

# TTEthernet

A Powerful Network Solution for All Purposes

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## From Ethernet to TTEthernet

Over the last years there has been discussion about how to adapt Ethernet for new application domains. Its focus has been on the use of Ethernet for real-time tasks in industrial environments. More than 20 different approaches are now struggling for recognition in industrial automation alone.

Today's Ethernet systems have limits when it comes to combining them with classical Ethernet networks, devices and services. The scalability of these systems is also limited and the network solution is tailored for a specific application area. TTEthernet combines the proven determinism, fault-tolerance and real-time properties of the time-triggered technology with the flexibility, dynamics and legacy of "best effort" of Ethernet and is therefore suited for all types of applications.

Considering networking technologies in general, one can distinguish between closed, statically configured embedded networks and open, dynamic networks allowing free-form communication. Whereas statically configured communication networks enable reliable data transmission in real time, free-form communication networks perform only on a best-effort basis, i.e., there is no guarantee if and when data messages are transmitted. As statically configured systems usually need to comply with strict safety are based on dedicated standards, the number of communication nodes is known and not very flexible. Open standards, like the TCP/IP/Ethernet stack that drives the

Internet, form the basis of free-form communication and the number of nodes in systems is arbitrary. TTEthernet brings together the high flexibility of free-form systems and the reliability and speed of statically configured systems (see Figure 1).

## TTEthernet Design Objectives

TTEthernet enables the seamless communication of all applications by way of Ethernet. Conventional PCs, web and office devices, multimedia systems, real-time systems and safety-critical systems are to use the same network. A single network that is completely compatible with the IEEE Ethernet 802.3 standards is suited for data transmission among different applications with various requirements. A single network solution could thus be used for all applications in airplanes, ranging from the entertainment program, to board supply, electronic navigation and guidance system, and internet access in passenger seats. Critical areas are accordingly made fail-safe or fail-operational. Fault tolerance mechanisms avoid the fault propagation in the system and prevent potential hackers from unauthorized access to resources.

TTEthernet is scalable. Networks that connect uncritical applications shall be able to transmit real-time data in distributed controls and shall be suited for safety-critical applications in the future. Existing applications need not be changed when the network is extended in terms of functionality. Time-critical messages always take precedence over less important messages in TTEthernet. This does not affect conventional applications. The temporal behavior of the time-critical messages is predictable and can be characterized depending on the required quality.

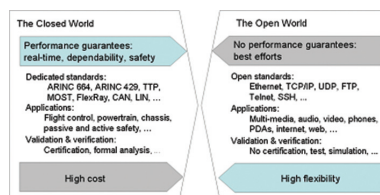


Fig. 1: TTEthernet combines closed-world and open-world systems on the basis of IEEE 802.3 Ethernet standards.

TTEthernet is used for safety-critical fail-operational applications. This means that the system remains fully functional even if a failure occurs. No matter if a node, a switch or a network branch is faulty, the network continues safe communication. This fact accounts for the essential difference between TTEthernet and other Safe Ethernet systems. The latter systems, which are sufficient for industrial applications detect faults in the network and switch the system to a safe state, e.g. stopping the engine. In order to secure the availability of the system even if a failure occurs, TTEthernet provides a variety of network services such as a clock synchronization service, a startup service and clique detection and recovery services. The behavior of TTEthernet is precisely predictable and thus formally verifiable.

## TTEthernet System Properties

TTEthernet has time-triggered services that enable time-triggered communication over Ethernet. These time-triggered services establish and maintain a global time, which is realized by the close synchronization of local clocks of the devices. The global time forms the basis for system properties such as temporal partitioning, precise diagnosis, efficient resource utilization, or composability.

**Temporal Partitioning:** The global time can be used as a powerful isolation mechanism when devices become faulty; we say that the global time operates as a “temporal firewall”. In case of failure it is not possible for a faulty application to untimely access the network. Depending on the location of the failure, either the communication controller itself or the switch will block faulty transmission attempts. Failures of the switch can be masked by powerful end-to-end arguments such as CRCs or by high-integrity designs.

**Efficient Resource Utilization:** The global time contributes to efficient resource utilization in several ways. Time-triggered communication allows minimizing the memory buffers in network devices as the time-triggered communication schedule is free of conflicts. Hence, switches do not have to be prepared for bursts of messages that have to be delivered over the same physical link. A minimal time-triggered switch design could even multiplex media access logic such as reception or transmission logic. A second way of effective resource utilization is buffer memory in the nodes, which can be minimized as the sensor values can be acquired according to the global time, immediately before sending the message. Finally, a third way of effective

resource utilization is power management in which energy can be seen, and saved, analogously to memory.

**Precise Diagnosis:** A global time stamping service simplifies the process of reconstruction of a chain of distributed events. On the other hand, the synchronous capturing of sensor values allows building snapshots of the state of the overall systems.

**Composability:** The global time allows the specification of devices not only in the value domain, but also in the temporal domain. This means that already during the design process of devices, the access pattern to the communication network can be defined. The devices can then be developed in parallel activities. Upon integration of the individual devices, it is guaranteed that prior services are stable

and that the individual devices operate as a coordinated whole.

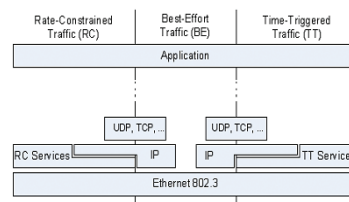


Fig. 2: Relation of TTEthernet to existing communication standards

## Dataflow Options in TTEthernet

TTEthernet specifies services that enable time-triggered communication on top of Ethernet. The time-triggered services can be viewed parallel to the usual

OSI layers: a communication controller that implements these services is able to synchronize with other communication controllers and switches in the system. It can then send messages at points in time derived from this system-wide synchronization. These messages are then called time-triggered messages.

As TTEthernet supports communication among applications with various real-time and safety requirements over a network, three different traffic types are provided: time-triggered (TT) traffic, rate-constrained (RC) traffic, and best-effort (BE) traffic. If required, the corresponding traffic type of a message can be identified based on a message's Ethernet Destination address. The relation of the TTEthernet traffic types to existing standards is depicted in Figure 2.

Messages from higher layer protocols, like IP or UDP, can be “made” time-triggered without modifications of the messages' contents itself. The TTEthernet protocol overhead is transmitted in dedicated messages termed protocol control frames, which are used to establish system-wide synchronization. In short, TTEthernet is only concerned

with “when” a data message is sent, not with specific contents within in a message.

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 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. Typically, RC messages are also used for multimedia systems.

In contrast to TT messages, RC messages are not sent with respect to a system-wide synchronized time base. Hence, different communication controllers may send RC messages at the same point in time to the same receiver. As a consequence, the RC messages may queue up in the network switches, leading to increased transmission jitter. As the transmission rate of the RC messages is bound a priori and controlled in the network switches, an upper bound on

the transmission jitter can be calculated off-line and message loss is prevented.

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 mes-

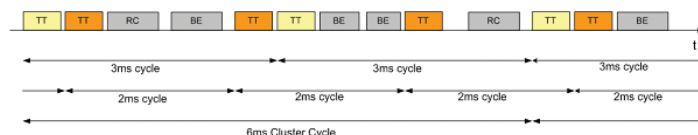


Fig. 3: TTEthernet includes TT, RC and BE messages.

sages 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. TTEthernet implements strong partitioning between non-critical BE traffic and all other service classes (see Figure 3).

## TTEthernet as Transparent Synchronization Protocol

TTEthernet is a transparent synchronization protocol, i.e., it is able to co-exist with other traffic, potentially legacy traffic, on the same physical communication network. For reasons of fault tolerance a multitude of devices can be configured to generate synchronization messages. The devices generating the synchronization messages may be distributed with a high number of intermediate devices in between each other.



Fig. 4: A test setup for TTEthernet

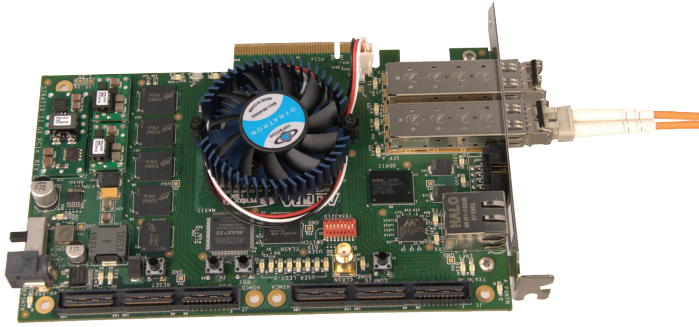


Fig. 5: A network card as used by TTTech for testing.

TTEthernet defines basic building blocks that allow the transparent integration of the time-triggered services on top of message-based communication infrastructures such as standard Ethernet. For this, TTEthernet defines a novel application of the transparent clock mechanism that enables the concept of the permanence point in time, which allows re-establishing the send order of messages in a receiver:

- Application of transparent clock mechanism: all devices in the distributed computer network that impose a dynamic delay on the transmission, reception, or relay of a synchronization message add this dynamic delay into a dedicated field in the synchronization messages used for the synchronization protocol.
- Novel precise calculation of the permanence point in time: the application of transparent clock mechanism allows a precise re-establishment of the temporal order of synchronization messages. In a first step the worst case delay is calculated off-line. In a second step, each synchronization message is delayed for "worst case delay minus dynamic delay" upon reception of the synchronization message, where the dynamic delay is the delay added to the synchronization message, as the synchronization message flows through the communication channel. This point after the reception point in time will be called the permanence point in time.

For fault-tolerant algorithms in general, and fault-tolerant synchronization algorithms in particular, the message send order is of highest importance. The re-establishment of the send order of synchronization messages is required for any fault-masking synchronization protocol that ensures synchronization of local clocks in a distributed computer network.

### Safety and Fault Tolerance

A high level of safety is provided by the time-triggered method of TTEthernet, which detects failures and irregularities in the network and certain systems. Additional measures need to be taken to achieve maximum safety, availability and fault tolerance.

TTEthernet networks can be set up with multiple redundant end systems, switches and segments. Thus the system will remain in operation even if faults occur. Redundant network paths are always used in fault-tolerant TTEthernet systems so that the failure of a single system or messages can be tolerated without affecting the application. If multiple redundancy is implemented, multiple faults can be tolerated. It is important that the entire system remains in operation without interrupts under the same temporal conditions as defined before.

TTEthernet allows the integration of guardians in switches and end systems. Guardians check if the communication on the network works in compliance with the predefined parameters. If faulty systems block network segments, the guardian disconnects the network segment or port. Multiple redundant guardians can be implemented to meet the highest safety requirements).

### Conclusion

TTEthernet enables time-triggered communication over Ethernet networks in all application areas. The network provides all necessary mechanisms for applications as diverse as classical web services and time-critical and safety-critical control system in airplanes. Existing networks can be extended step by step using TTEthernet-capable switches and end systems without the need to change existing applications and end systems. Reducing network solutions to established and recognized Ethernet standards opens up saving potentials that secure major advantages in competitive markets. 📌

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