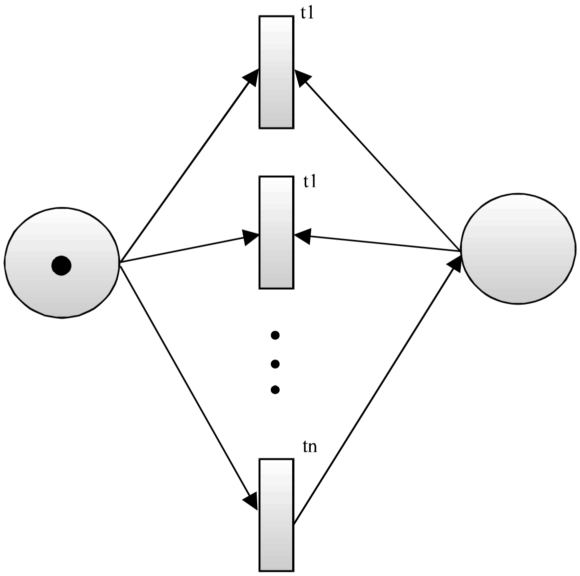

Fig. 5: Choice component

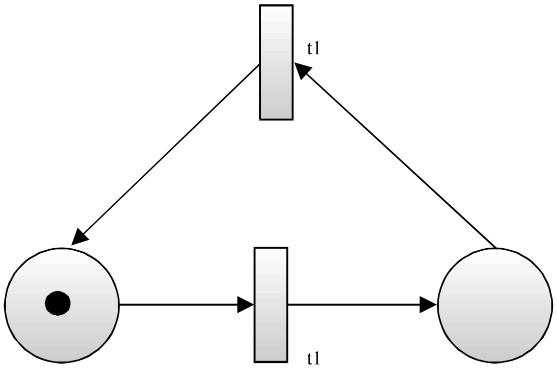

Fig. 6: Loop component

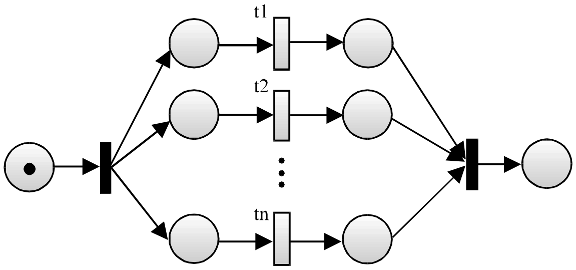

Fig. 7: Concurrent component

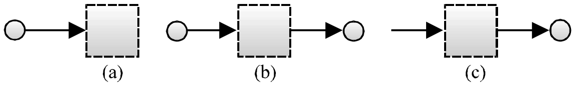

Fig. 8(a-c): (a) Data acquisition (b) Data processing and (c) Data receiving

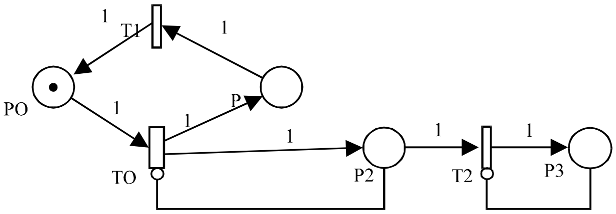

Fig. 9: Periodic message component

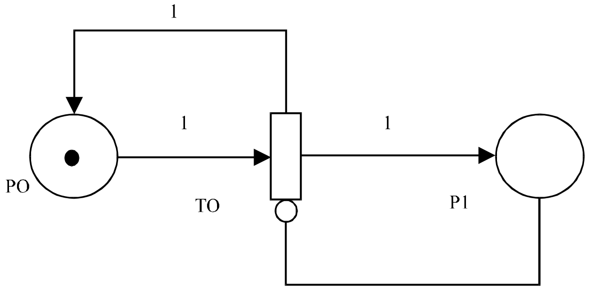

Fig. 10: Event message component

stochastic transitions t_1, t_2 .... t_n. They are mutually independent random variables and obey exponential distribution with the parameter λ_1, λ_2 ..... λ_n.

End system components: The end system components are used to describe the end systems connecting to the TTE switch through controllers. According to the data flow handling mode, the end systems can be classified into three kinds: data acquisition, data processing and data receiving components as shown in Fig. 8. Data acquisition components, such as various sensors, produce the data. Data processing components, such as the mission computer, receive and process the data and then output the result. Data receiving components, such as the cockpit display module, only receive and display the data.

In the TTE system, the end systems interact with each other through various messages. Message components can be used to model different messages. According to the features of messages in the TTE system, the kind of component includes the periodic message component and event message component.

The periodic message component can be used to model the TT messages in the TTE system. These messages are periodically generated and processed. Fig. 9 shows the DSPN model of a periodic message. The deterministic transition T_0 expresses the message's period and the immediate transition T_1 can ensure the message recurrence. Another immediate transition T_2 and the place P_3 expresses the subsequent processing for the periodic message. In addition, through the inhibitor arc $P_2 \rightarrow T_0$ can prevent the congestion to ensure the message can be completely handled.

The event message component can express the ET (including RC and BE) messages in the TTE system through injecting different parameters. Fig. 10 is a simple model of the event message component. Similarly, through the inhibitor arc can prevent the congestion.

Message scheduling components: The messages from end systems need be properly scheduled by the TTE switch to ensure them arriving the processing end in time, especially those TT messages. Therefore, the scheduling problem is very important in modeling the TTE System. We present two kinds of scheduling components against different scenarios: the preemptive first-in-first-out scheduling and priority scheduling.

The preemptive first-in-first-out scheduling component is shown in Fig. 11. In the figure, there are three messages T_0, T_1, T_2 competing for the resource P_0. The first occurring message will preempt the resource until it is finished processing.

The priority scheduling component is shown in Fig. 12. In the figure, there are also three messages T_0, T_1, T_2. However, the inhibitor arcs $P_0 \rightarrow T_1$ and $P_0 \rightarrow T_2$ make T_0's priority higher than T_1 and T_2 and the inhibitor

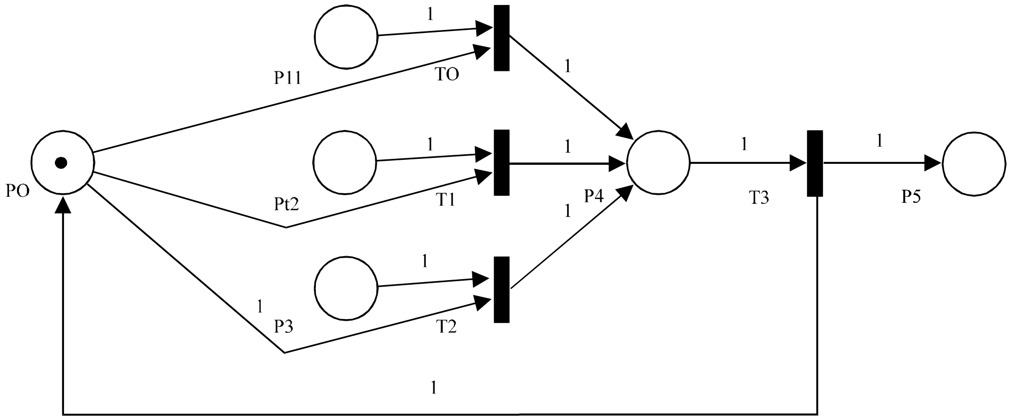

Fig. 11: Preemptive first-in-first-out scheduling component

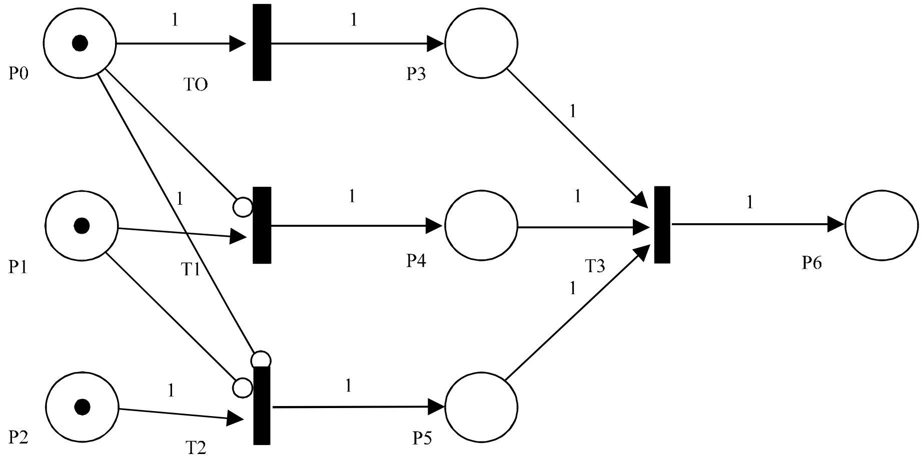

Fig. 12: Priority scheduling component

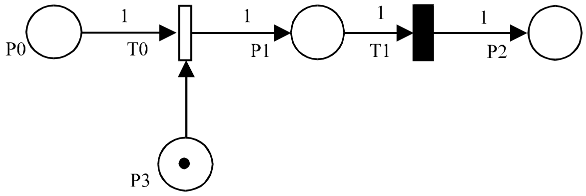

Fig. 13: Data transmission component-fixed delay

arc $P_1 \rightarrow T_2$ makes T_1's priority higher than T_2. In the TTE system, TT messages should be given a higher priority in order to ensure the real-time.

Data transmission components: The Data transmission components are used to model the data transmission delay form end to end. Three kinds of transitions can express three different transmission delays. The immediate transition means the delay is negligible, the deterministic transition indicates the delay is relatively fixed and the exponential transition implies the delay is a random variable. In Fig. 13, the fixed delay is expressed by the deterministic transition T_1 and the other kinds of delays are expressed by revising the T_1's type.

CASE STUDY

In this section, we present a case study of applying the DSPN components for modeling the TTE system.

Description of the case study: The Fire-Control System (FCS) is a number of components working together, usually a gun data computer, a director and radar, which is designed to assist a weapon system in hitting its target. It performs the same task as a human gunner firing a weapon, but attempts to do so faster and more accurately. The core modules of the system are MC and DCMS. The MC (Mission Computer) is responsible of computing the data and sending out the control instructions based on

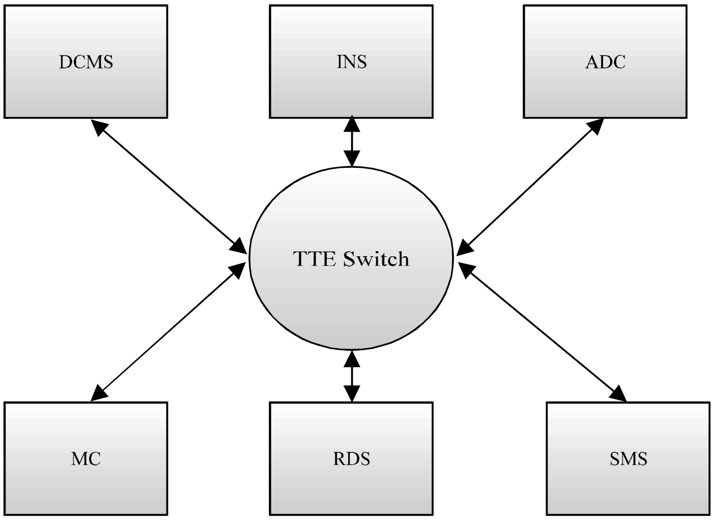

Fig. 14: Structure of FCS

Table 1: Messages between the end modules

Src.	Content	Msg. Type	Max. dlay (ms)	Dest.
C	Instruction	Event	ss	SMS
INS	Longitude latitude direction velocity	Period/200 ms	10	DCMS
RDS	Target	Period/100 ms	10	DCMS
ADC	Pressure altitude air velocity air direction	Period/200 ms	20	DCMS
SMS	Ready	Event	10	DCMS
	switch state	Event	5	
	available state	Event	10	
	allowance	Eent	10	

the other module's data. The DCMS (Display, Control and Management System) provide the input and output interfaces for pilots. Moreover, there are four external subsystems: INS, RDS, ADC and SMS. The INS (Inertial Navigation System) is a navigation aid that uses a computer, motion sensors and rotation sensors and can provide the velocity, position and attitude etc. The RDS (Radar System) can gain the information of target. The ADC (Atmosphere Data Computer) gathers the atmosphere data in the location of the aircraft. The SMS (Store Management System) manages the weapons in the aircraft. These Modules interconnect with the TTE switch as shown in Fig. 14.

These end modules interact with each other as shown in Table 1. There are some periodic messages in the INS, ADC and RDS and their priorities are the same and highest level. There are event messages in the MC and SMS and exist competitions between these messages. The messages in the MC own higher priority than in the SMS.

DSPN model of the case study: According to Table 1, we may construct the message scheduling model to ensure these messages can be processed normally. Fig. 15 gives a feasible timeline in the FCS. Three kinds of TT messages in the figure respectively express those messages in the INS, ADC and RDS. The first ET message expresses the weapon delivery instruction from the pilot and the second ET message means the delivery weapon event in the SMS after computing by the MC.

Following the process in the previous section, we inject the parameters from the case to those DSPN components and then may build the FCS's integrated model through the synthesis of Petri Nets. The DSPN integrated model is shown in Fig. 16. As can be seen, the DSPN model is combined with the DSPN components. We may analyze three periodic messages corresponding to three deterministic transitions t_1, t_7 and t_{11} and two event messages corresponding to two exponential transitions t_{22} and t_{23} proposed in the previous paragraph.

Based on the DSPN Model, we may conduct the model simulation and performance analysis by means of the DSPN's analysis methods. Figure 17 shows the network load analysis result and the network load may obtain through calculating $E\{\#P_{18}\}$ in the model. $E\{\#P_{18}\}$ expresses the average token number when the system is in the steady state.

In the figure, the horizontal axis represents the number of event messages and the vertical axis represents the load. As can be seen from the figure, the load increases with the number of messages and then reaches a steady state when the messages reach a certain number.

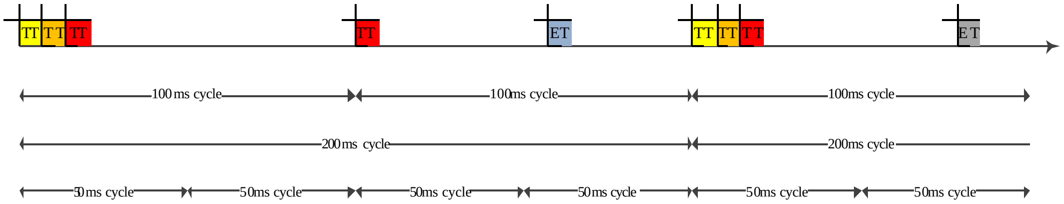

Fig. 15: Timeline of message arriving

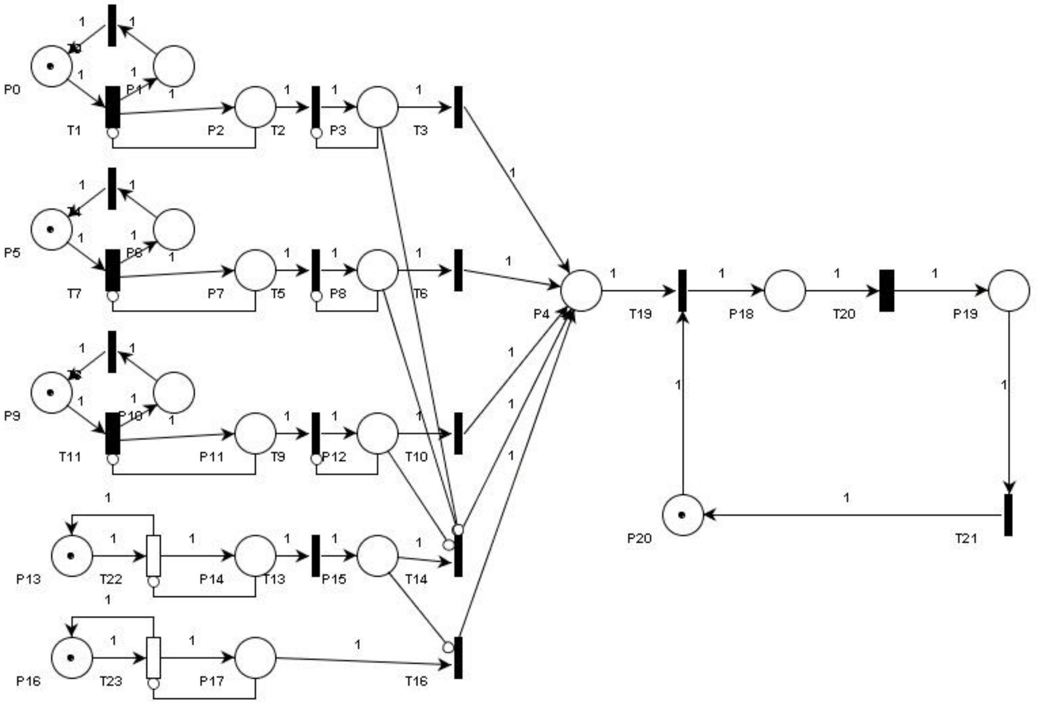

Fig. 16: DSPN model of FCS

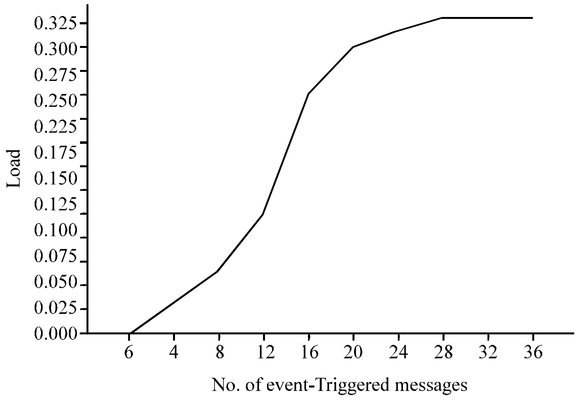

Fig. 17: DSPN model of FCS

CONCLUSION

As a new networking technology, TTE can meet the real-time and safety-critical software requirement and have been used in the safety-critical system. This paper analyzes the structure of the TTE system and the DSPN related concepts. On the basis, we present the method for modeling the TTE system and emphasize on four kinds of TTE components based on DSPN. Finally, it illustrates the modeling and analysis process through the case study. The future work would focus more attention on the performance analysis.

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