Real-time Performance Study of EPA Periodic Data Transmission

Liu Ning, Zhong Chongquan and Teng Hongfei

Abstract—EPA (Ethernet for Plant Automation) resolves the nondeterministic problem of standard Ethernet and accomplishes real-time communication by means of micro-segment topology and deterministic scheduling mechanism. This paper studies the real-time performance of EPA periodic data transmission from theoretical and experimental perspective. By analyzing information transmission characteristics and EPA deterministic scheduling mechanism, 5 indicators including delivery time, time synchronization accuracy, data-sending time offset accuracy, utilization percentage of configured timeslice and non-RTE bandwidth that can be used to specify the real-time performance of EPA periodic data transmission are presented and investigated. On this basis, the test principles and test methods of the indicators are respectively studied and some formulas for real-time performance of EPA system are derived. Furthermore, an experiment platform is developed to test the indicators of EPA periodic data transmission in a micro-segment. According to the analysis and the experiment, the methods to improve the real-time performance of EPA periodic data transmission including optimizing network structure, studying self-adaptive adjustment method of timeslice and providing data-sending time offset accuracy for configuration are proposed.

Keywords—EPA system, Industrial Ethernet, Periodic data, Real-time performance

I. INTRODUCTION

EPA (Ethernet for Plant Automation) is a type of fieldbus that is presented from China and specified in IEC 61158 as type 14 and in IEC 61784-2 as the CPF14 (Communication Profile Family 14) [1] - [3].

The EPA system is a distributed system which uses the Ethernet network defined by ISO/IEC 8802-3, IEEE 802 series and IETF (Internet Engineering Task Force) protocols to connect field devices and small systems, and to control/monitor equipment in the industrial field. EPA devices work together to provide I/O and control for automated processes and operations [3]. The objective of EPA is to provide a real-time networked control system for the efficient, frequent exchange of very small data in the industrial field based on the latest technologies of Ethernet (e.g. switches, duplex communication, and priority) and some key technologies (e.g. micro-segment system architecture, mechanism of deterministic schedule, communication model).

Real-time systems are those in which the temporal aspects of their behavior are part of their specification. The correctness of the system depends not only on the logical results of the computation, but also on the time at which the results are produced [4]. Communication in a real-time system has to be deterministic, because nondeterministic delay of data transmission can adversely affect the execution of tasks dependent on these data. EPA resolves the nondeterministic problem of Ethernet by means of micro-segment topology and deterministic scheduling mechanism and accomplishes real-time communication. Real-time performance of EPA system determines whether it can meet the requirement of industrial application. Real-time performance of an EPA device and an EPA network as well as requirements of industrial application is specified by real-time indicators. Users are able to match EPA devices and EPA network with the requirements of industrial application by real-time indicators.

At present, there has been much work relating to EPA has been reported. EPA system architecture, deterministic communication scheduling mechanism, application layer specification, device description and others were specified [5]. Miu et al. introduced several types of industrial Ethernet and real-time Ethernet including EPA, indicating their advantages and advancement [1], [2], [3], [6]. Chen et al. analyzed the real-time performance of standard Ethernet in industrial application and described the architecture of EPA network including the application layer and management layer [7], [8]. Wang et al. studied the conformance test method of EPA protocol state machine and presented a concrete method to judge the conformance degree between EPA protocol state machine implementation and EPA protocol [9]. etc. However, previous efforts have been directed mainly toward the introduction of EPA specification and the development of EPA devices. As the groundwork of EPA, the research on its real-time performance has just started and is not enough for the requirement of industrial application. Some performance indicators for RTE (Real-time Ethernet) were specified [3] and Li et al. have given the test principles for some of the indicators in EPA system [10]. But some important indicators that reflect the real-time characteristics of EPA system and the test platform for real-time performance of EPA system was not mentioned in [3] and [10]. Furthermore, there is no study on the

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limiting factors and the improvement methods for EPA real-time performance up to now. Thus, it is necessary for the real-time performance of EPA to be studied so that it can improve its real-time performance and meet the requirement of industrial applications.

EPA information is categorized as periodic data or nonperiodic data and transferred using distinct mechanisms so as to meet the requirement of control and monitor. In this paper, 5 indicators to specify the real-time performance of EPA periodic data transmission are studied. They are time synchronization accuracy, delivery time, utilization of configured timeslice, non-RTE bandwidth and data-sending time offset accuracy. The former 3 indicators are presented in [3] and the later 2 are presented in this paper. In section 1, the information transmission regularity and EPA deterministic scheduling mechanism of periodic data is introduced. In section 2 to section 6, 5 real-time indicators for EPA periodic messages transmission including delivery time, time synchronization accuracy, data-sending time offset accuracy, utilization percentage of configured timeslice and non-RTE bandwidth are presented and studied respectively, during which their test purposes, test principles, test methods are given and some important formulas for real-time performance of EPA system are derived. In section 7, an experimental platform is developed and the indicators are tested. In the last section, this paper is concluded and the improvement methods for the real-time

performance of EPA periodic data transmission are proposed.

II. DETERMINISTIC SCHEDULING MECHANISM

EPA uses Ethernet/IP/UDP protocols as the lower four communication stack layers, and also defines ECSME (EPA Communication Scheduling Management Entity) between Ethernet and IP to manage the deterministic communication [5].

According to the installation position and communication relationship, EPA system divides the field devices into several isolated micro-segments. In each micro-segment, an EPA bridge is needed to isolate the communication flux among the field devices in the belonging micro-segment from others. Moreover, another function of bridges is to forward the messages among the micro-segments, so that the broadcast storm problem is avoided in effect in the EPA system. In a micro-segment, ECSME controls the sending time of periodic messages and nonperiodic messages according to pre-configured scheduling mechanism: periodic messages are sent out in the precise pre-configured time whereas nonperiodic messages are sent out according to the time availability, message priority and devices' IP. This scheduling mechanism avoids the collision between the messages to ensure the communication deterministic and real-time performance among the EPA devices.
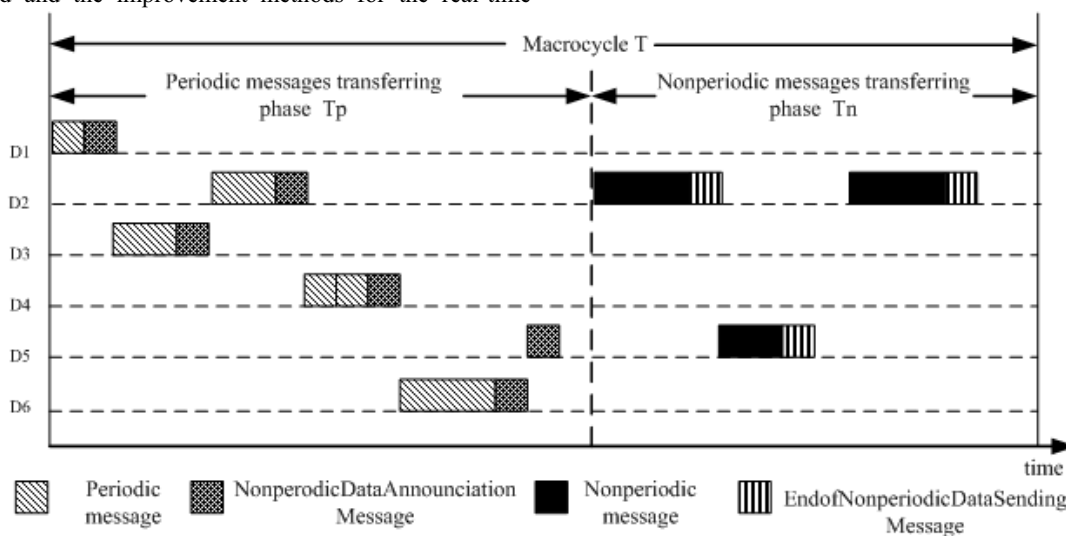

Fig. 1 EPA Deterministic Scheduling

Within an EPA micro-segment, the communication procedure is repeated. The time to complete a communication procedure is called communication macrocycle T. As shown in Fig.1, each macrocycle is divided into two phases: periodic messages transferring phase Tp and nonperiodic messages transferring phase Tn. Each EPA device transfers its periodic messages that contain the periodic data in the phase Tp. Periodic data are the data relevant to process parameters, such as measurement and control data which need to be transmitted periodically in the control loop, or the input/output data which need to be updated cyclically between FBs (Function Block).

During the phase Tn, each EPA field device transfers its nonperiodic messages that contain the nonperiodic data. Nonperiodic data are the primitives of program upload/download, variable read/write, event notification, trend report and RARP, HTTP, FTP, TFTP, ICMP, IGMP application data etc. [5] Nonperiodic messages are seldom produced when the control system works in operation state [12]. There are 6 priorities from 0 to 5 in the EPA system and the priority of periodic messages is 0 that is the highest. Real-time systems can be categorized as either hard or soft real-time. In a soft real-time system, the value of the computations is sensitive

to deadlines, but the system will not fail if some deadlines are occasionally missed. In hard real-time systems, catastrophic failure can occur even if one deadline is missed [11]. In EPA system, the transmission of periodic messages is time-critical, i.e. the task of the transmission of periodic messages is hard real-time [12].

The deterministic communication of the periodic and nonperiodic messages is accomplished through ECSME's four states and their transition in EPA system. The four states are: Standby, Ready, PeriodicDatasending and NonPeriodicDatasending [5]. Periodic messages are transferred during the PeriodicDatasending state.

ECSME becomes the PeriodicDataSending state when it detects the sending time of periodic messages. The sending time of periodic messages is determined by the equation: $MOD(T_c, T) = ST$. T_c is the local current time, ST is the periodic-data-sending offset and T is the timeslice for macrocycle. In a micro-segment, the pre-configured timeslice for device i to transfer its periodic messages is determined by the following equation.

$$B_i = \begin{cases} ST_{i+1} - ST_i & i \prec n \\ NST - ST_i & i = n \end{cases} \quad (1)$$

The n and the NST is respectively the number of the devices and the nonperiodic-data-sending offset in a micro-segment.

ECSME will firstly check whether there are messages with priority 0 in the device during the PeriodicDataSending state. If not, it will transfer a NDA (Nonperiodic Data Annunciation) message which announces the highest priority of the nonperiodic messages waiting to be transferred in queue to all other devices in the same micro-segment directly. Or it will transfer all the periodic messages to the network in sequence,

and then send out the NDA message and change current state to the state Ready.

III. DELIVERY TIME

Delivery time shall indicate the time needed to convey an APDU (Application Protocol Data Unit) containing data (Message Payload) that has to be delivered in real-time from one node (Source) to another node (Destination) [3]. In real-time networked control system, it is necessary that data must be exchanged between devices or tasks in a determinate time delay in order to ensure smooth control [13]. Thus, industrial field has highly critical constraints on the delivery time of EPA system.

The delivery time is measured at the interface between the AP（Application Process）and the (Fieldbus) AE（Application Entity）[3]. It is determined by the communication protocols, the performance of devices, network load and scheduling mechanism in an EPA system. As shown in Fig. 2, according to the process of EPA information transmission, the components of the delivery time between two nodes include processing time t_1, queuing time t_2, transmitting time t_3 and receiving time t_4. Thus the delivery time is: $t_d = t_1 + t_2 + t_3 + t_4$.

The processing time t_1 is the time during which information is processed by the sender stack (e.g. EPA application layer, UDP layer and IP layer). It is determined by the performance of the software and the CPU/memorizer in the sender node and it can be predicted according to the performance of the concrete software and hardware.
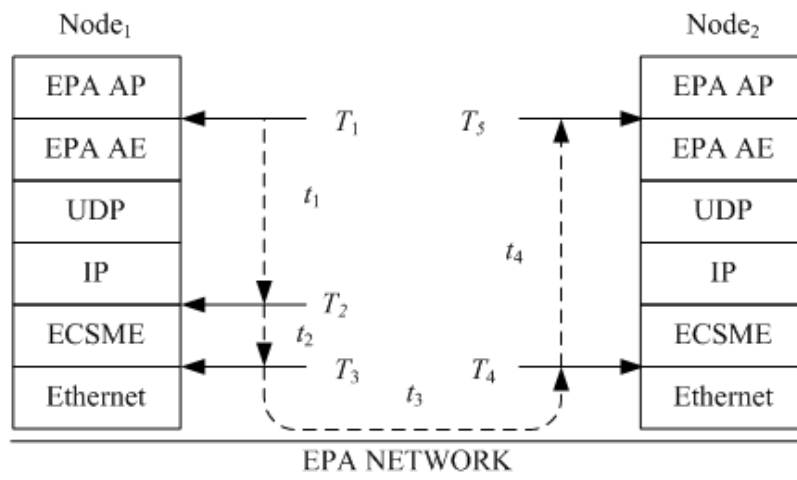

Fig. 2 Delivery Time of EPA Messages Transmission

The transmitting time t_3 is the time during which message is transferred through the network. It can be determined by equation: $t_3 = s_1 + s_2 + s_3 + s_4$. s_1 is the sender traversal time through MAC and PHY layer of Ethernet; s_2 is the transfer time for a message and it can be determined by the size of the frame L and the time s for 1 bit to be transferred: $s_2 = L \cdot 8 \cdot s$; s_3 is the propagation time during which signal propagates through cable and it can be determined by the cable length l and the speed v that electromagnetic wave propagates in cable: $s_3 = l/v$; s_4 is switch delay and it can be determined by the number of

switches between two nodes and the delay of each switch sd: $s_4=\sum sd_i$.

The receiving time t_4 is the time during which the receiver node receives, analyzes and passes the message to the destination task. It is determined by the processing time of interrupt and the performance of the system software and hardware in the receiver node. It can be predicted according to the performance of the concrete system.

The above components of EPA delivery time are similar as those of other fieldbuses and can be predicted according to the performance of the software and hardware of network devices and field devices. The queuing time t_2 in the DLL (Data Link Layer) during which messages wait to be transferred at the ECSME in the sender node is a very especial component of delivery time because it is determined by the scheduling mechanism of DLL and the network load. The nondeterministic problem of standard Ethernet mainly comes from its queuing time because of the collision from 1-persistence CSMA/CD and its solution based on BEB algorithm. However, the collision in standard Ethernet can be avoided and deterministic transmission can be accomplished in EPA system because it uses ECSME to schedule the message transmission. The queuing time t_{2p} of EPA periodic messages transmission can be predicted through analyzing EPA deterministic scheduling mechanism according to the network load in a concrete system.

If device i has more than one periodic message to transfer, the queuing time t_{2p} of its m-th periodic message in transferring sequence is equal to the waiting time from the message's entering-queue time to its starting-transferring time. It is determined by (2).

$$t_{2p} = D_p + T_l \qquad (2)$$

T_l is the time when device i transfers the periodic messages previous to the m-th message in transferring sequence. It can be determined by the following equation:

$$T_l = \begin{cases} \sum_{j=1}^{m-1}(L_j \cdot 8 \cdot s + g_j) + (m-1)\cdot l/v & m \succ 1 \\ 0 & m = 1 \end{cases} \qquad (3)$$

L_j is the frame size of the j-th message in transferring sequence by device i. g_j is the inter frame gap between the j-th periodic messages and the next message in device i.

D_p is the delay during which the message waits for the periodic messages transmission timeslice for device i. It is determined by the message's entering-queue time T_r and the device's ST as shown in (4):

$$D_p = \begin{cases} ST_i - MOD(T_r,T) & MOD(T_r,T) \le ST_i + T_l \\ T + ST_i - MOD(T_r,T) & MOD(T_r,T) \succ ST_i + T_l \end{cases} \qquad (4)$$

In (2) - (4), the t_{2p} is influenced by the ST_i and the T that should be configured according to the number of the nodes and the network load of periodic messages and nonperiodic messages in the micro-segment. Thus, if the delivery time is set to the bounded delivery time in the field application, the number of nodes and their network load is restricted.

Furthermore, according to (2) - (4), a periodic message will have to wait to the next macrocycles if it enters the queue after its device starts transferring NDA message and thus considerable queuing time is generated. Therefore, in order to improve the real-time performance of EPA periodic messages transmission, it is necessary for the periodic messages to enter the queue before the NDA message starts to be transferred.

As shown in Fig. 2, when generating timestamps at the time point of T_1, T_2, T_3, T_4, T_5, the components of the delivery time can be made according to the following equations: $t_1=T_2-T_1$, $t_2=T_3-T_2$, $t_3=T_4-T_3$, $t_4=T_5-T_4$. Thus, the total delivery time is: $t_d=t_1+t_2+t_3+t_4$.

IV. TIME SYNCHRONIZATION ACCURACY

Time synchronization accuracy shall indicate the maximum deviation between any two node clocks [3].

In EPA system, all devices should be synchronized to support deterministic scheduling and distributed FB scheduling. Time synchronization accuracy is an important real-time indicator that indicates the degree of the time synchronization in an EPA network. High deviation between the devices' clocks in an EPA micro-segment will bring the failure of function block scheduling and the collision of messages transmission. Either SNTP defined in RFC2030 or PTP defined in IEC 61588 can be used according to practical application. Because there is no collision between the messages transmission in EPA network, its network delay between master clock and slave clocks in a micro-segment is more symmetric and constant than standard Ethernet. Thus, EPA system can readily achieve higher degree of time synchronization accuracy than standard Ethernet when using PTP to synchronize the clocks and generating timestamps at DLL. In EPA system, time synchronization accuracy depends on synchronization cycle and switch delay. The synchronization cycle depends on the number of devices and the switch delay depends on the number of switches between devices[3].

As shown in Fig.3, the TE (Testing Device) issues a Test_Req (Test Request) message and generates a timestamp T_{S1} at the DLL. The master clock and the device 1 - n respectively generate the timestamps T_{R0} and T_{R1} - T_{Rn} at their DLL when they receive the message. The delays for the Test_Req message to be transferred from TE to device 1 - n are approximately equal because the master clock and the device 1 - n belong to one micro-segment. There are the following equations if describing the delay as D, the deviation between TE's clock and the master clock as F_0 and describing the deviations between the clocks of device 1 - n and the master clock as F_1 - F_n:

$$T_{R0} = T_{S1} + F_0 + D$$

$$T_{R1} = T_{S1} + F_0 + D + F_1$$

$$\dots$$

$$T_{Rn} = T_{S1} + F_0 + D + F_n$$

From the above equations, we can get:

$$F_1 = T_{R1} - T_{R0}$$

$$\dots$$

$$F_n = T_{Rn} - T_{R0}$$

The master clock and the devices transfers T_{R0} and $T_{R1} - T_{Rn}$ to the TE and the TE calculates time synchronization accuracy according to the above equations.
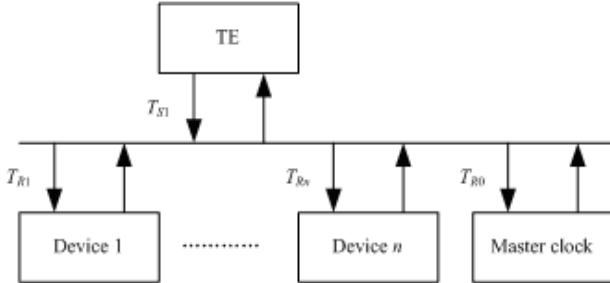

Fig. 3 Test of Time Synchronization Accuracy

V. UTILIZATION PERCENTAGE OF CONFIGURED TIMESLICE

Utilization percentage of configured timeslice for EPA periodic messages transmission shall indicate the percentage of a device's configured timeslice which is actually used for the device to transfer its periodic messages and NDA message during the periodic messages transferring phase Tp. The utilization percentage of configured timeslice for EPA periodic messages transmission of device i can be described by the following equation.

$$R_{pi} = \frac{B_{pi}}{B_i} \cdot 100\% \tag{5}$$

In the above equation, R_{pi} is the utilization percentage of configured timeslice for EPA periodic messages transmission of device i, B_{pi} is the demanding time for device i to transfer its periodic messages and NDA message and B_i is the configured timeslice of device i.

As introduced in section 1, the time for device i in a micro-segment to start to transfer its periodic messages is determined according to the configured ST_i and its configured timeslice is $B_i = ST_{i+1} - ST_i$. Utilization percentage of configured timeslice for EPA periodic messages transmission reflects whether the configuration of the timeslice for the periodic messages transmission of a device is efficient or not. If the utilization percentage of configured timeslice is too low, it not only means the waste of configured timeslice but also makes the macrocycle unnecessarily long, which will deteriorate the real-time performance of EPA system. If the utilization percentage of configured timeslice exceeds 100%, it means that the configuration of the timeslice is wrong and the device has no enough time to transfer its messages.

In the phase Tp, the demanding time B_{pi} is determined by its network load of periodic messages and EPA deterministic scheduling mechanism. According to the features of data transported by periodic messages, the network load of periodic messages for a device can be determined by the configuration

of the FBs at the user layer. It is assumed that the device i in a micro-segment transfers p_i periodic messages in a macrocycle. The B_{pi} is determined by the following equation.

$$B_{pi} = \sum_{j=1}^{p_i} (L_j \cdot 8 \cdot s + g_i) + p_i \cdot l / v + L \cdot 8 \cdot s + g + l / v \tag{6}$$

In the equation, L_j and L is respectively the frame size of the j-th periodic message and the NDA message transferred by device i. g_i and g is respectively the inter frame gap between the periodic messages and the inter frame gap between the periodic messages and the NDA message. s is the time for 1 bit to be transferred and the l and the v is respectively the cable length and the speed that electromagnetic wave propagates in cable.

During the test of utilization percentage of configured timeslice for EPA periodic messages transmission, the most important is to test the actual demanding time B_{pi}. When device i in an EPA micro-segment detects its sending time of periodic messages, it generates timestamp T_{ai} and when the device detects that it finishes transferring all its periodic messages and the NDA message, it generates timestamp T_{bi}. The equation of demanding time for the device to transfer its periodic messages and NDA message in a macrocycle is $B_{pi} = T_{bi} - T_{ai}$. Then, the utilization percentage of configured timeslice for EPA periodic messages transmission can be calculated according to (5).

VI. NON-RTE BANDWIDTH

Non-RTE bandwidth indicates the percentage of bandwidth which can be used for non-RTE communication on one link [3].

In an EPA micro-segment, the non-real-time messages are transferred during the nonperiodic messages transferring phase Tn in one macrocycle and they are distinguished from real-time nonperiodic messages by their priorities. Thus, the non-RTE bandwidth of EPA system can be gained in EPA system as shown in (7).

$$B_w = \frac{T_n}{T} \cdot 100\% \tag{7}$$

In the above equation, the B_w is the non-RTE bandwidth, the T_n is the timeslice for the nonperiodic messages transferring phase Tn and the T is the timeslice for macrocycle. The non-RTE bandwidth for a micro-segment can be calculated according to (7) after the micro-segment is configured.

VII. DATA-SENDING TIME OFFSET ACCURACY

Data-sending time offset accuracy for the periodic messages transmission shall indicate the maximum deviation between the actual offset that is calculated according to the actual data-sending start time and the configured data-sending offset, i.e. the maximum deviation between the actual data-sending start time and the configured data-sending start time.

Data-sending time offset deviation reflects the delay that an EPA device reacts to the configured data-sending start time. Devices from different manufacturers in an EPA micro-segment may have much difference for this indicator because of the difference of their hardware and software. If

Data-sending time offset deviation of a device is too big, it will waste much configured time of the device and degrade its utilization efficiency of the configured timeslice. Sometimes, it will even cause the device has no enough time to transfer all the periodic messages in its configured timeslice and lead to congestion. In contrast to the above indicators that reflects the real-time performance of an EPA network, data-sending time offset accuracy is a real-time indicator for an EPA device.

When device i in an EPA micro-segment detects its sending time of periodic messages, it generates a timestamp T_{ai} and transfers it to the TE to analyze. The data-sending time offset deviation E_{pi} is defined as the following equation.

$$E_{pi} = \text{MOD}(T_{ai}, T) - ST_i \qquad (8)$$

For a device, when $E_{pi}+F_i<0$, it's possible that the collision will occur between the device's periodic message transmission and other devices'; or it is not possible that the collision will occur.

VIII. EXPERIMENTS

In the following content, an experiment platform is designed to test the above real-time indicators for EPA periodic messages transmission. The experiment reflects the real-time performance for periodic messages transmission and the main bottleneck that restricts its further improvement.

As shown in Fig.4, the experimental platform is composed of 1 PC （Personal Computer）, 1 EPA bridge, 1 TE and 4 DUTs (Device Under Test). The DUTs are all EPA control modules. Their hardware is composed of AT91RM9200 CPU, 8 M FLASH, 32M SDRAM and 10/100Base-T Ethernet, whereas the software applies trimmed ARM Linux kernel and ramdisc file system as OS (Operation System) and EPA deterministic scheduling mechanism is performed in the communication protocol stack of OS. The TE is an EPA control module as the DUTs and specific testing program runs in it for it to test time synchronization accuracy. The EPA bridge is used to forward the messages between the micro-segment and the PC. The bandwidth of the Ethernet HUB is 10M/s and the clocks of the DUTs and TE in the micro-segment are synchronized according to IEEE1588. A configuration and analysis software runs in the PC to configure the micro-segment and to process the tested data.
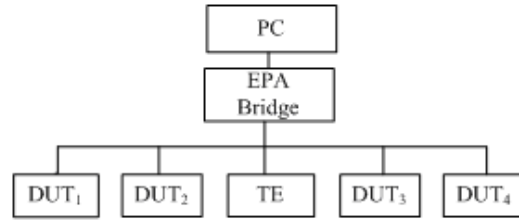

Fig. 4 Experiment Platform

The testing of time synchronization accuracy is accomplished straightly by the TE and displayed by the software in the PC. The testing of the other indicators need to generate timestamps during the transmission of messages. There is a testing FB that produces specific periodic messages at the user layer in each DUT. Some Especial codes are added into the communication protocol stack to generate timestamps at the time points T_1, T_2, T_3, T_4, T_5, T_{ai} and T_{bi} in the above sections. During the experiment, the testing FB running at the user layer in the sender node generates a specific periodic message and puts it into the queue in the ECSME every 4 ms from the time $\text{MOD}(T_c, T)=0$ (T_c is the local current time) to simulate the generation of periodic messages from the FBs at the user layer in industrial application. The frame sizes of the specific periodic messages are all 74 bytes which is the size of the EPA variable distribution frame. As shown in Table 1, the pre-configured timeslice for the periodic messages transmission of every DUT is 5 ms and the timeslice for the macrocycle is 40 ms. The *NST* is 25 ms (*NST*=∑B_i).

TABLE I EXPERIMENTAL MICRO-SEGMENT CONFIGURATION

Source	Destination	ST (ms)	B (ms)	NST (ms)	T (ms)
1	4	0	5		
2	1	5	5		
3	2	10	5	25	40
4	3	15	5		
TE	–	20	5		

According to Table 1 and the (7), we can get that the non-RTE bandwidth B_w of the experimental micro-segment is 37.5%. In order to reduce the error in the experiment, the timestamps T_1, T_2, T_3, T_4, T_5, T_{ai} and T_{bi} are memorized in the corresponding files in the local DUTs and downloaded into the PC after the experiment. The configuration and analysis software running in the PC accesses and processes the data in the files and makes the average of the indicators from 100 macrocycles to display. The testing results during the experiment are shown in Tables 2-Table 6.

TABLE II DELIVERY TIME OF DUT 1

message	t_1 (ms)	t_2 (ms)	t_3 (ms)	t_4 (ms)	t_d (ms)
1	0. 164	1.407	0.072	3.681	5.324
2	0. 147	35.839	0.076	2.506	38.568
3	0.155	32.019	0.074	2.732	34.980
4	0.149	28.193	0.073	3.025	31.440
5	0.152	24.365	0.074	3.252	27. 843
6	0.152	20.535	0.073	3.468	24.228
7	0.144	16.716	0.073	3.686	20.619
8	0.159	12.884	0.074	3.903	17.020

| 9 | 0.157 | 9.055 | 0.072 | 4.126 | 13.410 |
| 10 | 0.152 | 5.226 | 0.074 | 4.339 | 9.791 |

TABLE III DELIVERY TIME OF DUT 2

message	t_1 (ms)	t_2 (ms)	t_3 (ms)	t_4 (ms)	t_d (ms)
1	0.149	6. 239	0.076	2. 427	8.891
2	0.154	2.411	0.074	2.634	5.273
3	0.156	36.834	0.073	1.571	38.634
4	0.154	33.011	0.074	1.794	35.033
5	0.157	29.185	0.076	2.025	31.443
6	0.158	25.356	0.074	2.243	27.831
7	0.152	21.538	0.072	2.459	24.221
8	0.157	17.708	0.071	2.674	20.610
9	0.154	13.886	0.072	2.913	17.025
10	0.158	10.057	0.075	3.131	13.421

TABLE IV DELIVERY TIME OF DUT 3

message	t_1 (ms)	t_2 (ms)	t_3 (ms)	t_4 (ms)	t_d (ms)
1	0.146	11.065	0.075	2.467	13.753
2	0.152	7.236	0.073	2.747	10.208
3	0.155	3.411	0.074	2.935	6.575
4	0.147	37.843	0.072	2.074	40.136
5	0.152	34.015	0.074	2.299	36.540
6	0.153	30.193	0.078	2.522	32.946
7	0.159	26.364	0.072	2.868	29.463
8	0.154	22.539	0.075	3.126	25.894
9	0.152	18.716	0.073	3.347	22.288
10	0.158	14.884	0.076	3.669	18.787

TABLE V DELIVERY TIME OF DUT 4

message	t_1 (ms)	t_2 (ms)	t_3 (ms)	t_4 (ms)	t_d (ms)
1	0.158	15.694	0.072	3.792	19.716
2	0.152	11.874	0.074	4.027	16.127
3	0.156	8.046	0.072	4.267	12.541
4	0.158	4.216	0.076	4.545	8.995
5	0.163	0.385	0.074	4.764	5.386
6	0.155	34.836	0.072	1.375	36.438
7	0.159	31.007	0.073	1.589	32.828
8	0.154	27.178	0.072	1.844	28.248
9	0.149	23.349	0.071	2.085	25.654
10	0.159	19.517	0.076	2.347	22.099

TABLE VI THE F, R_P AND E_P OF DUTS

DUT	F (ms)	R_p (ms)	E_p (ms)
1	0.008	39.26%	0.163
2	0.010	39.52%	0.159
3	0.009	39.63%	0.174
4	0.008	39.72%	0.168

The components of the delivery time for the periodic messages transferred by the DUTs are shown in Tables 2 -5 and the indicators including F, R_p and E_p are shown in Table 6. From the above Tables, we can found 3 points from the experimental results.

1) Among the components of delivery time, processing time t_1, transmitting time t_3 and receiving time t_4 have little influence on the delivery time of EPA. Comparatively, the range of queuing time t_2 covers very wide and delivery time fluctuate with it. Thus, it is the most important component that dominates the variation of delivery time. The periodic messages' queuing time t_2 of a DUT has a very big jump at the point close to its *ST*

and then begins to descend. The reason is that the ECSME of a DUT changes to the PeriodicDataSending state and begins to transfer its periodic messages when the DUT detects its data-sending start time of periodic messages. After finishing the transmission of all the periodic messages waiting in the queue, it transfers NDA message and becomes the Ready state. Thus, in an EPA macrocycle, the periodic messages entering the queue before NDA message starts to be transferred can be transferred during the current macrocycle whereas the periodic messages entering the queue after then have to wait until the next macrocycle and very big delay is generated. For example, the message 5 in DUT 4 is produced when MOD(T_c, T)=16 and

enters queue before the DUT starts to transfer NDA message, so it can be transferred during current macrocycle. On the contrary, the message 6 is produced when MOD(T_c, T)=20. It has to wait until the next macrocycle because it enters queue after the DUT has transferred NDA message and rejects transferring periodic messages even if the DUT has not spent its configured timeslice. This is compatible to the analysis of (2)-(4).

2) The utilization percentage of configured timeslice R_p of each DUT is less than 40% in Table 6. It is shown that the configuration of timeslice for EPA periodic messages transmission is not efficient. If the utilization percentage of configured timeslice R_p is improved by optimizing the configuration of timeslice for EPA periodic messages transmission, the performance of delivery time and non-RTE bandwidth will be improved.

3) The time synchronization accuracy F of the DUTs in the experimental micro-segment are roughly 10 microseconds and the data-sending time offset accuracy E_p is less than 180 microseconds. Because E_p is far bigger than F for each DUT, the probability of collision of messages transmission is very little. In fact, collision has not been found and the scheduling mechanism was implemented successfully during the experiment. Thus, the performance of the two indicators for the experimental micro-segment and the DUTs is acceptable according to the configured timeslice.

IX. CONCLUSION

The real-time performance of EPA periodic messages transmission was investigated during which some real-time indicators were presented and analyzed as an emphasis in this paper. Some equations for the real-time performance of EPA system were derived and an experiment for the test of the indicators was implemented. According to the analyses and the experiment, we can present the following conclusions and methods to improve the real-time performance of EPA periodic messages transmission.

1) The delay D_p during which the messages wait for the periodic messages transmission timeslice for their device is the major factor leading to considerable delivery time. In order to reduce it, the network structure of EPA system should be optimized. EPA deterministic scheduling mechanism of the periodic messages transmission at the DLL should coordinate with the scheduling of the distributed FBs at the user layer. In a macrocycle, a device must finish executing its FBs and putting the periodic messages containing their output data into queue before the NDA message starts to be transferred in order to ensure the periodic messages to be transferred in current macrocycle. At present, a device has only one chance to transfer its periodic messages in a macrocycle because only one ST can be pre-configured in the most of the EPA networks. In order to reduce the delay D_p, it should be allowed that more than one ST for a device is pre-configured and thus one device will have more than one chance to transfer its periodic messages. By this means, the configuration of FBs and periodic

messages transmission can be coordinated more easily and flexibly.

2) It is very important to enhance the efficiency of the configured timeslice for the periodic messages transmission in order to improve the real-time performance of EPA system. At present, there is not an effective method to optimize the configuration of the timeslice for the periodic messages transmission and the configuration is implemented without a guideline in industrial application. There are two methods to ameliorate the configuration of the timeslice for the periodic messages transmission. One method is to configure the periodic messages transmission timeslice based on the demanding time that can be determined according to the configuration of the FBs and the performance of the software and hardware of devices. When an EPA system is working, the utilization percentage of configured timeslice for the periodic messages transmission should be tested and displayed for the configuration to be modified and improved. Another better method is the self-adaptive adjustment algorithm of timeslice that dynamically adjusts the timeslice according to the fluctuation of network load to improve the efficiency of timeslice for the periodic messages transmission through each device monitoring its current utilization percentage of timeslice and coordinating with the other devices in the micro-segment.

3) Data-sending time offset accuracy is an important indicator to choose and configure an EPA device in industrial application. Thus such an indicator of an EPA device should be tested or provided by manufacturers before it is applied in industrial field.

The work in this paper provides a groundwork for the improvement of EPA real-time performance and a useful guideline for choosing and configuring an EPA system in industrial field. The indicators and their test methods can also be used to the real-time performance study of some other fieldbuses.

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