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Time-Triggered Ethernet and IEEE 1588 Clock Synchronization

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Abstract

The Time-Triggered Ethernet unifies real-time and non-real-time traffic into a single communication architecture. We have built a prototype implementation of an FPGA TT-Ethernet switch and an FPGA TT Ethernet communication controller supporting a network bandwidth of 100Mbit/sec. Time-Triggered Ethernet introduces two message classes, i) the standard event-triggered Ethernet messages, denoted as ET messages, and ii) the time-triggered Ethernet messages, denoted as TT messages. All TT messages are transmitted periodically and are scheduled a priori in a way that there are no conflicts on the network. The network handles these messages according to the cut-through paradigm. Computer nodes containing TT Ethernet communication controllers establish and maintain global time base. However nodes containing standard Ethernet controllers can be connected to a TT Ethernet system and can send ET messages without affecting the temporal properties of the TT messages. The global time format of the TT Ethernet deploys the UTC time format which is compatible with the time format of the IEEE 1588 standard. In these work we present how we deploy the IEEE 1588 in order to synchronize the TT Ethernet controllers which require a tight synchronization among them. Additionally the IEEE 1588 clock synchronization based protocol will be implemented at standard Ethernet controllers such that they can be establish and maintain a global time base.

Index Terms *— Ethernet, real-time communication, global time, clock synchronization.*

1. Introduction

The duration of the protocol execution depends on the assumptions made about the network traffic. In principle we can distinguish between two different scenarios: cooperative senders or competing senders. If senders are competing (like in standard Ethernet) there is always the possibility that many messages are sent to a single receiver simultaneously. There are two possibilities to resolve this conflict: back-pressure flow control to the sender (like in bus-based "Vintage Ethernet" or the storage of the messages within the network (like in switched Ethernet). Both alternatives are unsatisfactory from the point of view of real-time performance. In real-time systems the senders must cooperate in order to avoid message conflicts that cause non-deterministic message transmission delays. This coordination can be achieved by the reference to an established global view of time. Time-Triggered Ethernet allows competing senders to coexist with cooperative senders on the same network while yet preserving the temporal predictability of the traffic among the cooperative senders. To integrate competing traffic seamlessly in the same network without interference of the cooperative traffic, Time-Triggered Ethernet introduces two message classes:

- The standard event-triggered Ethernet messages (denoted as ET messages) that originate in an open (uncontrolled) environment and are handled by the network according to the *store-and-forward paradigm* of standard switched Ethernet.
- The time-triggered Ethernet messages (denoted as TT messages) that originate in a closed cooperating environment. All TT messages are transmitted periodically as broadcast messages and are scheduled a priori in a way that there are no conflicts on the network. The network handles these messages according to the *cut-through paradigm.*

The TT-Ethernet message format is based on the format of standard raw Ethernet messages according to the IEEE 802.3 standard. A standard Ethernet frame contains a two-byte *Type Field* that specifies the type of an Ethernet message. The type field provides a context for interpretation of the data field of the frame (protocol identification). In order to assure consistent development of Ethernet protocols, the contents of the type field is administered by the Ethernet standard authority of the IEEE. This authority has assigned the value *0x88d7* as the content of the type field in order to identify uniquely a TT Ethernet message. This ensures the compatibility of TT-Ethernet to standard Ethernet and enables the use of legacy Ethernet devices with standard Ethernet communication controllers sending only ET packets within a TT-Ethernet system. Since only TT traffic is coordinated by a schedule, it might come to run-time conflict situations between an ET message and a TT message. This conflict is resolved by the TT Ethernet switch.

2. TT Ethernet Switch

Since standard switches cannot guarantee predictable transmission delays for TT traffic in the case of message conflicts between TT and ET messages, time-triggered Ethernet deploys a specific switch, which is denoted as the *TT-Ethernet switch* [1]. The TT-Ethernet switch guarantees predictable transmission delays for TT traffic, even in the case when ET and TT packets are transmitted simultaneously.

In case of a collision between a TT and an ET message, the TT Ethernet switch *pre-empts* the transmission of the ET message and transmits the TT message with a constant and a-priori known transmission latency. As ET messages are stored in the memory of the switch, the preempted ET message will be retransmitted by the switch as soon as the transmission of the TT message has finished (*best-effort method*). In a fault-free case, collisions between TT messages are prevented by the design of the communication schedule. In case of an error the switch resolves these collisions by an a-priory known priority schema and transfers only one TT message whereas all other TT messages involved in the message conflict are discarded. This mechanism provides a deterministic message transmission for conflict-free TT messages. The TT Ethernet switch can distinguish between a TT message and another Ethernet based messages based on the content of the Ethernet Type-Field.

TT Ethernet switch allows the exchange of ET messages in the same network with TT messages:

- without affecting the message transmission delays of TT messages, and
- without any need to configure or change the existing Ethernet-based communication protocols (like, TCP or UDP) for the exchange of ET messages in a TT Ethernet system.

In the case when only TT messages are exchanged over the network a COTS switch can be deployed instead of a TT Ethernet switch.

3. TT-Ethernet Controller

A node of a distributed system consists of a host computer and a communication controller. The host is responsible for execution of application tasks, whereas the communication controller executes the communication protocol. The incoming and outgoing TT Ethernet messages are stored in the *communication network interface* (CNI) which acts a data exchange interface between the TT Ethernet controller and the host computer. The CNI acts as a temporal firewall between the host and the controller, i.e., TT messages are written and are read from the CNI at the predefined points in time. The main difference between a TT Ethernet controller and the COTS Ethernet controller is the temporal delays when accessing the data in the CNI. The TT Ethernet controller writes and reads the data at the specified time interval (with deterministic delays), whereas in the case of COTS Ethernet controller the delay caused by the exchange the data is not deterministic as it depends on the current usage of the onboard bus (e.g., PCI bus) used for data exchange between the Ethernet controller and the memory.

In order to establish cooperation between all TT-Ethernet nodes, each TT-Ethernet controller has to synchronize its local clock to the global time base of the cluster. After power up the TT message transmission of the controller is suspended until the synchronization is established. In order to keep the local time synchronous to the global time base, the clock synchronization is performed periodically.

The transmission of TT messages is done according to the static schedule which is configured by the host. The TT-Ethernet controller autonomously transmits each TT message on the scheduled transmission time. It creates the message header, transfers the payload data from the host (or the CNI) and transmits the packet according to the schedule. The reception of TT messages is also scheduled and controlled by time. A controller will receive a TT message within a receive window specified in the communication schedule. If the message arrives within this window, it is valid in terms of temporal requirements.

A computer node with a standard Ethernet controller without the clock synchronization mechanism can be used to send and receive ET messages and it can receive TT messages but it cannot send TT messages.

We will investigate the case where we deploy a node consisting of COTS Ethernet controller and a host computer that implements an IEEE 1588 based clock synchronization protocol. In this case, this node can be considered as a TT Ethernet controller (without CNI) which can send TT messages.

The subject of our future work is to investigate to what extend does the clock synchronization precision differ in two different setups, *1)* by deploying COTS Ethernet controllers with the IEEE 1588 synchronization mechanism as TT Ethernet controllers (without a CNI), compared to the setup *2)* by deploying FPGA TT Ethernet controllers with the CNI that implements IEEE 1588.

4. TT-Ethernet and 1588

The interlink between the TT-Ethernet and the IEEE 1588 exists in the following cases:

- In a configuration with a single TT Ethernet cluster with the *TT Ethernet switch*, it is possible to establish and maintain the global time base by only using a simple master–slave clock synchronization algorithm and not the IEEE 1588, as the message transmission delays of TT messages among the TT Ethernet nodes remains constant, and there is no need for a mechanisms to measure the delay among the nodes, as it is the case of IEEE 1588. However in the case of synchronization to an external clock, the master clock needs to be synchronized to an external clock source. In that case the master clock will deploy the IEEE 1588 clock synchronization.
- In the current prototype implementation of the TT Ethernet, the TT Ethernet switch allows the transmission of the TT messages with guarantied and constant transmission delay. This allows implementation of a simpler clock sync algorithms compared to IEE 1588. However, if another switch is deployed, e.g., a COTS switch, which cannot guarantee constant message transmission delays, TT-Ethernet controllers will deploy the IEEE 1588 clock synchronization.
- In a TT Ethernet system, nodes with COTS controller can be deployed to exchange ET messages or to receive TT messages. These nodes can establish a local view of global time by deploying the IEEE 1588 clock synchronization (e.g., a monitoring node can timestamp the incoming ET and TT messages).
- In the case of standard TT Ethernet configuration, the TT Ethernet switch does not need to be synchronized with the rest of the system, as it handles the TT Ethernet messages according to the *cut-through paradigm*. In the case of the fault-tolerant TT Ethernet [2], the central bus guardian controlling the input and the output ports of the switch needs to be synchronized with the rest of the cluster. IEEE 1588 can be deployed in this case as well. In safety-critical real-time systems, it is required that the clock synchronization mechanism gives deterministic guaranties regarding the precision of the global time [3]. In case that IEEE 1588 is deployed in such systems, it is required to investigate to what extend the IEEE 1588 standard can maintain the associated precision guarantee in the presence of faults.

5. Conclusion

The global time format of the TT Ethernet deploys the UTC time format which is compatible with the time format of the IEEE 1588 standard. The IEEE 1588 standard forms a solid basis for implementing clock synchronization mechanisms also for distributed computer systems that deploy communication networks that do not guarantee deterministic transmission delays. As in TT Ethernet different configurations are possible, the IEEE 1588 is suitable for implementing the clock synchronization mechanism. In this paper we have identified four cases where the IEEE 1588 can be deployed in the TT Ethernet. Additionally the IEEE 1588 clock synchronization based protocol will be implemented at standard COTS Ethernet controllers such that they can establish and maintain a global time base in a TT Ethernet system. The implementation of these mechanisms is an ongoing work.

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