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Abstract. A passive optical network (PON) based real-time Ethernet (PONRTE), which can take advantage of PON features such as broad bandwidth, high reliability, and easy maintenance to satisfy the determination and real-time requirements of high performance industrial applications, is proposed. The protocol model and network architecture having a compatible physical layer and MAC layer with Ethernet passive optical network are presented for the proposed PONRTE. A fixed periodic time slot allocation mechanism including a synchronic time division multiplexing transmission and an asynchronic data transmission is adopted to guarantee the determination and real-time of the communication. A simple and easy to implement time synchronization approach, where the starting time of the first transmission slot of an access node is synchronized by a relative time synchronization while the starting time of subsequent slots is determined by the fixed period and a dynamic time synchronization, is designed to support the fixed time slot allocation mechanism and avoid the collision in PONRTE. A 100 Mb/s PONRTE experimental testbed with 16 access nodes and a time allocation period of 240 μs is demonstrated. The results show that the experimental PONRTE can work stably and reliably with a frame loss ratio less than 10^{-7}. © *2013 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.52.2.025007]

Subject terms: real time Ethernet; passive optical network; time synchronization; communication protocol.

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1 Introduction

Reliable real-time and deterministic data transfer communication is a key issue in many industrial applications in a range of areas including the automobile industry, vehicle and space engines, and industrial automation. Several conventional field buses such as controller area network (CAN) and Profibus have been widely used in industrial automation control systems. However, these conventional field buses cannot satisfy the increasing requirement for high performance real-time data transfer in modern industrial applications using current information technology such as TCP/IP and XML. Ethernet has become the dominated local area network (LAN) technology for corporate networks, which not only can support most of the network protocols such as TCP/IP, but also has the advantage of low cost hardware components because of massive volumes. Therefore, real-time Ethernet solutions, which overcome the nondetermination of the media access protocol (CSMA/CD) used in conventional Ethernet, have been proposed as an alternative of conventional field buses to improve cost, performance and safety.[1–3] Several kinds of real time Ethernet have been in production, such as EtherCAT, Profinet, Powerlink, Ethernet for plant automation (EPA), and Ethernet/IP with CIPSync.[4–7]

Optical fiber communication has achieved great success in backbone networks for its advantages such as broad bandwidth, low loss, immunity to electromagnetic interferences, and light weight. Real time Ethernet can also benefit from the features of the optical fiber communication technology. And point to point optical fiber links have been used in some real-time Ethernet solutions for applications within rugged environments.

In this paper, we propose a passive optical network (PON) based real time Ethernet (PONRTE), which implements multipoint to multipoint all optical connections through a PON with the advantages of broad bandwidth, high reliability and easy maintenance,[8,9] and which guarantees the determination and real-time requirements of high performance real-time applications by adopting a fixed periodic time slot allocation mechanism. The protocol model and the network architecture for the proposed PONRTE are presented. A simple and easy to implement time synchronization approach is designed to support the fixed time slot allocation mechanism in the PON. A 100 Mb/s PONRTE experimental testbed with 16 access nodes (AN) and a time allocation period of 240 μs is demonstrated accordingly.

The paper is organized as follows. Section 2 presents the network architecture of PONRTE. Section 3 describes the real time MAC control mechanism for PONRTE, including time slot allocation control, time synchronization, and node discovery. Section 4 demonstrates a 100 Mb/s PONRTE testbed with 16 AN, a central node (CN), and a management node. Section 5 draws the conclusions.

2 PONRTE Network Architecture

Figure 1 shows the proposed PONRTE network, which consists of a CN, a management node connected to the CN through a point to point link, and several ANs connected to the CN by a passive optical distribution network (ODN). The ODN made up of passive optical couplers and optical fibers can adopt different topologies such as star and tree according to specific application requirements.

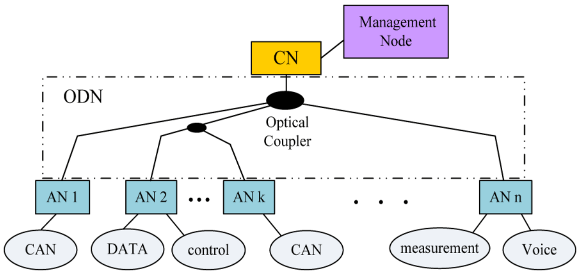

Fig. 1 Schematic diagram of the PON based real time Ethernet network.

The ANs and the CN connect to the ODN through the optical network unit (ONU) physical interface and the optical line terminal (OLT) physical interface of the standard PON, respectively.

In order to avoid collision and guarantee determination and real time requirements, a master/slave network control and management mechanism is adopted in PONRTE. The CN is the master node which implements a central network control and management such as time allocation and fault management. Each AN is a slave node which can only passively actuate the instructions of the CN, such as transmitting data in the time slots assigned by the CN. Users' services such as real-time control and measurement information are encapsulated into PONRTE frames at the ANs. PONRTE frames are transmitted to the CN along corresponding upstream links (from ANs to the CN) of the ODN during the assigned time slots, which are then broadcasted to all ANs through the downstream links (from the CN to ANs) of the ODN by being transferred to the downstream port at the CN. The downstream PONRTE frames are decapsulated into original data at destination ANs to be distributed to corresponding control device/unit, subnet, and so on.

Figure 2 shows the protocol model for the proposed PONRTE, which conforms to the layer structure of Ethernet standard.[9] The physical layer, which is responsible for line coding, transmission and receiving of bit streams, and electro-optical conversion, is completely compatible with that of Ethernet passive optical network (EPON). The PONRTE MAC sublayer is also compatible with the MAC of EPON in encapsulation/decapsulation of MAC frames, and transmission/ receiving of MAC frames. Therefore, commercial components for the physical and MAC layer of EPON can be used in PONRTE directly. The real-time MAC control sublayer is responsible for the discovery and registration of ANs, time slot allocation, and downstream transfer of data frames coming from ANs at the CN. The OAM sublayer provides the operation, administration and maintenance mechanisms (OAM) in the data link layer, such as fault indication and location, remote state configuration, and performance monitoring, which can be combined with the higher layer network management protocol to guarantee the reliability, robustness and usability of PONRTE.

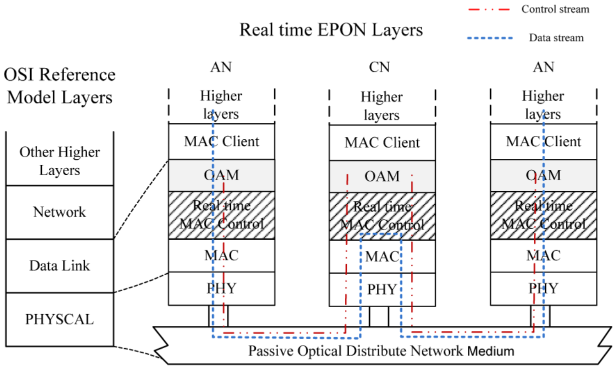

Fig. 2 The PONRTE protocol model, PHY: physical layer device, MAC: media access control, OAM: operation, administration and maintenance.

3 Real-Time MAC Control for PONRTE

Figure 3 illustrates the function block diagram of the real time MAC control sublayer of PONRTE. MAC frames from MAC sublayer are parsed by the parser module firstly. The information such as time and address carried by MAC frames is transferred to the time slot allocation control module, which is responsible for the assignment and control of the communication time of the whole network. The OAM PDUs (protocol data units) are submitted to OAM sublayer for further OAM processing. The discovery PDUs are sent to the discovery-processing module for the discovery and registration of ANs. The loop back module, which is only included in the CN, is used to transfer data frames received from ANs to the downstream port. The multiplexer is responsible for selecting the transmitted frames from the loop back module, the discovery module, and the OAM sublayer in control of the time allocation control module. The OAM control module can collect and monitor the statistical information and the relevant state information from the loop back module, the discovery module, and the time allocation control module for network management. Moreover, it also can configure the network by sending instructions to those modules.

3.1 *Time Slot Allocation Control*

In order to guarantee determination and real time communication, a fixed periodic time slot allocation mechanism for PONRTE is proposed. Figure 4 shows the proposed time slot allocation process in PONRTE. The transmission time of the network is assigned according to a fixed period (T) in the view of the CN. Each fixed period includes two phases: synchronic time division multiplexing transmission

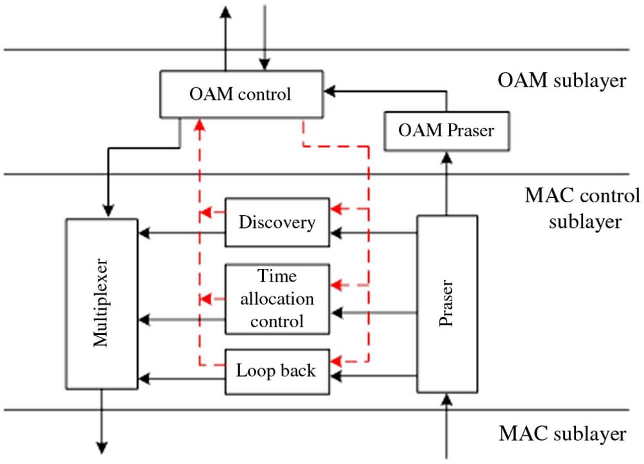

Fig. 3 The function block diagram of real time MAC control sublayer and OAM sublayer.

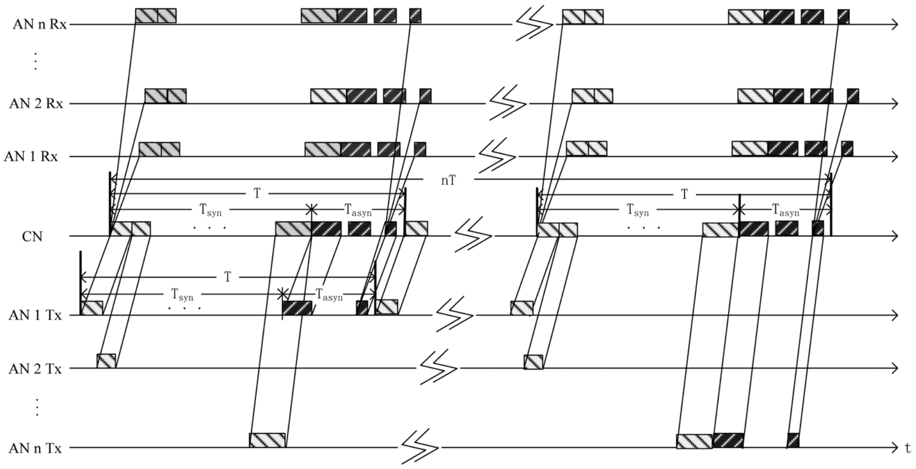

Fig. 4 Diagram of time slot allocation in PONRTE, AN *i* Tx: the transmitter in the MAC of the *i*th AN, AN *i* Rx: the receiver in the MAC of the *i*th AN.

(SynTDM) and asynchronic data transmission (AsynDATA). Each SynTDM phase consists of a series of time slots corresponding to ANs one by one to transmit real time and/or deterministic data such as control instructions and measurement data. The length of each time slot is determined according to the requirements of the corresponding AN. Each AsynDATA phase is allocated to an AN as a whole to complete node discovery, OAM operation and the transmission of unreal-time user services of the corresponding AN. AsynDATA phases are allocated to the ANs according to a certain sequence in a period of nT, where "*n*" is the number of ANs, see Fig. 4.

The above time allocation mechanism is implemented in the time allocation control module in Fig. 3. At the CN, the time allocation control module maintains a time allocation list of the exact time slot assigned to each activated AN according to the fixed periodic allocation mechanism, synchronizes each AN to the CN by a time synchronization procedure (see detail in Sec. 3.2), and controls the transmission of frames at the CN according to the time allocation list. At each AN, the time allocation control module keeps in sync with the CN by the time synchronization mechanism, records the time slots assigned to it, and enables the transmission during each time slot assigned to the AN.

3.2 *Time Synchronization and Node Discovery*

In order to support the above fixed time allocation mechanism, a time synchronization which takes into account the distances between each AN and the CN is needed to synchronize each AN to the CN relatively since the distances from each AN to the CN, the starting time and the frequency of the clock at each AN are difference generally. Although the time synchronization methods such as the ranging method for EPON[9] and IEEE1588 protocol[10] can still be adopted, considering the fixed periodic time allocation mechanism used in PONRTE, we propose another simple and easy to implement time synchronization approach for PONRTE, which synchronizes the starting time of the first transmission slot of each AN by a relative time synchronization and determines the starting time of subsequent slots by the fixed period and a dynamic time synchronization.

The relative time synchronization is combined with the process of the node discovery. The CN activates node discovery processing during each AsynDATA section when the AN corresponding to the AsynDATA section is not registered in the current node list at the CN or receiving a node discovery instruction from OAM sublayer. Figure 5 shows the schematic of node discovery and the related time synchronization. The CN sends a REG_OPEN frame to detect AN$_i$. The AN$_i$ replies a REG_REQ frame containing the requirements of the AN such as the required time slot length and the types of services, and records the starting transmission time of REG_REQ, t_{s0}. While the CN receives the REG_REQ, it records the arriving time of the REG_REQ, t_{r0}, allocates the time slot to AN$_i$ according to the time allocation mechanism in Sec. 3.1, and registers the node. After that, the CN replies with a REG_ACK to AN$_i$, which includes the length of the assigned time slot and the difference, Δt_i, between the starting time (t_i) of the latest transmission time slot assigned to AN$_i$ in the view of the CN and t_{r0}. When AN$_i$ receives the REG_ACK, it records the length of the assigned time slot, and calculates the starting time of the first transmission time slot, t_{s1}, by adding Δt_i to t_{s0}. From Fig. 5, one can see that the starting time of the first transmission slot at AN$_i$, t_{s1}, is synchronized to the assigned one, t_i, at the CN while considering the distance and the clock time difference between AN$_i$ and the CN. The process of the node discovery and relative time synchronization will be stopped if the CN does not receives the replied REG_REQ frame within a designated time after sending a REG_OPEN frame, and will be activated again in the next AsynDATA section assigned to the AN.

After obtaining the starting time of the first transmission time slot, ANs themselves can determine subsequent time slots easily according to the fixed time allocation period. The synchronization state, however, may be lost when the accumulated offset, which may be caused by the frequency offset and/or drift between local clocks at nodes and the drift of transmission delay for the change of ambiences, exceeds designed threshold. We propose a dynamic time synchronization approach shown in Fig. 6, which can dynamically keep the synchronization between the CN and ANs by adjusting the transmission time of each AN according the real-time detected offset between the assigned exact arriving time and the actual arriving time of frames from ANs. For example, when a data frame (D_TDM) from AN$_i$ arrives the CN during a SynTDM section, the actual arriving time

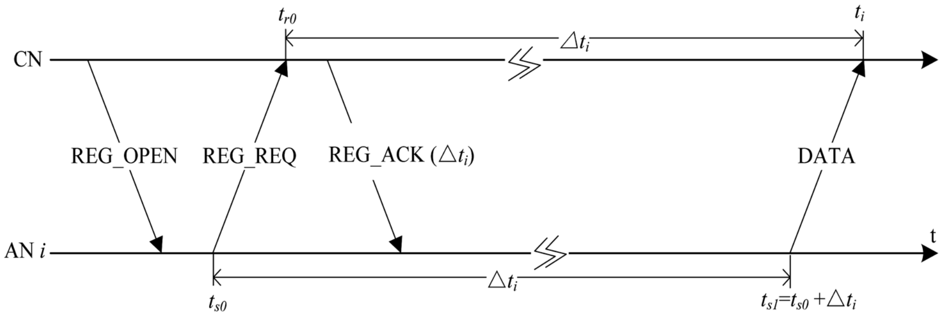

Fig. 5 The schematic of node discovery and relative time synchronization.

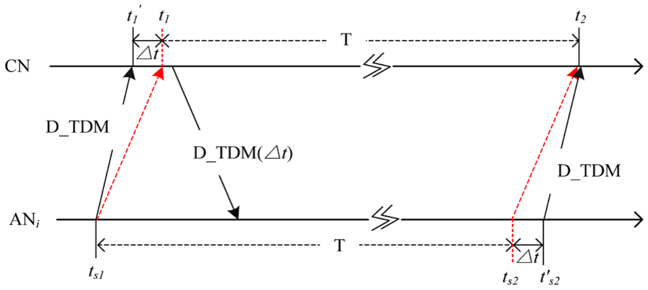

Fig. 6 The schematic of dynamic time slot synchronization.

of the frame from AN$_i$ (t'_1) is compared with the designated arriving time of the frame (t_1) at the CN. The offset time, $\Delta t = (t_1 - t'_1)$, is sent to AN$_i$ by filling it into the data frame broadcasted along the downstream link. The AN$_i$ picks up the offset time from the received data frame with the source address same as the address of the AN$_i$, and adjusts the starting time of its next TDM transmission slot to $t'_{s2}(= t_{s1} + T + \Delta t)$. From Fig. 6, we can see that the next D_TDM frame from the AN$_i$ arrives at the CN at the designated time (t_2) after the dynamic time synchronization.

4 Experimental Testbed of PONRTE

We demonstrated a 100 Mb/s PONRTE experimental testbed with a CN, 16 ANs and a management node, shown in Fig. 7. The management node completes configuration management, fault management, and performance management by exchanging network management messages with the CN through a 100 Mb/s Ethernet link. The CN and the 16 ANs are connected to an ODN with a 1∶16 optical coupler through commercial OLT and ONU EPON transceivers (Hisense Optoelectronics, Ltd., LTE4302 and LTB4321), respectively, which can support a distance of 20 km for a 1∶16 splitter. CAN services are emulated by a CAN test software (Zhouligong Ltd., ZLGCANTest-USBCAN) in computers and inputted to the experimental testbed through USBCAN converters.

Figure 8 shows the hardware block diagrams of the CN and each AN. Except for a few peripheral interfaces such as the Ethernet controller, OLT, ONU and the CAN transceiver, most processing functions are implemented in FPGA (Altera, EP3C40F324). At the CN, a SOPC (System on a Programmable Chip) based on a Nios II processor is built in the FPGA. A PONRTE controller for the CN, which contains a lower layer OAM, a PONRTE MAC control, an Ethernet MAC, and a 125 Mb/s burst mode transceiver (BM-PHY), is designed and implemented in the hardware layer of the SOPC using Verilog. The Nios II processor runs a uClinux operation system to complete higher layer processing of OAM, network management agent and the communication with the management node through a 100 Mb/s Ethernet link. At each AN, a PONRTE controller for ANs is implemented in the FPGA to complete the PONRTE MAC control, OAM, the functions of Ethernet MAC and EPON PHY at ONU. A CAN controller is also implemented in the FPGA for the accessing/forwarding of CAN frames from/to computers with CAN emulators.

Figure 9 shows the designed PONRTE frames in the testbed. The protocol type of the following field in each

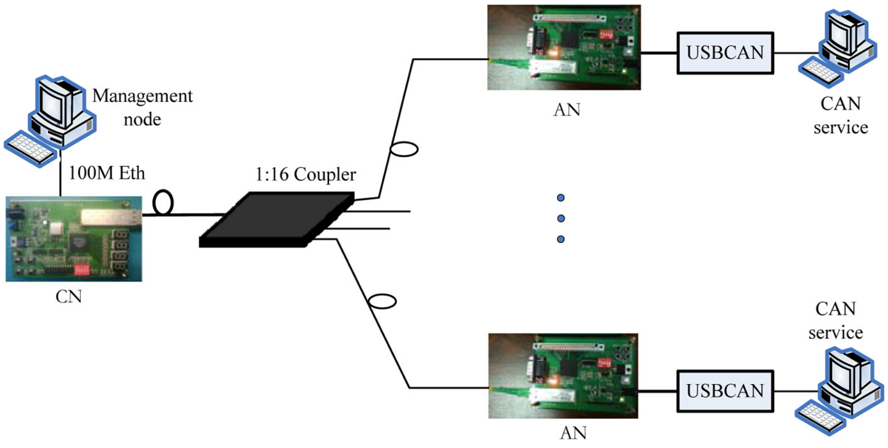

Fig. 7 PONRTE experimental testbed.

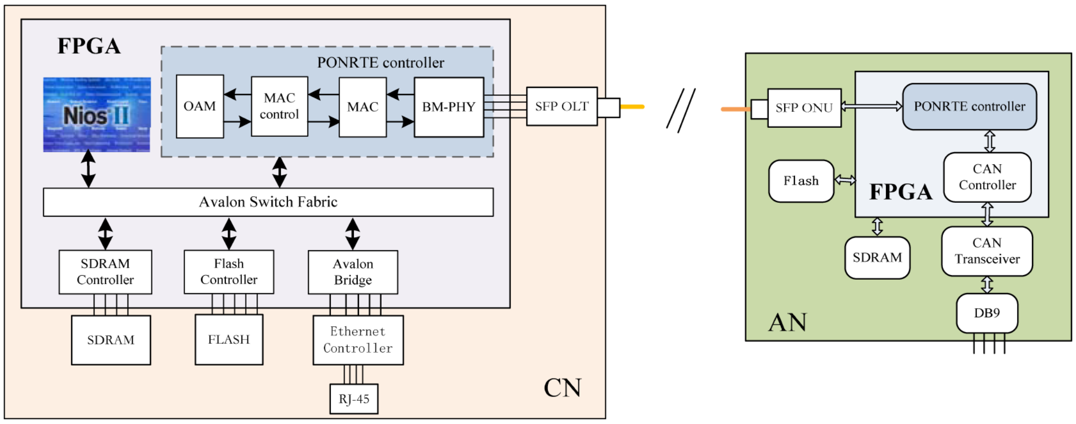

Fig. 8 The hardware block diagrams of the CN and ANs.

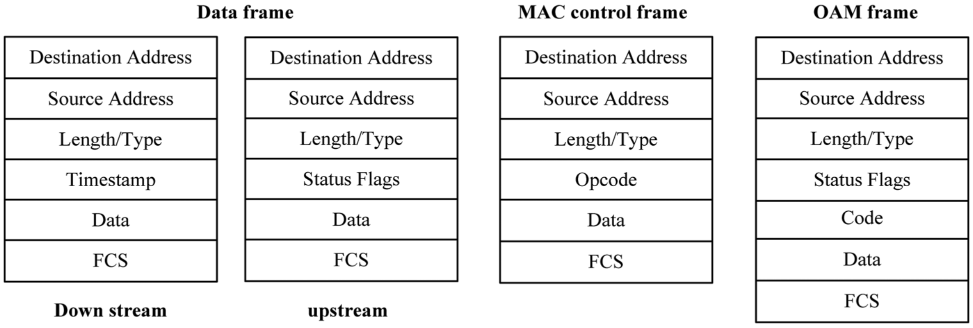

Fig. 9 The formats of PONRTE frames.

frame is identified by the length/type field. The data frame is responsible for carrying MAC client data such as CAN. The timestamp field in downstream data frames is used to carry the adjusting time for the dynamic time synchronization. The status flags field in upstream data frames contains the state information of the AN sending the frame, which will be used for the OAM processing at the CN. The MAC control frame is used for the MAC control protocol such as the time synchronization and the node discovery. The specific MAC control frame such as REG_OPEN, REG_REQ and REG_ACK is identified by the opcode field, and the corresponding control or operation parameters are contained in the data field. The OAM frame is used for the transformation of OAM information between the CN and ANs. The status Flags field is used to report fault or state information of ANs. The code field is used to indicate the specific OAM frame. The specific OAM information is included in the data field. In our testbed, two kinds of OAM frames, OAM configuration frames and OAM performance frames, are defined. OAM configuration frames are used to configure operation parameters of ANs on line from the CN, such as the reset of ANs, and the access speed limitation. The OAM performance frames are used to collect the transmission parameters at ANs such as the number of error frames and throughput.

In the experimental test, the time allocation period is set to 240 μs including a SynTDM section of 200 μs and an AsyDATA section of 40 μs. Time slot assigned to each AN in one time allocation period is 12.5 μs. The length of the data frame is 128 bytes while both the control frame and the OAM frame have a length of 64 bytes. The emulated CAN application services in each computer are sent to the CAN emulators in other computers through PONRTE. The number of transmitted CAN frames and the number of the received CAN frames are measured at each AN and computer.

Figure 10 shows the measured number of lost CAN frames and the frame loss ratio on each point-to-point link along computer to computer paths when the number of tested CAN frames changes from 10^4 to 10^7. From the figure, we can see that all lost CAN frames are dropped on the CAN links between computers and AN while there

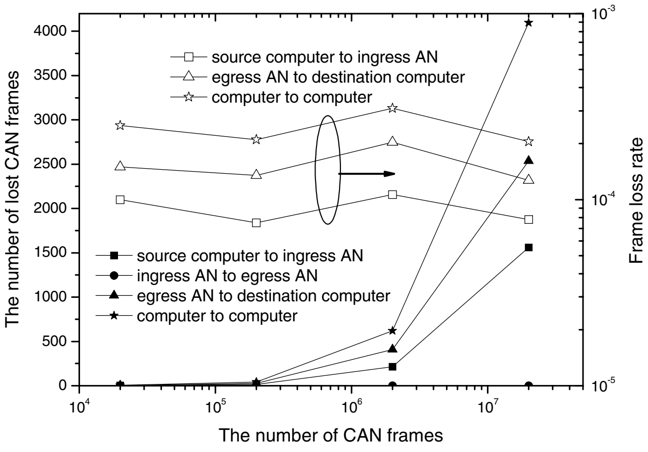

Fig. 10 The measured number of lost CAN frame and the frame loss rate in different numbers of tested CAN frames.

is no CAN frame to be lost on AN-to-AN optical paths. One can also see that the computer-to-computer frame loss ratio in each case are always about 10^{-4} and equal to the sum of the frame loss ratios on the CAN links. The results validates that PONRTE can work stably and reliably with a frame loss ratio less than 10^{-7} and a bit error rate less than 10^{-9} considering the length of CAN frames (13 bytes for a CAN extended frame).

5 Conclusions

In the paper, we propose a passive optical network based real time Ethernet, which adopts a kind of fixed period based time slot allocation mechanism and has a layer structure conforming the IEEE Ethernet standard protocol model, to satisfy the determination and real-time requirements of the high performance industrial applications and take advantages of PON such as broad bandwidth, high reliability, and easy maintenance. A simple and easy to implement time synchronization approach considering the fixed periodic time allocation mechanism is designed to support the fixed period based time slot allocation and avoid the collision in PONRTE. A 100 Mb/s PONRTE testbed with a CN, 16 ANs and a management node is experimentally demonstrated. The test results show that the emulated CAN services can be supported on the experimental PONRTE stably and reliably with a time allocation period of 240 μs and a frame loss ratio less than 10^{-7}.

Acknowledgments

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