Ensuring Reliable Networks TTTech

Deterministic Ethernet as Reliable Communication Infrastructure for Distributed Dependable Systems

DREAM Seminar

UC Berkeley, January 21st, 2014

Wilfried Steiner, Corporate Scientist
wilfried.steiner@tttech.com

MOTIVATION

What They Have in Common …

Boeing 787


NASA Orion

Reliable Networks

Are a key element of a dependable system

Audi A8

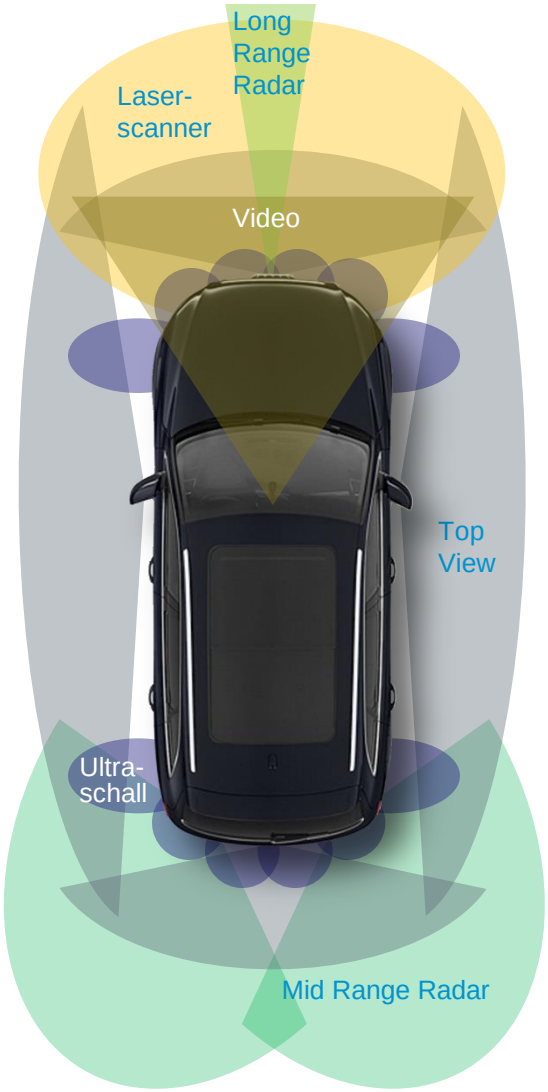
Airbus A380

Trend towards Advanced Driver Assistant Systems (ADAS)

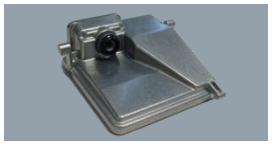
Ensuring Reliable Networks TTTech

Sensors

Ensuring Reliable Networks TTTech



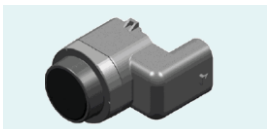
Long-Range-Radar (LRR 4)



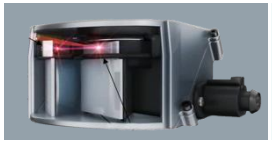
Video Camera

Top view Camera

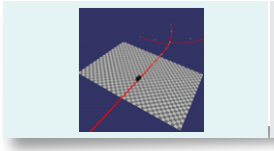
Middle-Range-Radar (MRR)



Ultra Sonic



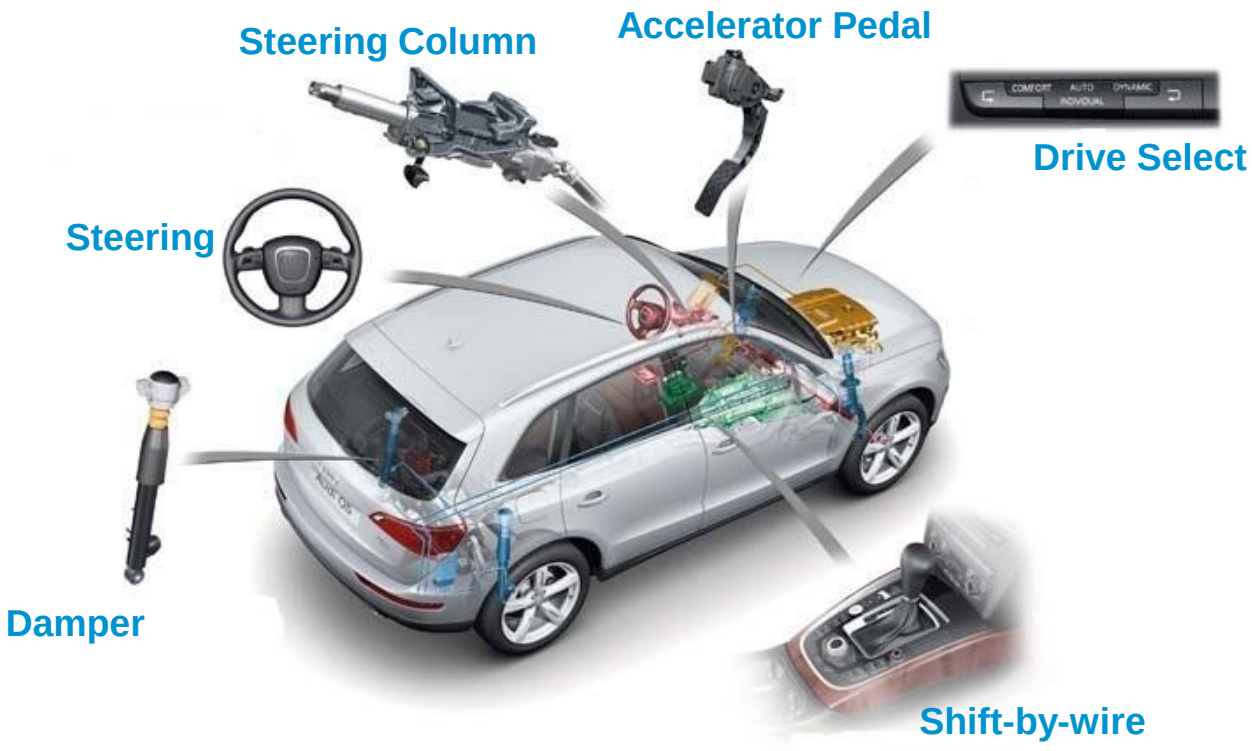
Laser Scanner



Predicitive Map Data
Car2x Connectivity

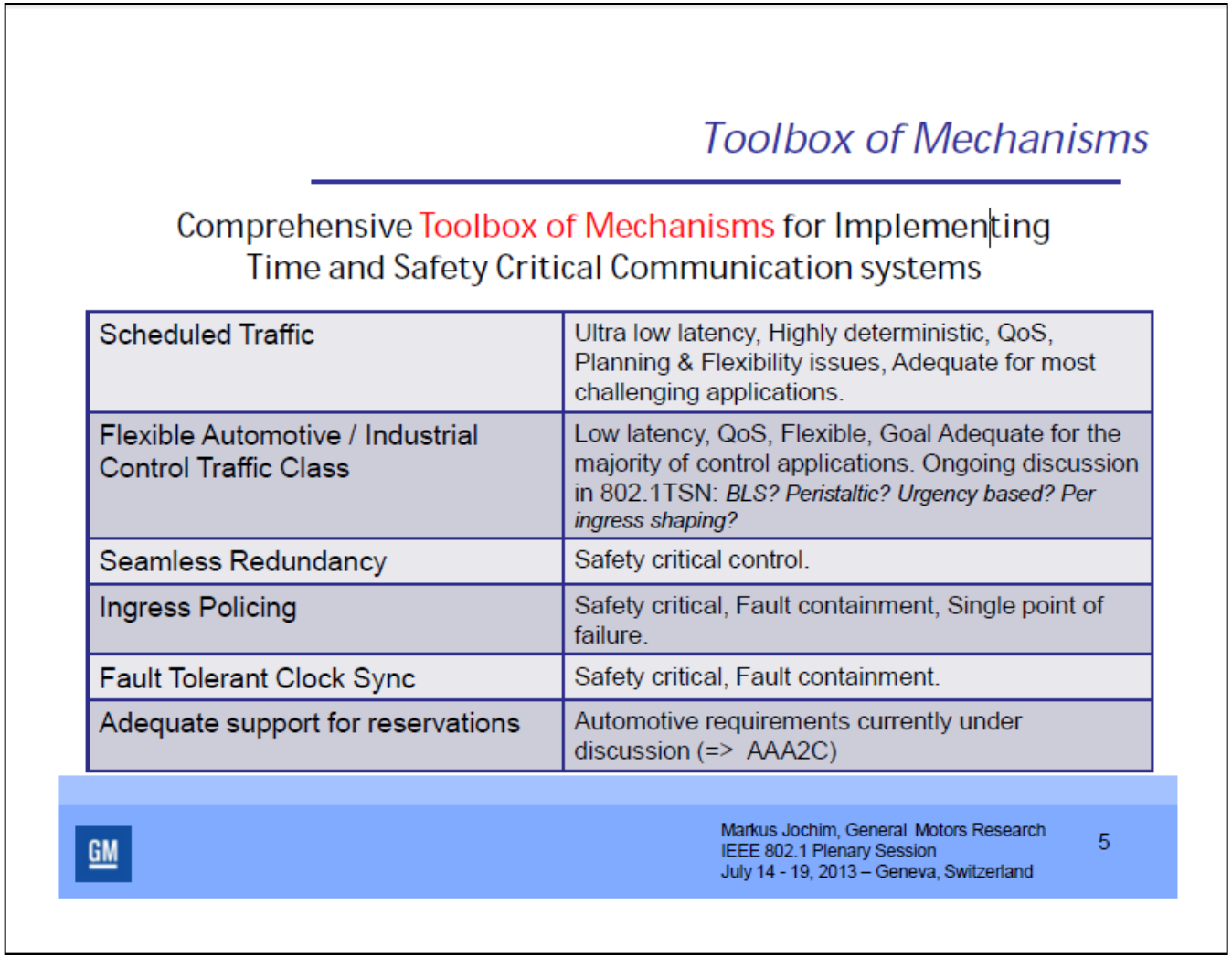
Actuators

Necessary Actuators for Automated Driving	
▸ Electronic Stability Control	▸ Powertrain Coordination
▸ Hold management system	▸ Shift-by-Wire
▸ Decelleration management	▸ Electric Power Steering



NETWORK BECOMES MORE AND MORE IMPORTANT

Automotive Need of a Reliable Communication Infrastructure



Toolbox of Mechanisms

Comprehensive Toolbox of Mechanisms for Implementing Time and Safety Critical Communication systems

Scheduled Traffic	Ultra low latency, Highly deterministic, QoS, Planning & Flexibility issues, Adequate for most challenging applications.
Flexible Automotive / Industrial Control Traffic Class	Low latency, QoS, Flexible, Goal Adequate for the majority of control applications. Ongoing discussion in 802.1TSN: *BLS? Peristaltic? Urgency based? Per ingress shaping?*
Seamless Redundancy	Safety critical control.
Ingress Policing	Safety critical, Fault containment, Single point of failure.
Fault Tolerant Clock Sync	Safety critical, Fault containment.
Adequate support for reservations	Automotive requirements currently under discussion (=> AAA2C)

GM

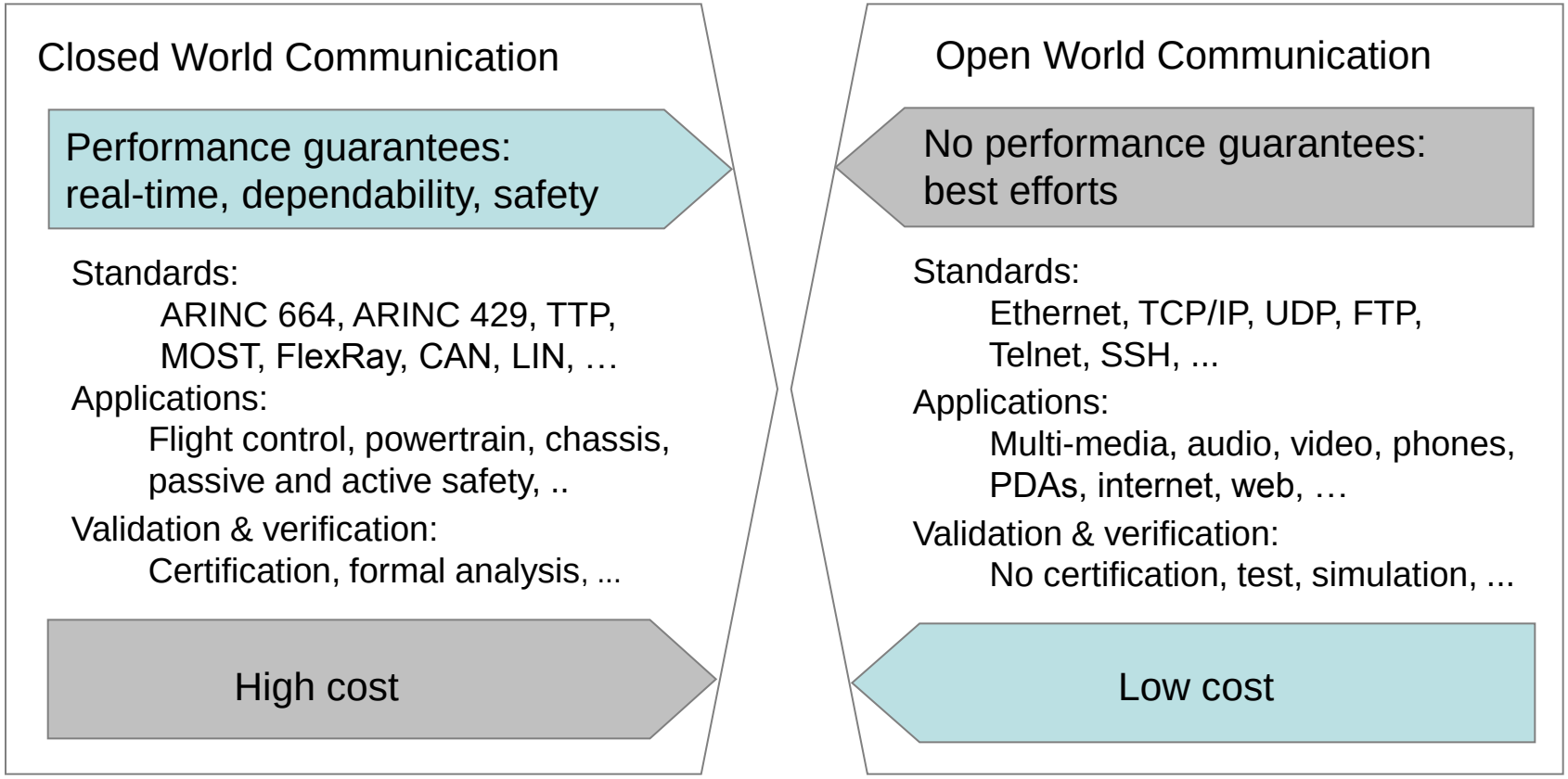
Markus Jochim, General Motors Research
IEEE 802.1 Plenary Session
July 14 - 19, 2013 – Geneva, Switzerland

5

http://www.ieee802.org/1/files/public/docs2013/new-tsn-jochim-goals-of-802-1tsn-0713-v01.pdf

General Industrial Trend towards Converged Networks

Ensuring Reliable Networks TTTech



We see a market requirement to use the same physical network for data flows from both worlds.

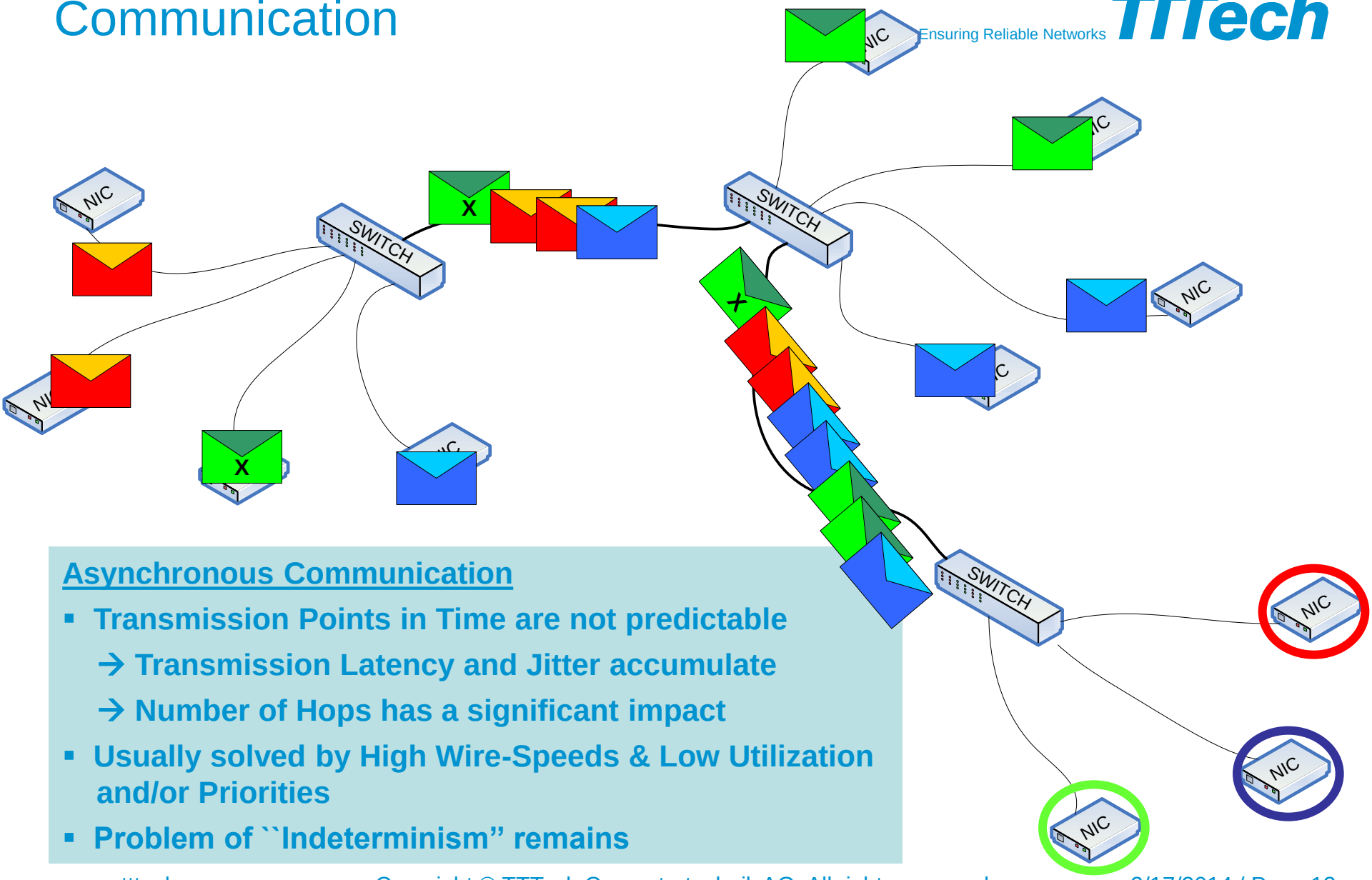
The Motivation for Ethernet

- Ethernet hardware is low cost.
- Ethernet is a well-established open-world standard and very scaleable.
- The OSI reference model gives a well-structured classification of concepts that can be built on top of Ethernet.
- Existing tools can be leveraged as cost-efficient diagnosis tools.
- Standard protocols like SNMP can be leveraged for maintenance and configuration.
- Engineers learn about Ethernet at school.

Ethernet means to use well-established technology, but needs real-time and dependability improvements.

DETERMINISTIC ETHERNET

Ethernet = Asynchronous Communication

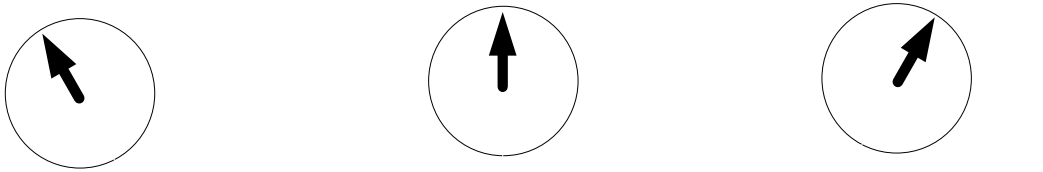


Asynchronous Communication

- **Transmission Points in Time are not predictable**
  - **→ Transmission Latency and Jitter accumulate**
  - **→ Number of Hops has a significant impact**
- **Usually solved by High Wire-Speeds & Low Utilization and/or Priorities**
- **Problem of ``Indeterminism'' remains**

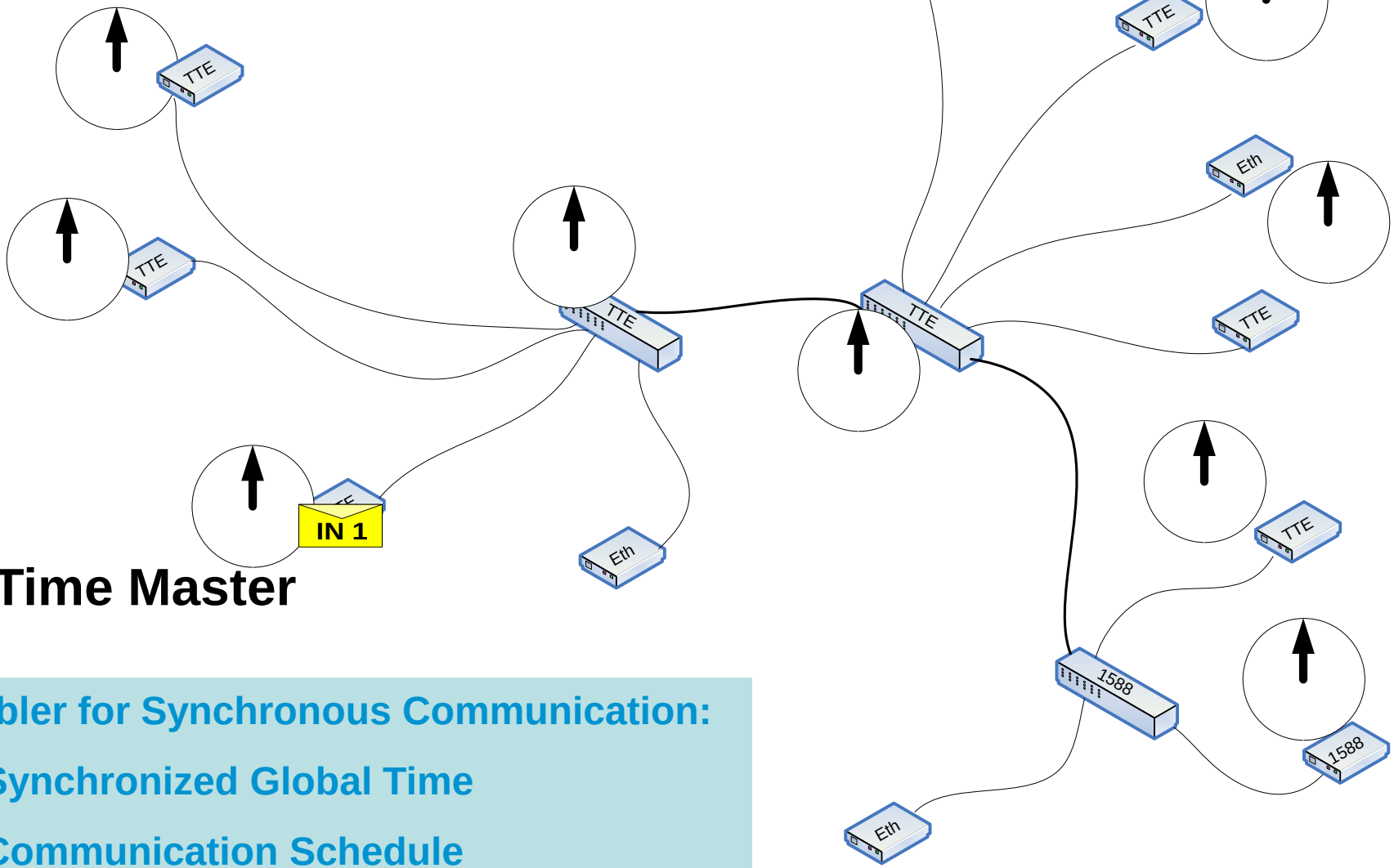
Towards Determinism: Synchronization of the distributed local clocks

In an ensemble of clocks, the precision is defined as the maximum distance between any two synchronized non-faulty clocks at any point in real time.



Late Clock Perfect Clock Early Clock

Single-Master Clock Synchronization



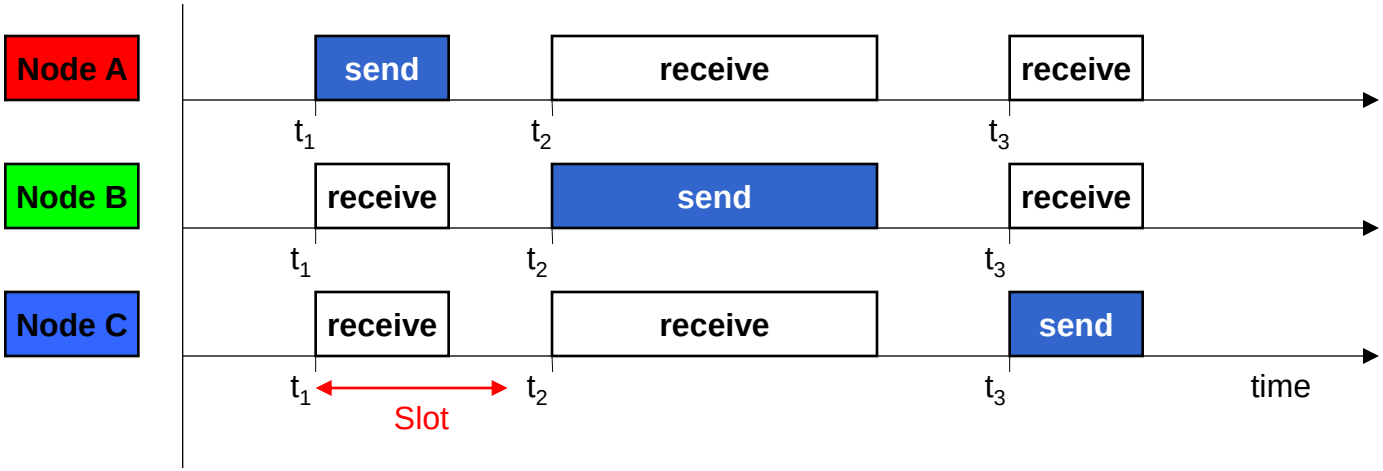
Enabler for Synchronous Communication:

- **Synchronized Global Time**
- **Communication Schedule**

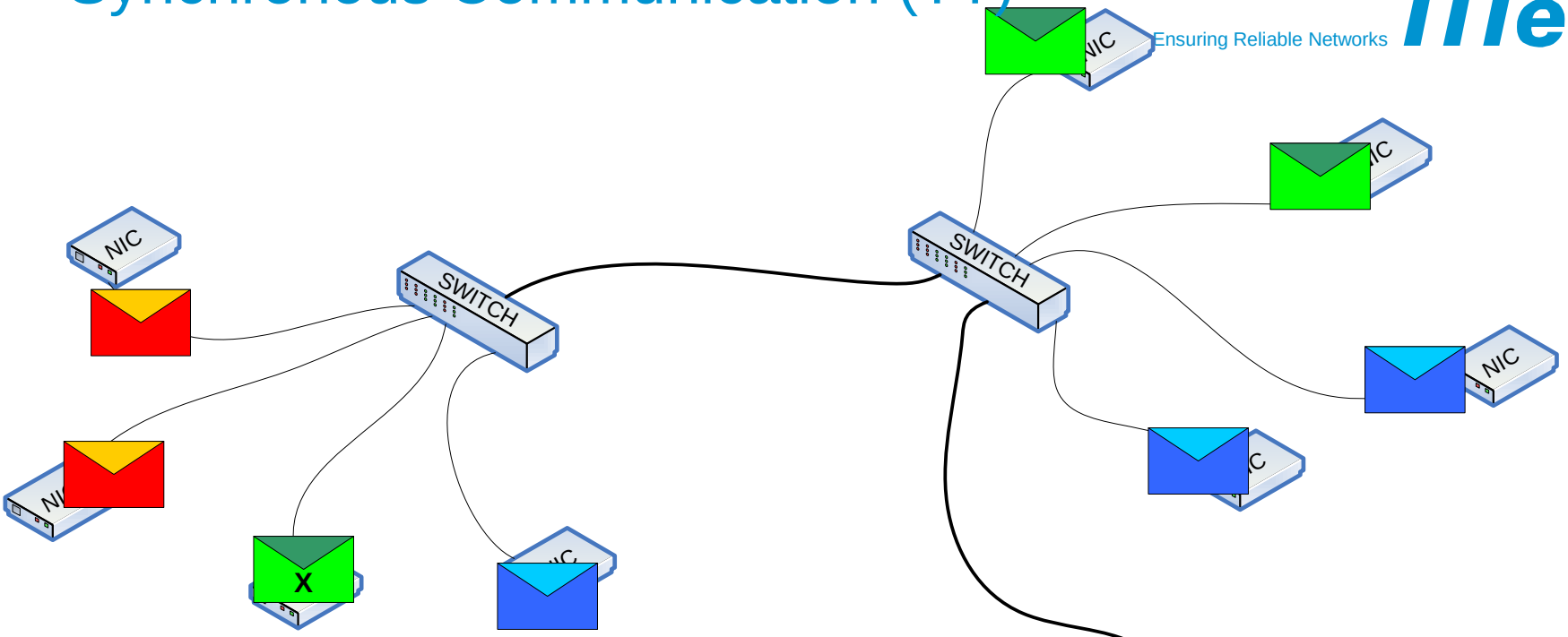
Time-Triggered Operation

Ensuring Reliable Networks TTTech

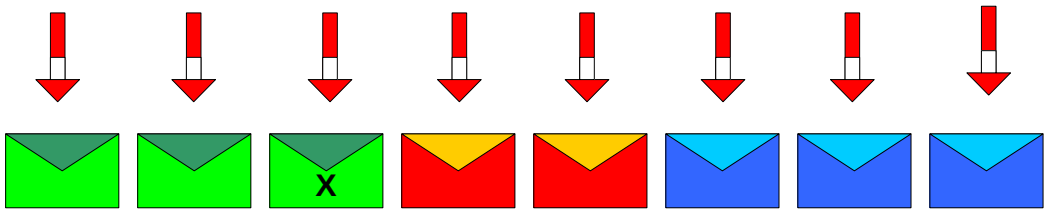
Synchronized time and a communication schedule allows to realize the time-triggered communication paradigm.



Synchronous Communication (TT)

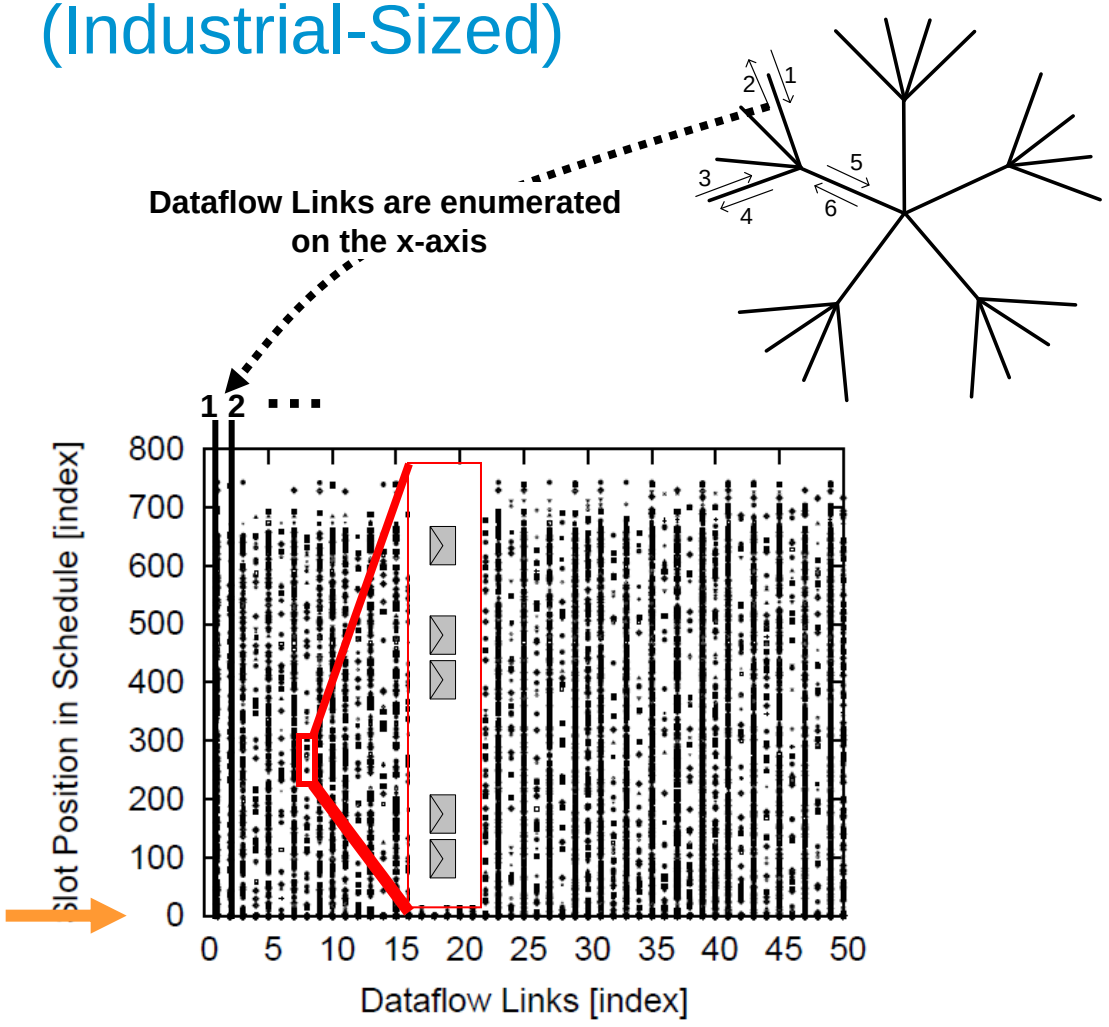


Synchronous Communication



Exactly one order of messages M_i
(in contrast to PERM(M_i) in async. comm)

Example: 1,000 Frames (Industrial-Sized)



Time-Triggered Only

Deterministic (TT)Ethernet – Traffic Classes

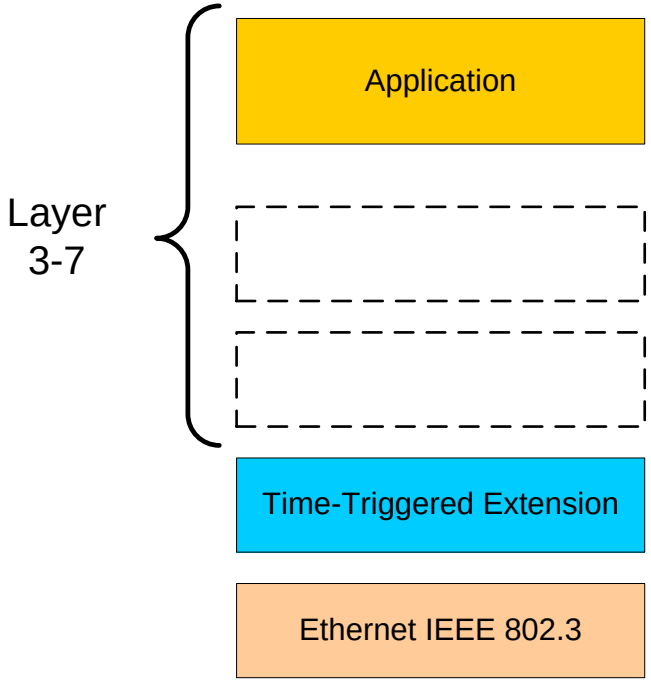
Ensuring Reliable Networks TTTech

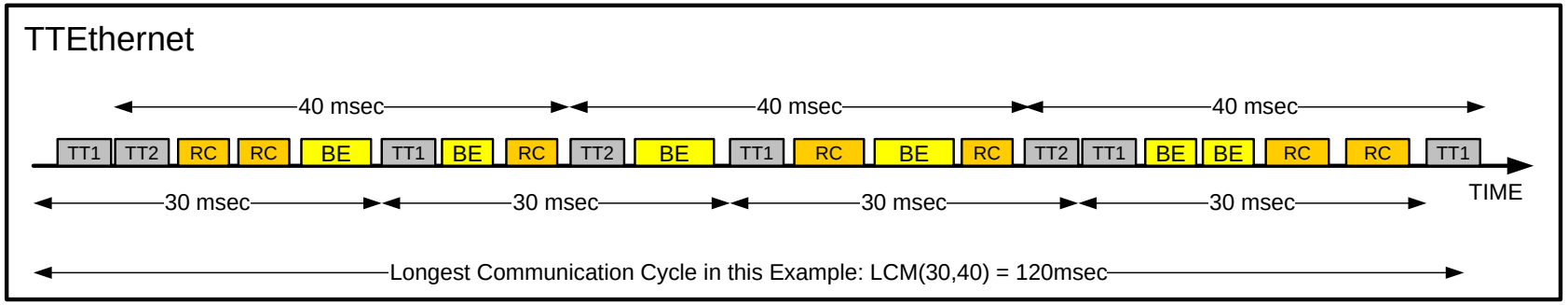
TTEthernet provides several traffic classes in parallel: time-triggered, rate-constrained, and best-effort

Time-Triggered: dispatch messages according a predefined communication schedule

Rate-Constrained: enforce minimum duration between two frames of the same stream

Best-Effort: standard Ethernet communication paradigm – no temporal guarantees are given

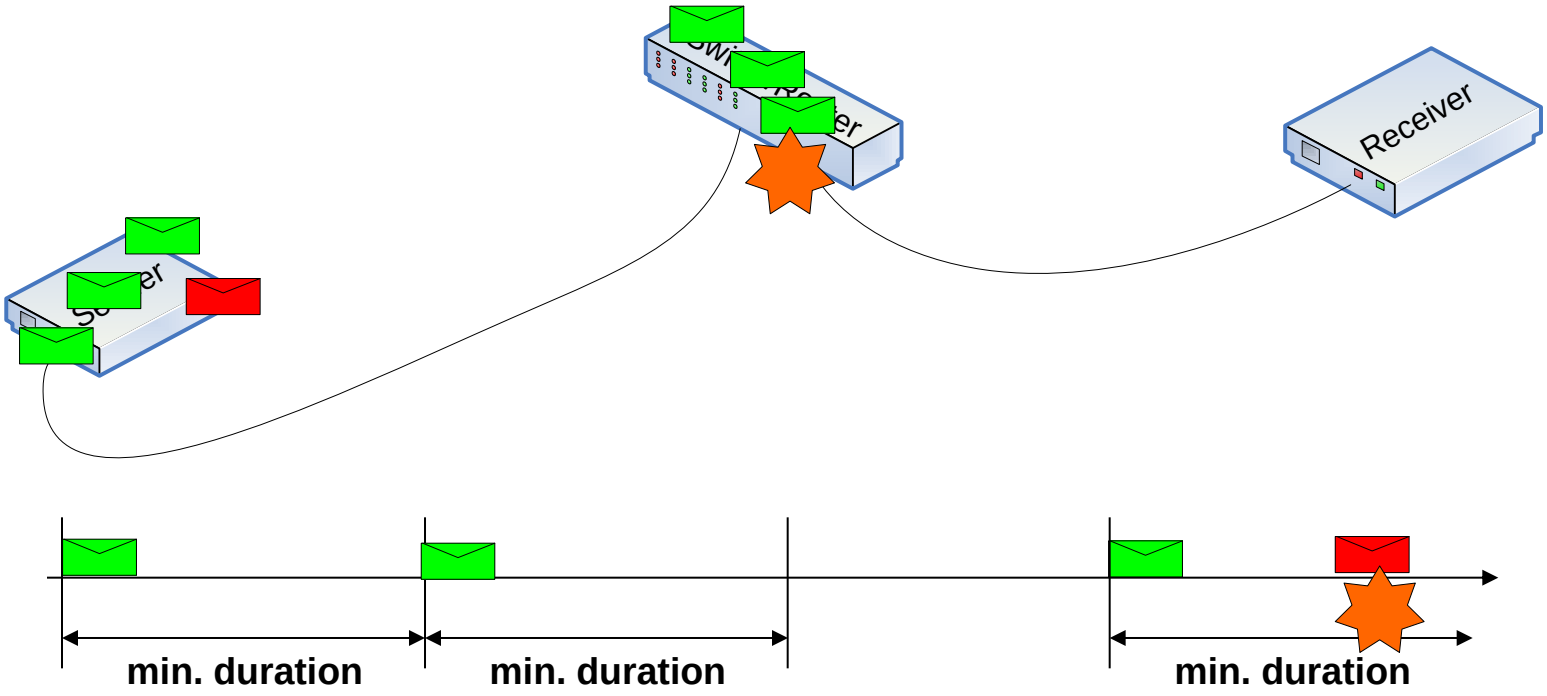




TTEthernet Dataflow: Rate-Constrained Traffic

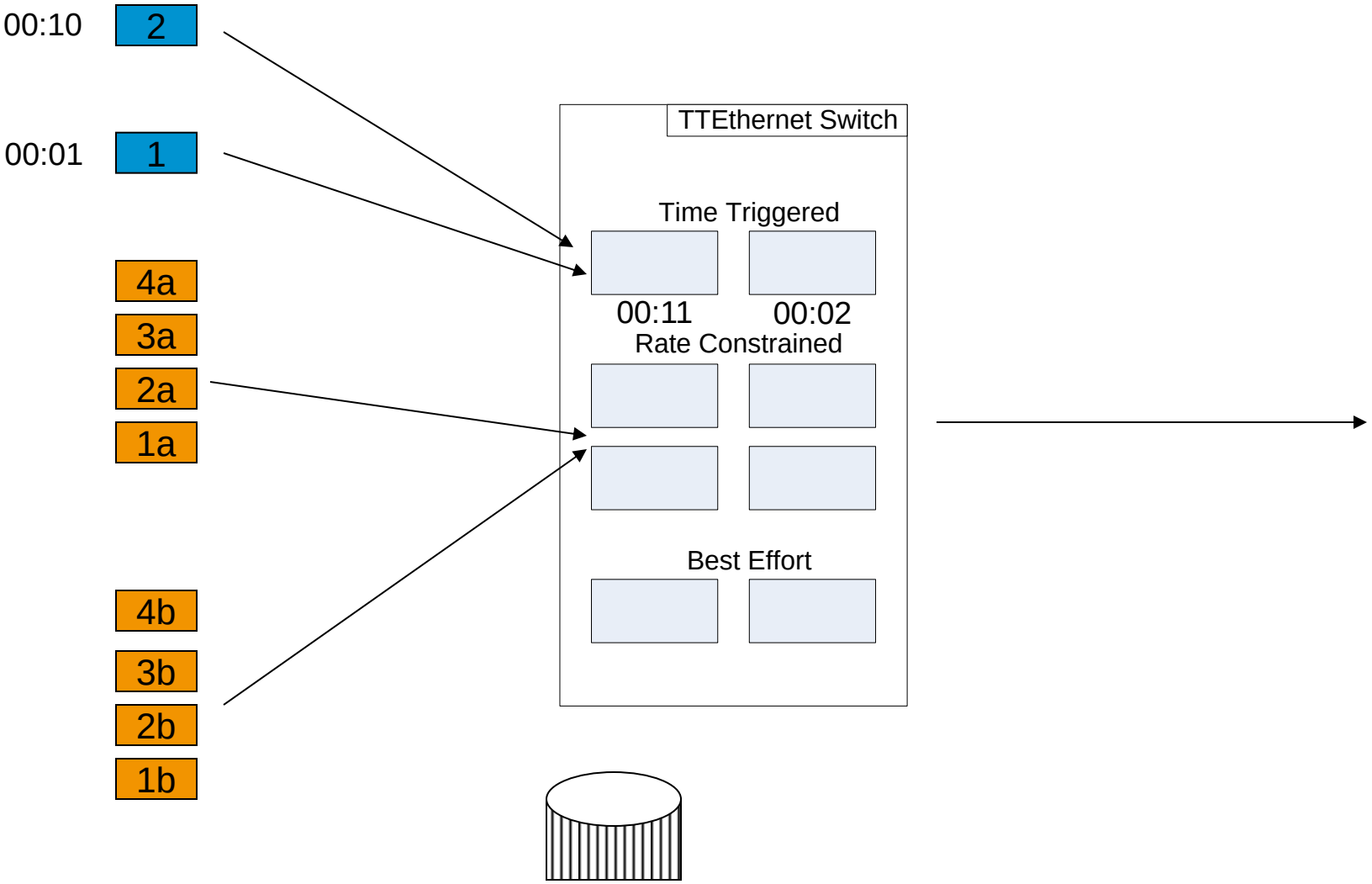
Ensuring Reliable Networks TTTech

Rate-Constrained Traffic (RC)



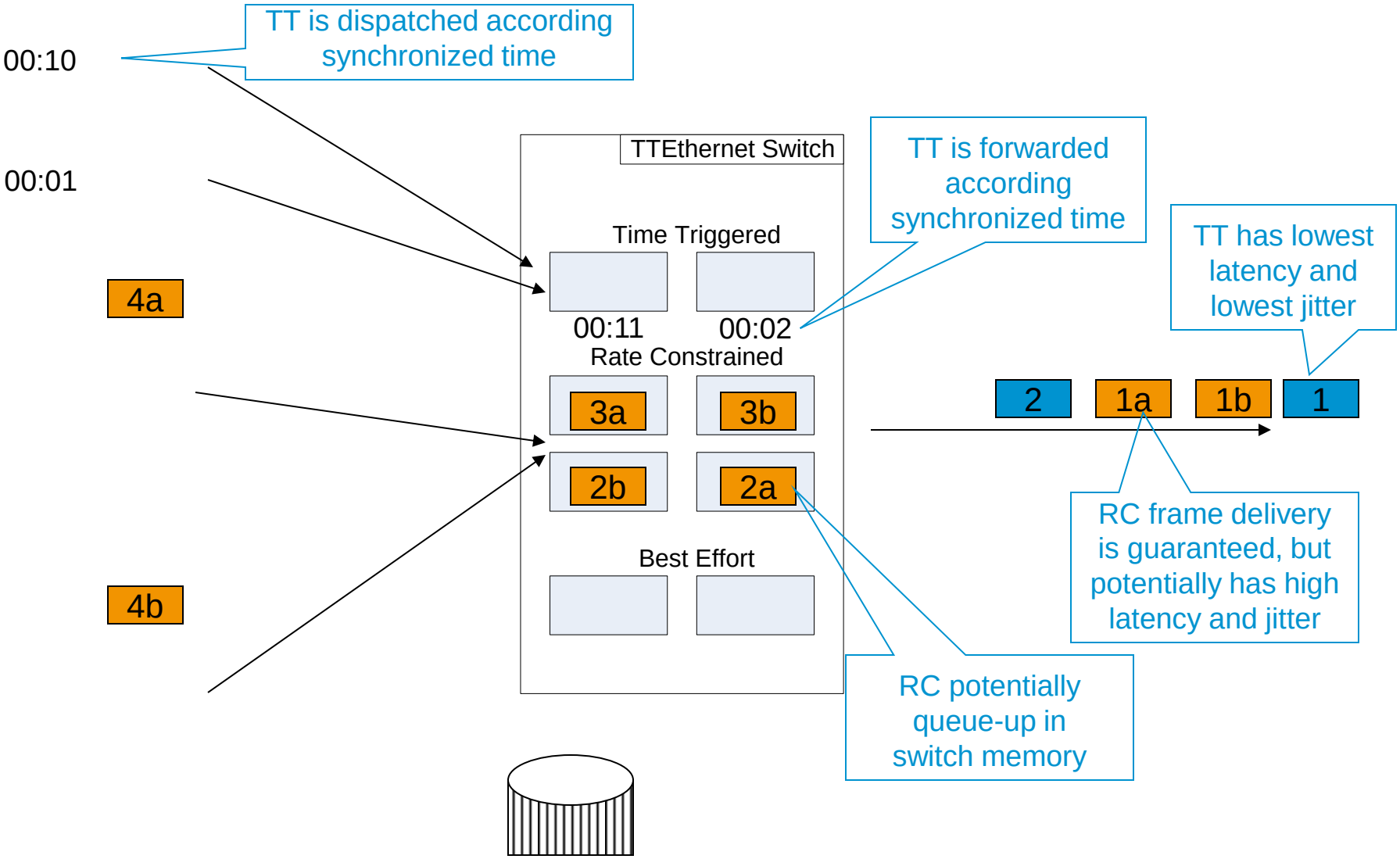
Mixed Traffic on Ethernet – RC Accumulated Jitter

Ensuring Reliable Networks TTTech



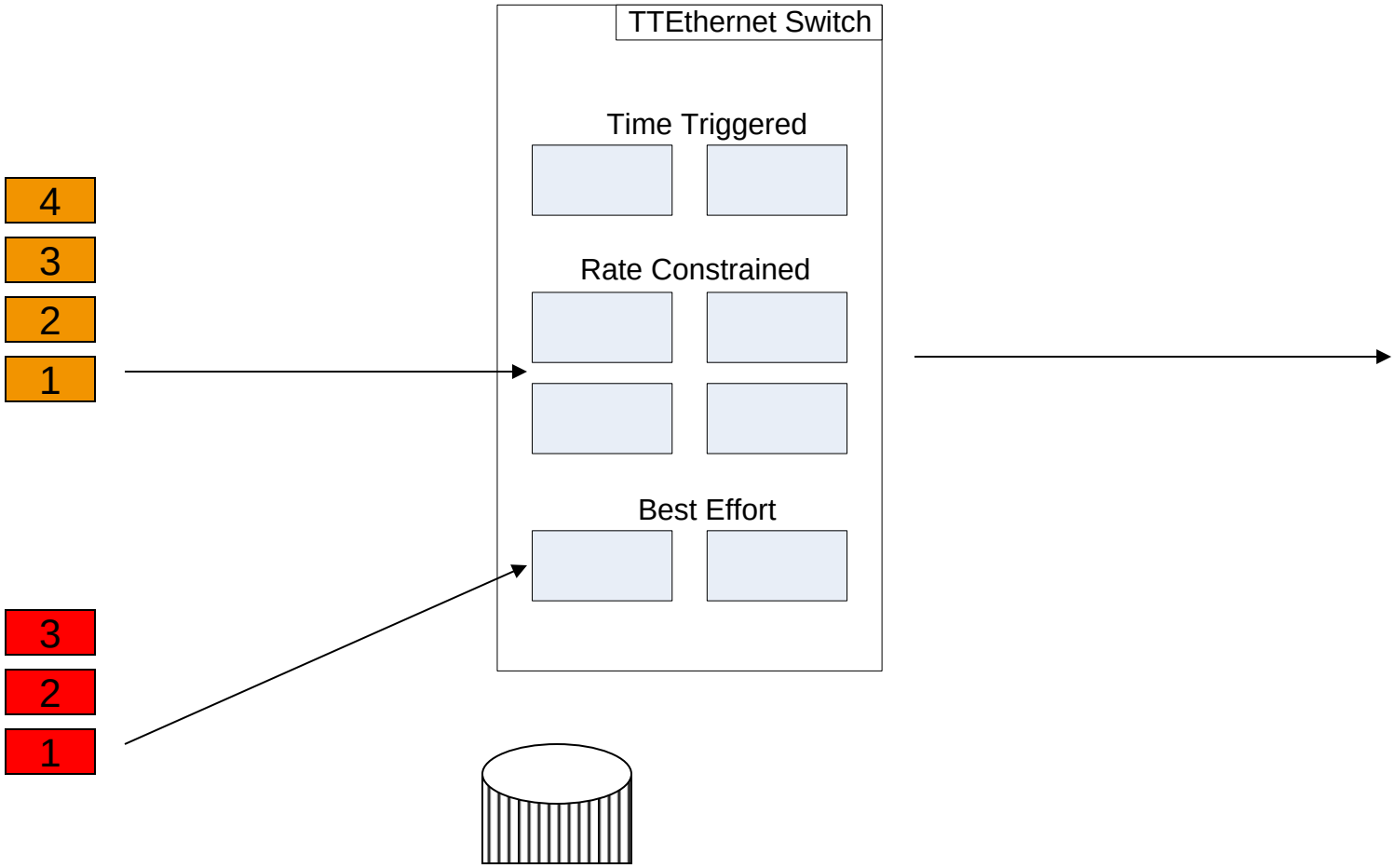
Mixed Traffic on Ethernet – RC Accumulated Jitter

Ensuring Reliable Networks TTTech



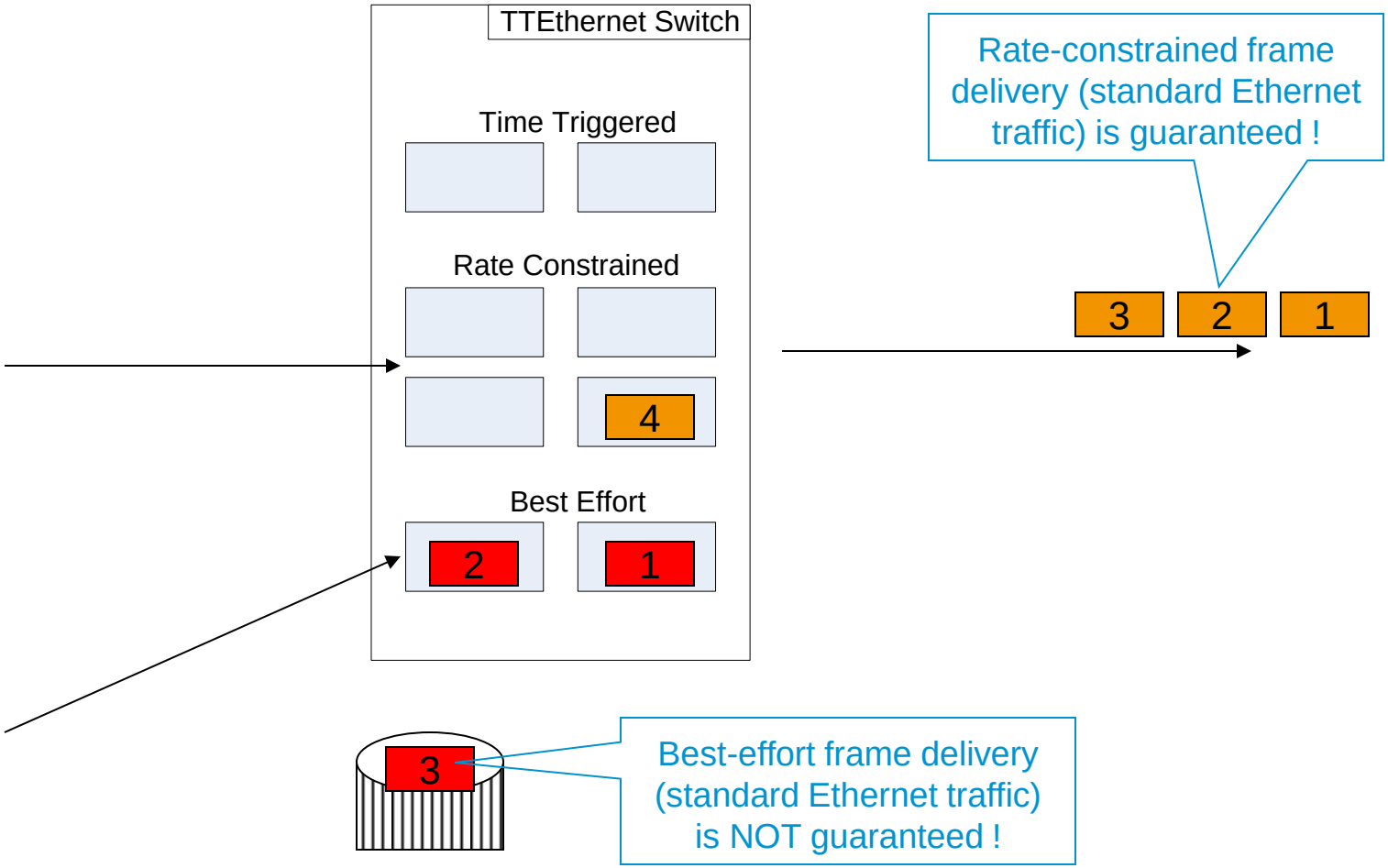
Mixed Traffic on Ethernet – BE Buffer Overflow

Ensuring Reliable Networks TTTech



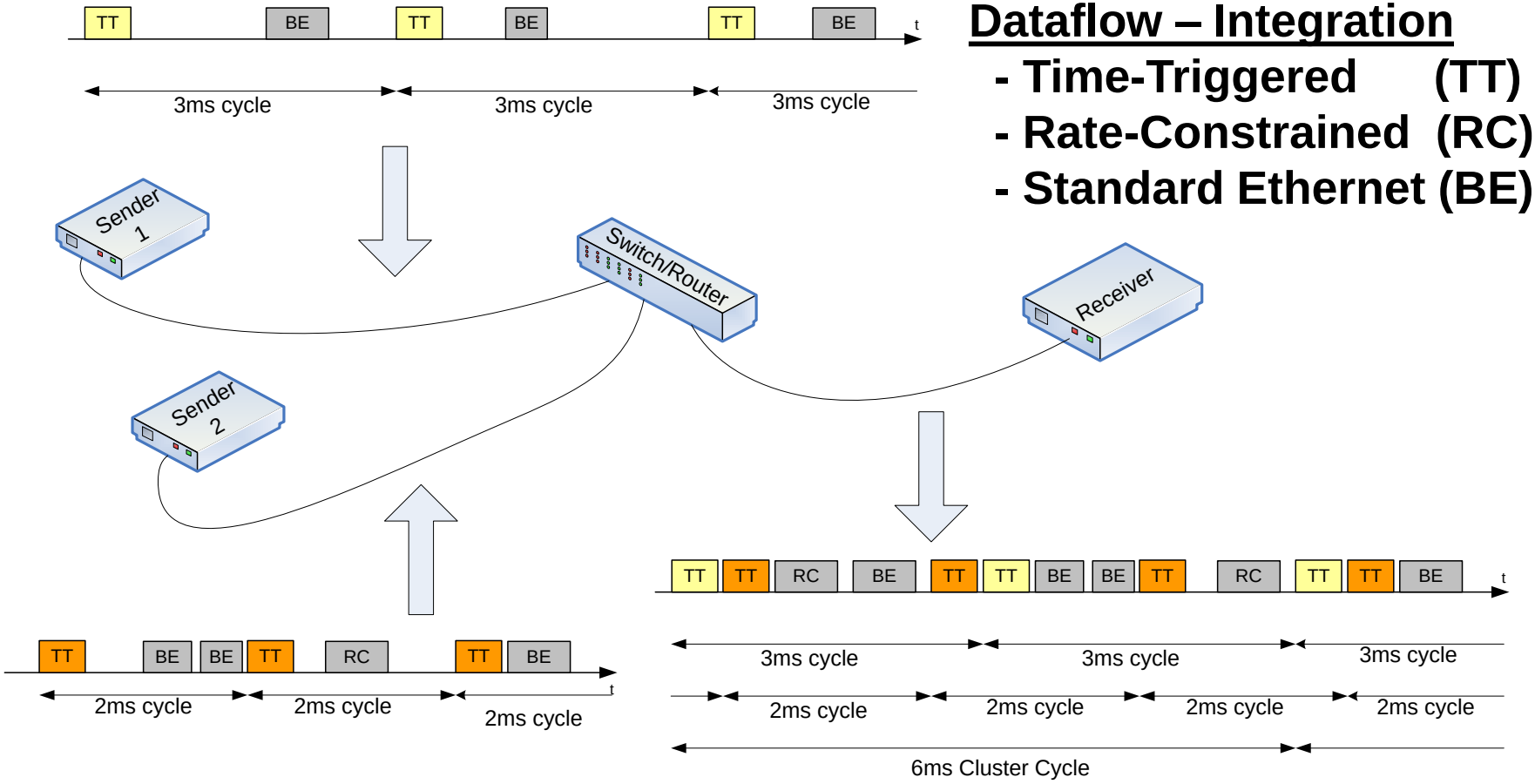
Mixed Traffic on Ethernet – BE Buffer Overflow

Ensuring Reliable Networks TTTech



Converged Network Example

Ensuring Reliable Networks TTTech



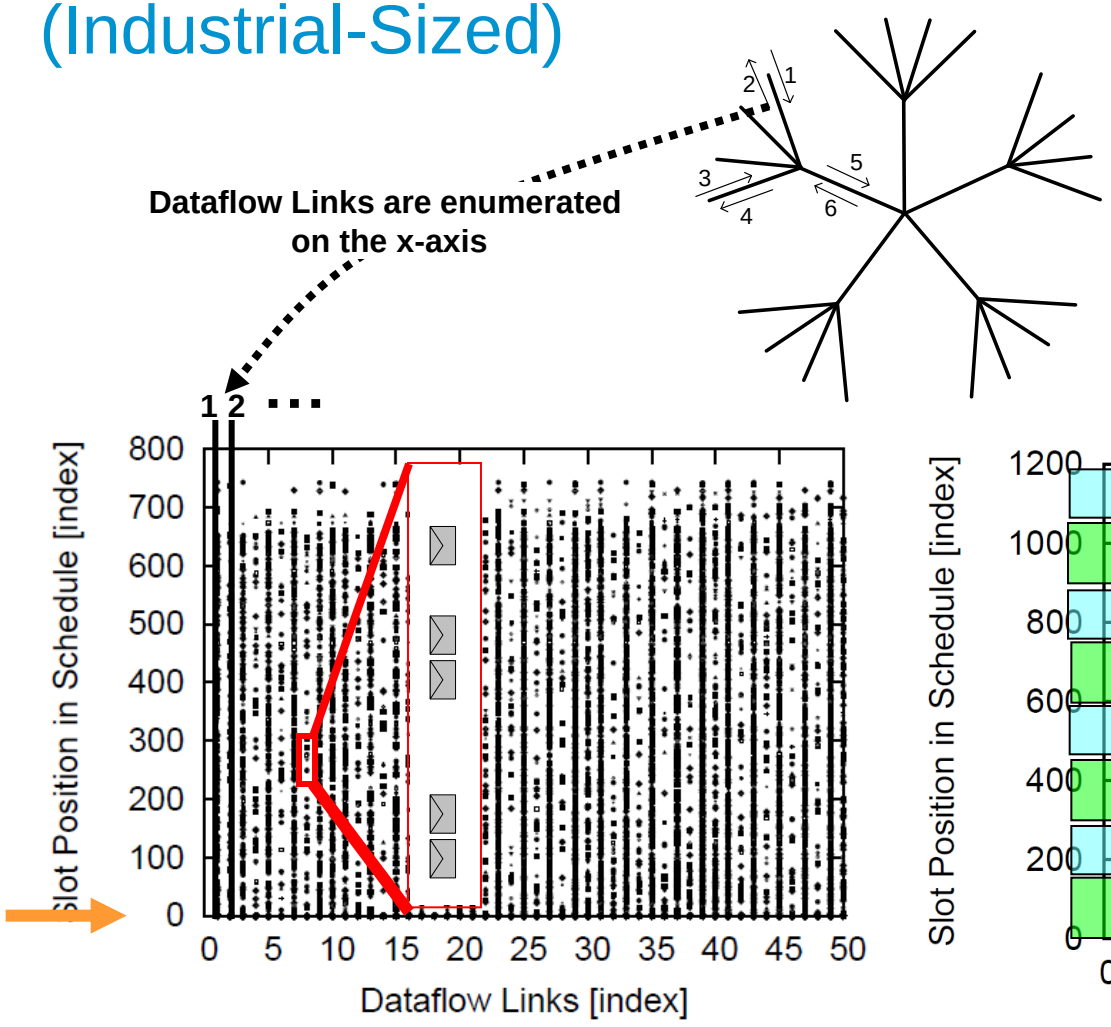
Dataflow – Integration

- Time-Triggered (TT)
- Rate-Constrained (RC)
- Standard Ethernet (BE)

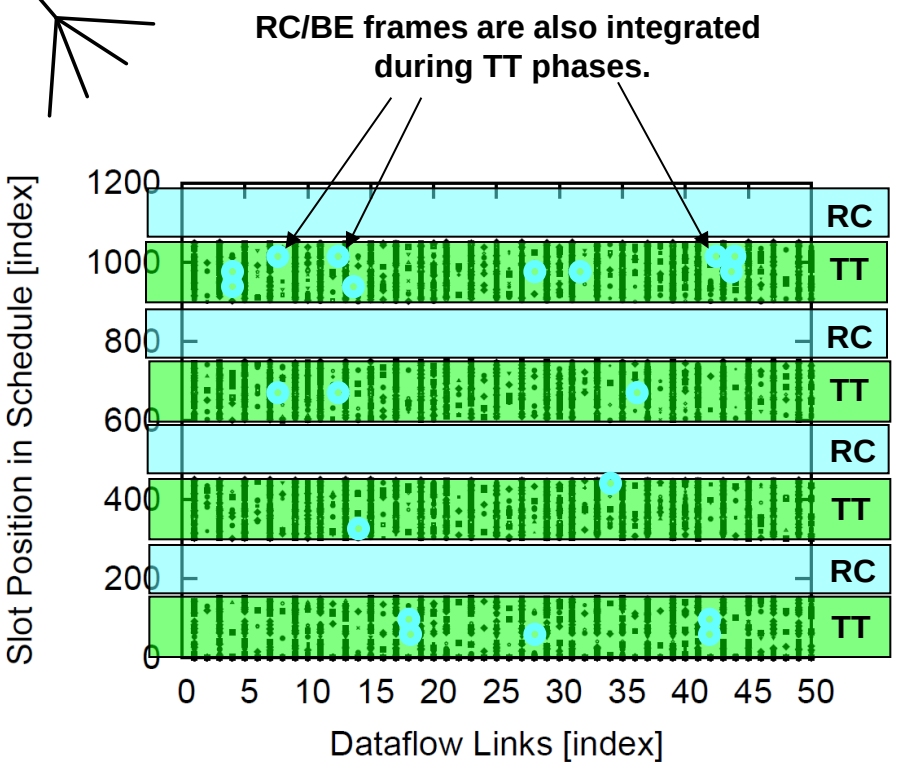
TTEthernet Switches are non-preemptive store-and-forward switches using priorities

Example: 1,000 Frames (Industrial-Sized)

Ensuring Reliable Networks TTTech

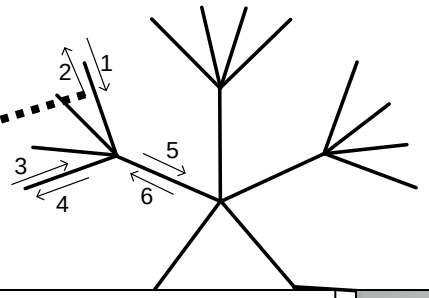


Time-Triggered Only

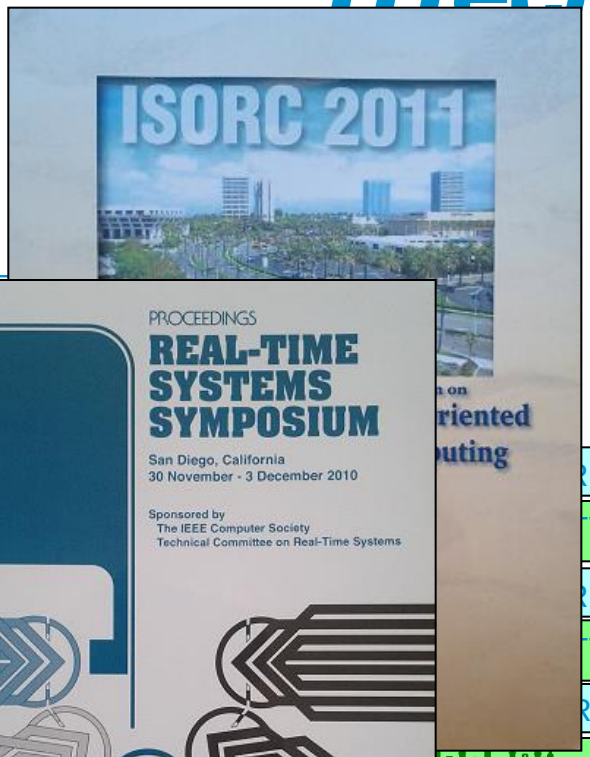


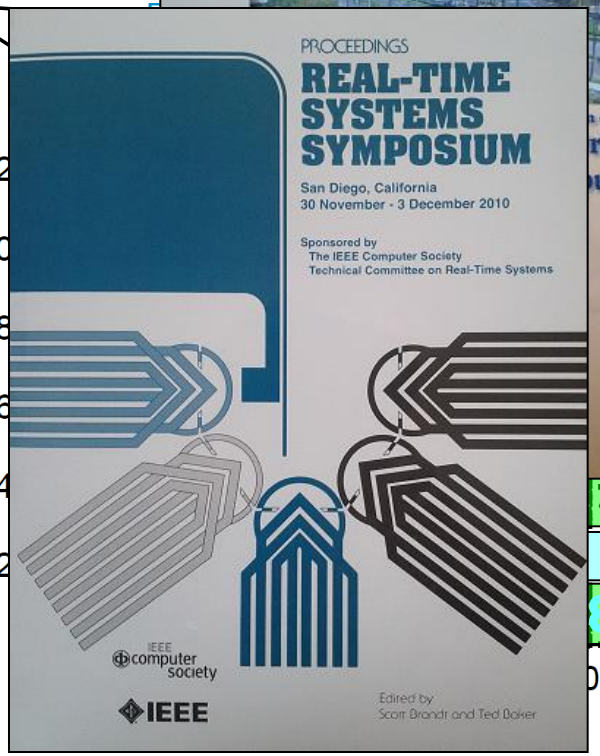
Time-Triggered + Event-Triggered

Example: 1,000 Frames (Industrial-Sized)



Dataflow Links are enumerated on the x-axis





Synthesis of Static Communication Schedules for Mixed-Criticality Systems

Wilfried Steiner
Chip IP Design
TTTech Computertechnik AG

An Evaluation of SMT-based Schedule Synthesis For Time-Triggered Multi-Hop Networks

Wilfried Steiner
Chip IP Design
TTTech Computertechnik AG
wilfried.steiner@tttech.com

Abstract—**Networks for real-time systems have stringent end-to-end latency and jitter requirements. One cost-efficient way to meet these requirements is the time-triggered communication paradigm which plans the transmission points in time of the frames off-line. This plan prevents contentions of frames on the network and is called a time-triggered schedule (tt-schedule).**

In general the tt-scheduling is a bin-packing problem, known to be NP-complete, where the complexity is mostly driven by the freedom in topology of the network, its associated hardware restrictions, and application-imposed constraints. Multi-hop networks, in particular, require the synthesis of path-dependent tt-schedules to maintain full determinism of time-triggered communication from sender to receiver.

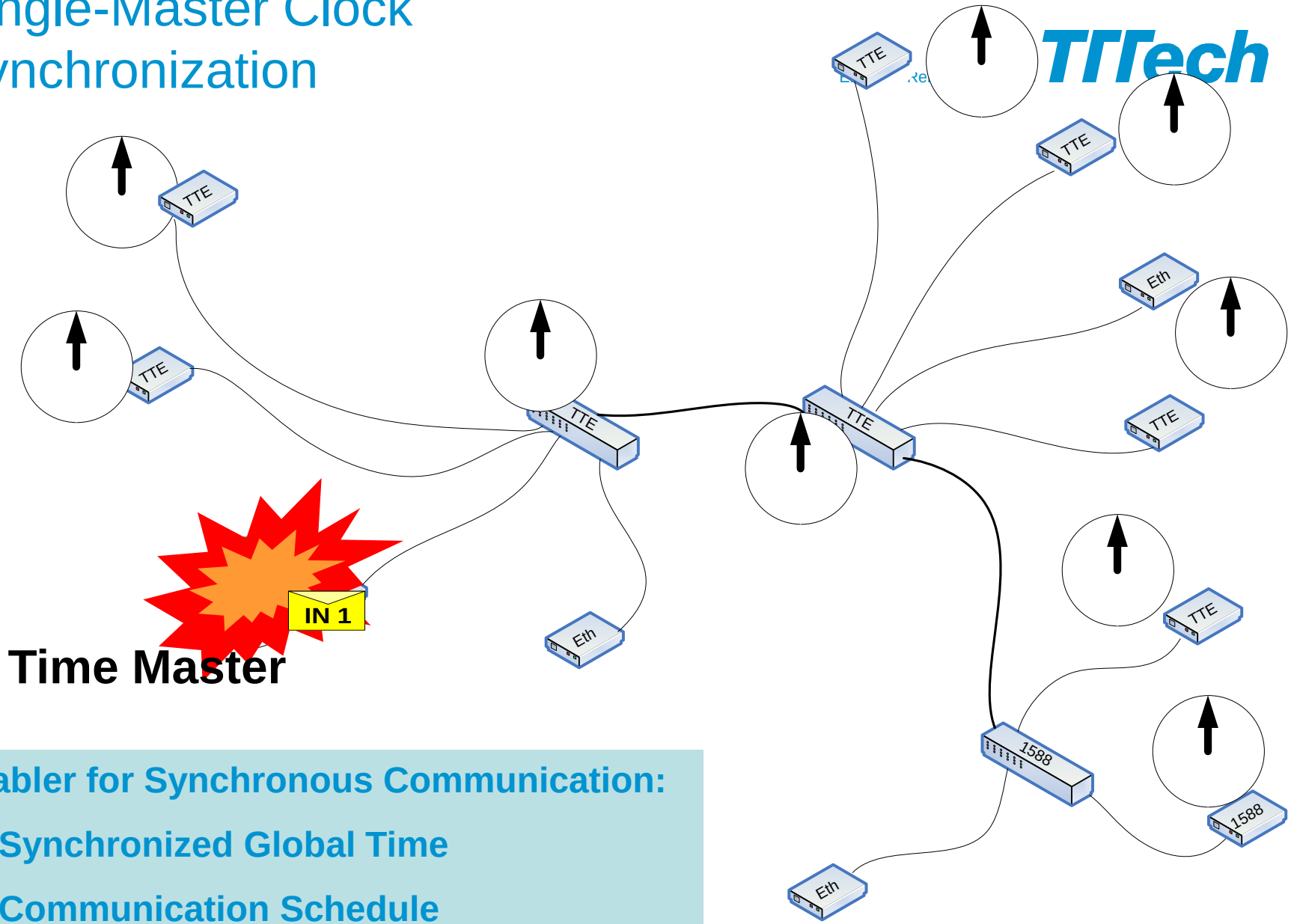
Our experiments using the YICES SMT solver show that the scheduling problem can be solved by YICES out-of-the-box for a few hundred random frame instances on the network. A customized tt-scheduler using YICES as a back-end solver allows to increase this number of frame instances up to tens of thousands. In terms of scheduling quality, the synthesis produces up to ninety percent maximum utilization on a communication link with schedule synthesis times of about half an hour for the biggest examples we have studied. As a nice side-effect the YICES out-of-the-box approach is immediately applicable for the verification of existing (even large-scale) tt-schedules and for

SAFEbus [6], [7] in the Boeing 777 and TTP [8] in the Airbus A380 and the Boeing 787 aircrafts. While these protocols are broadcast-based with the intent to operate on physical bus or hub topologies, Ethernet-like protocols introduce network switches that allow concurrent time-triggered dataflows. TTEthernet [9] which has been selected for upcoming space programs is one of the first time-triggered protocols that inherently supports concurrent time-triggered communication also in multi-hop topologies. Furthermore, as time-synchronization services such as IEEE 1588 find their way into standard Ethernet equipment it seems only a matter of time when time-triggered communication shows up also in a "consumer" flavor. As we are looking at these developments in system size and complexity, scheduling for time-triggered networks becomes even more a challenge.

The scheduling problem for a time-triggered system like many other problems in system design can be formulated as solutions to systems of constraints. The constraints for different types of problems have different characteristics and specialized solvers have been developed for each class of

Time-Triggered
+ Event-Triggered

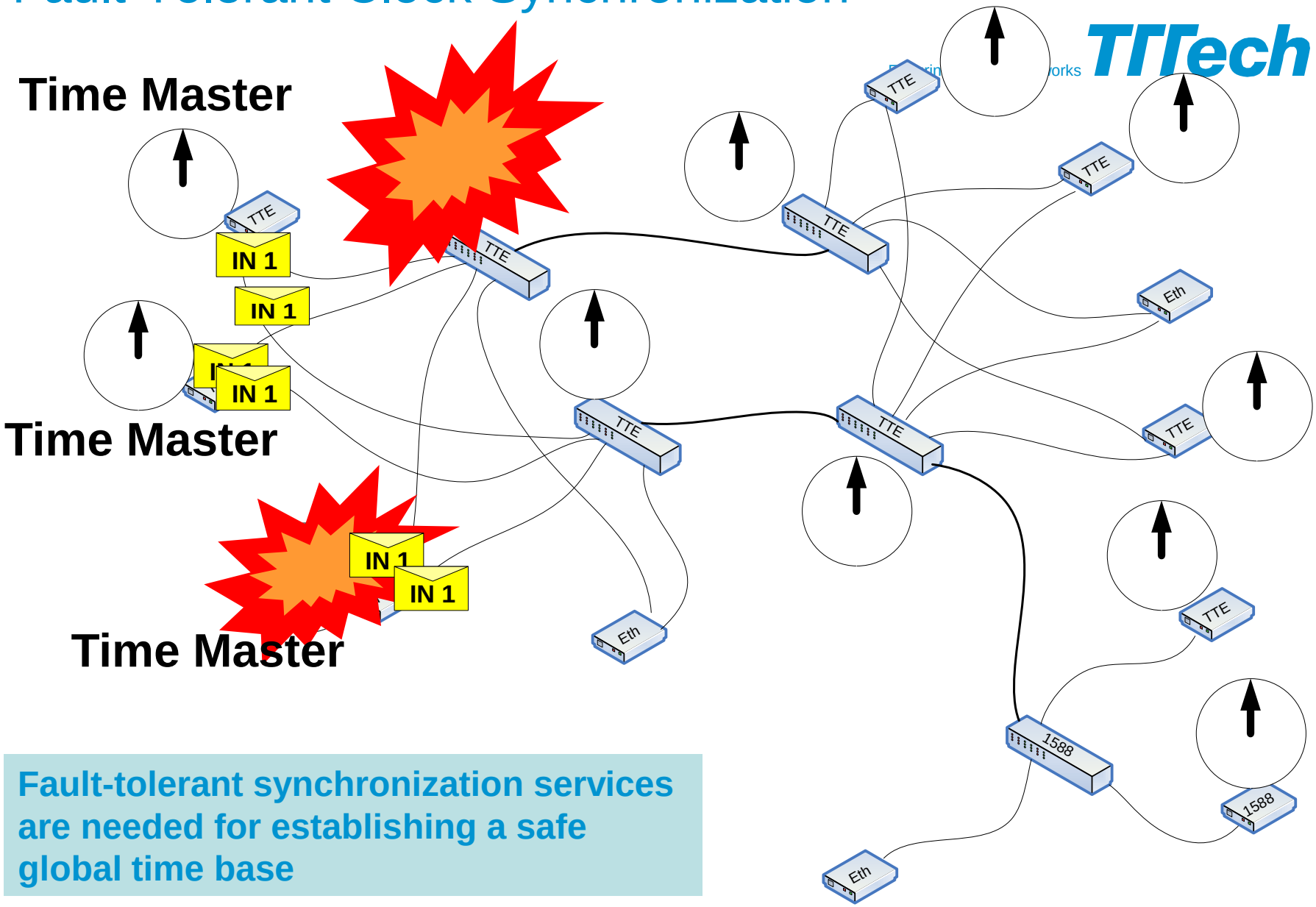
Single-Master Clock Synchronization



Enabler for Synchronous Communication:

- **Synchronized Global Time**
- **Communication Schedule**

Fault-Tolerant Clock Synchronization

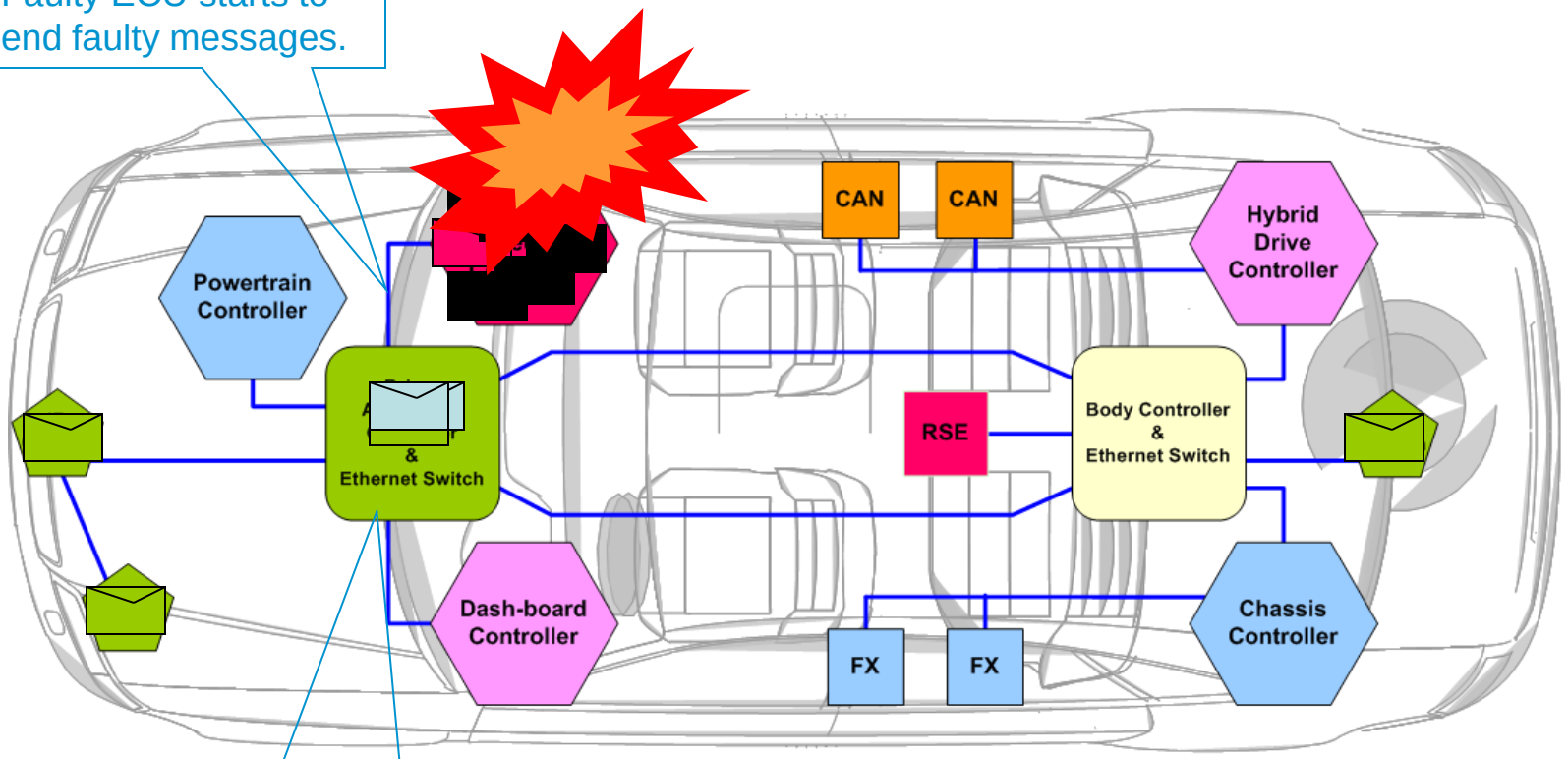


Fault-tolerant synchronization services are needed for establishing a safe global time base

Need to cover complex failure modes, e.g. Babbling ECU

Ensuring Reliable Networks TTTech

Faulty ECU starts to send faulty messages.



Without traffic policing functions, the switch forwards all faulty frames.

At some threshold of faulty frames, the switch starts loosing correct frames from other, independent applications.

NATIVE ETHERNET BECOMES MORE DETERMINISTIC

Native Ethernet becomes more deterministic

Ensuring Reliable Networks TTTech

IEEE 802.1 is standardizing general architectures for local area networks (LANs) and metropolitan area architectures (MANs).

Together with IEEE 802.3 they are the main working groups working standards for Ethernet switches.

Efficient utilization of the communication bandwidth and plug-and-play capabilities are topmost requirements in IEEE 802.1.

With AVB, IEEE 802.1 moved into the area of real-time communication.

With TSN, IEEE 802.1 moves into the area of dependable communication.

Upcoming mainstream IT equipment aims to provide real-time and dependable communication features (to a significant higher degree than today).

AVB – Audio/Video Bridging

802.1AS Timing and Synchronization for Time-Sensitive Applications in Bridged Local Area Networks: a protocol and technique to synchronize local clocks in the network to each other.

802.1Qat Stream Reservation Protocol (SRP): a protocol that allows applications to dynamically reserve bandwidth in the network.

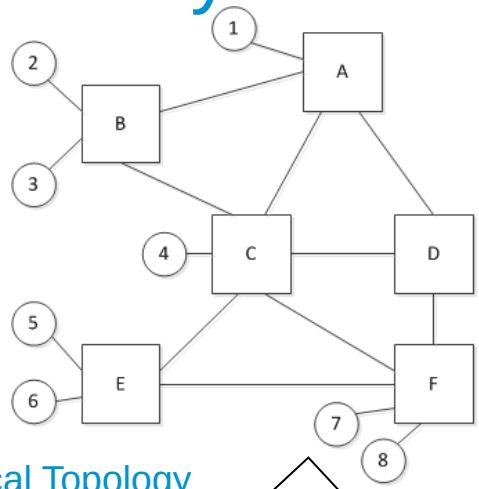
802.1Qav Forwarding and Queuing Enhancements for Time-Sensitive Streams: an enhancement over strict priority based forwarding and queueing mechanisms that establishes fairness properties for lower priority traffic in the network.

802.1BA: definition of profiles for AVB systems.

→ AVB is incorporated in the IEEE 802.1 standards documents since 2011.

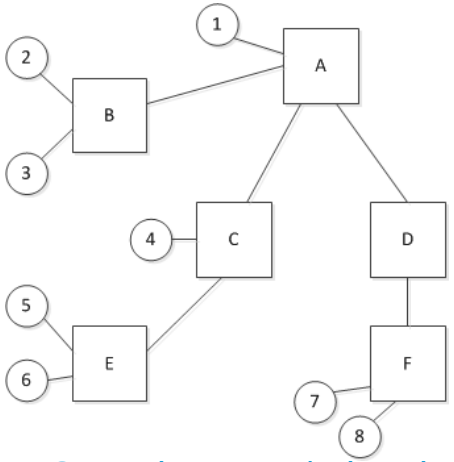
Native Ethernet improves its Reliability

Ensuring Reliable Networks TTTech



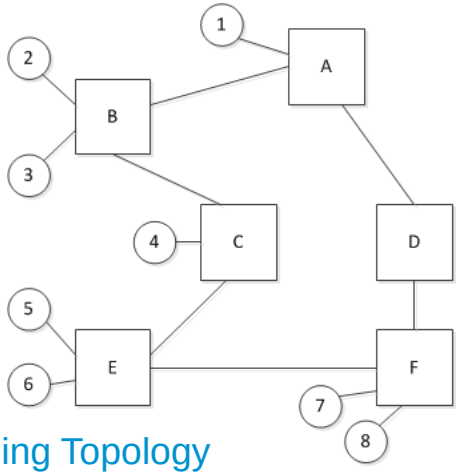
Physical Topology

IEEE 802.1Q



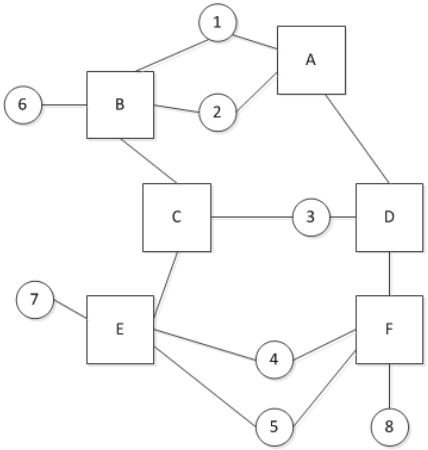
Spanning Tree / Virtual LANs

TSN



Ring Topology

TSN



Redundant “Networks”

TSN – Time-Sensitive Networks

802.1ASbt Timing and Synchronization: Enhancements and Performance Improvements

802.1Qbv Enhancements for Scheduled Traffic: a basic form of time-triggered communication

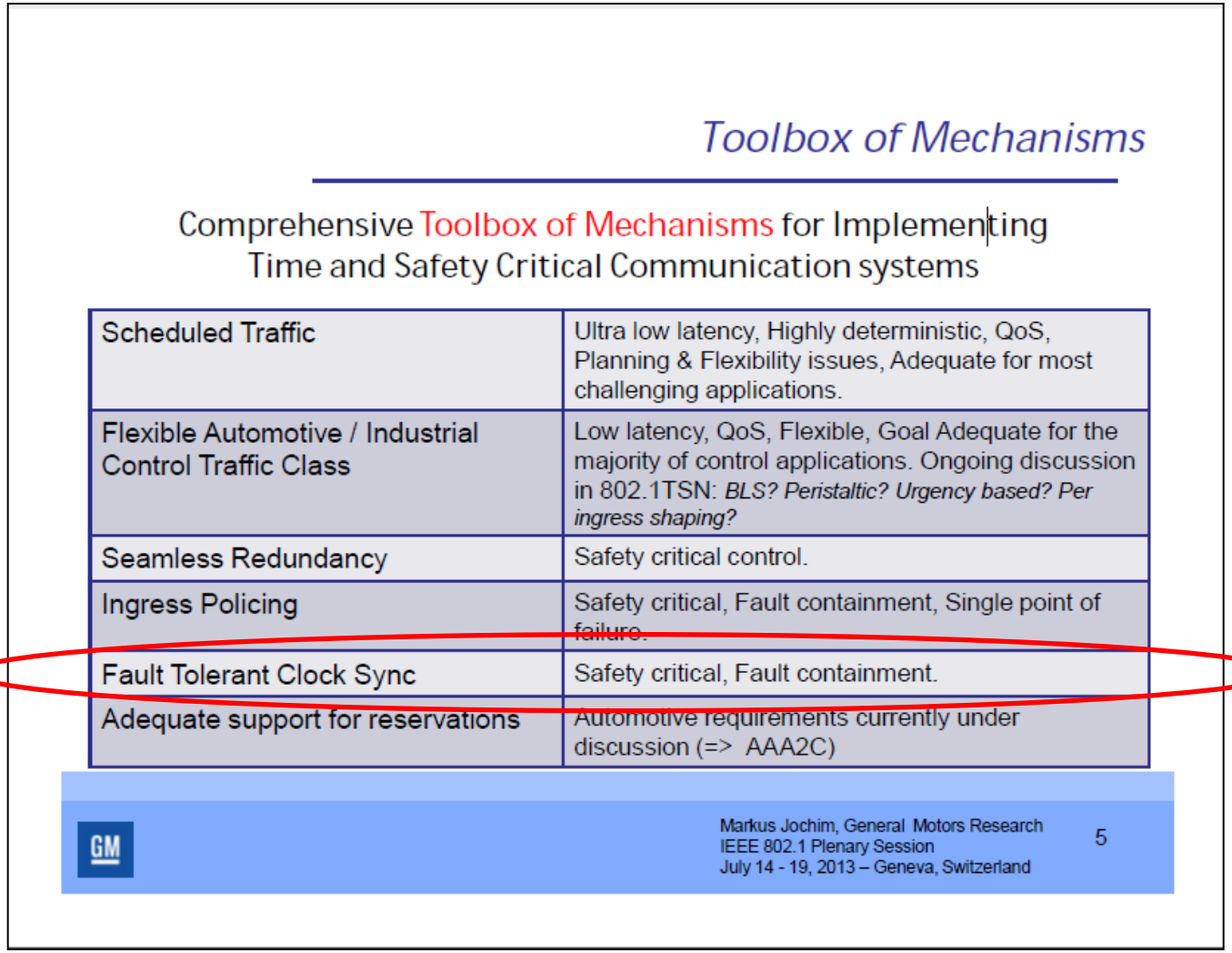
802.1Qbu Frame Preemption: a mechanism that allows to preempt a frame in transmit to intersperse another frame.

802.1Qca Path Control and Reservation: protocols and mechanisms to set up and manage the redundant communication paths in the network.

802.1CB Frame Replication and Elimination for Reliability: to eliminate redundant copies of frames transmitted over the redundant paths setup in 802.1Qca.

802.1Qcc – enhancements and improvements for stream reservation

Background:
Industrial Need for FT Clock-Sync



Toolbox of Mechanisms

Comprehensive Toolbox of Mechanisms for Implementing Time and Safety Critical Communication systems

Scheduled Traffic	Ultra low latency, Highly deterministic, QoS, Planning & Flexibility issues, Adequate for most challenging applications.
Flexible Automotive / Industrial Control Traffic Class	Low latency, QoS, Flexible, Goal Adequate for the majority of control applications. Ongoing discussion in 802.1TSN: *BLS? Peristaltic? Urgency based? Per ingress shaping?*
Seamless Redundancy	Safety critical control.
Ingress Policing	Safety critical, Fault containment, Single point of failure.
Fault Tolerant Clock Sync	Safety critical, Fault containment.
Adequate support for reservations	Automotive requirements currently under discussion (=> AAA2C)

GM

Markus Jochim, General Motors Research
IEEE 802.1 Plenary Session
July 14 - 19, 2013 – Geneva, Switzerland

5

http://www.ieee802.org/1/files/public/docs2013/new-tsn-jochim-goals-of-802-1tsn-0713-v01.pdf

TSN – Time-Sensitive Networks

802.1ASbt Timing and Synchronization: Enhancements and Performance Improvements

802.1Qbv Enhancements for Scheduled Traffic: a basic form of time-triggered communication

802.1Qbu Frame Preemption: a mechanism that allows to preempt a frame in transmit to intersperse another frame.

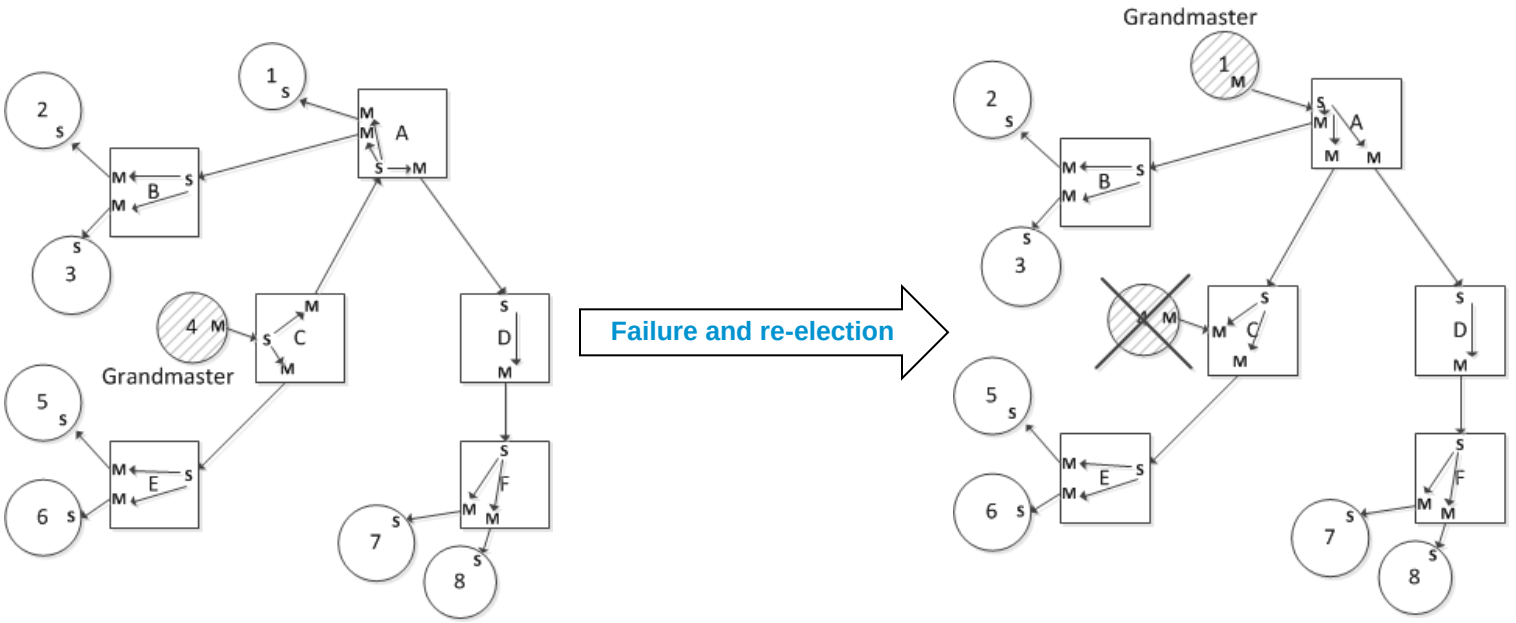
802.1Qca Path Control and Reservation: protocols and mechanisms to set up and manage the redundant communication paths in the network.

802.1CB Frame Replication and Elimination for Reliability: to eliminate redundant copies of frames transmitted over the redundant paths setup in 802.1Qca.

802.1Qcc – enhancements and improvements for stream reservation

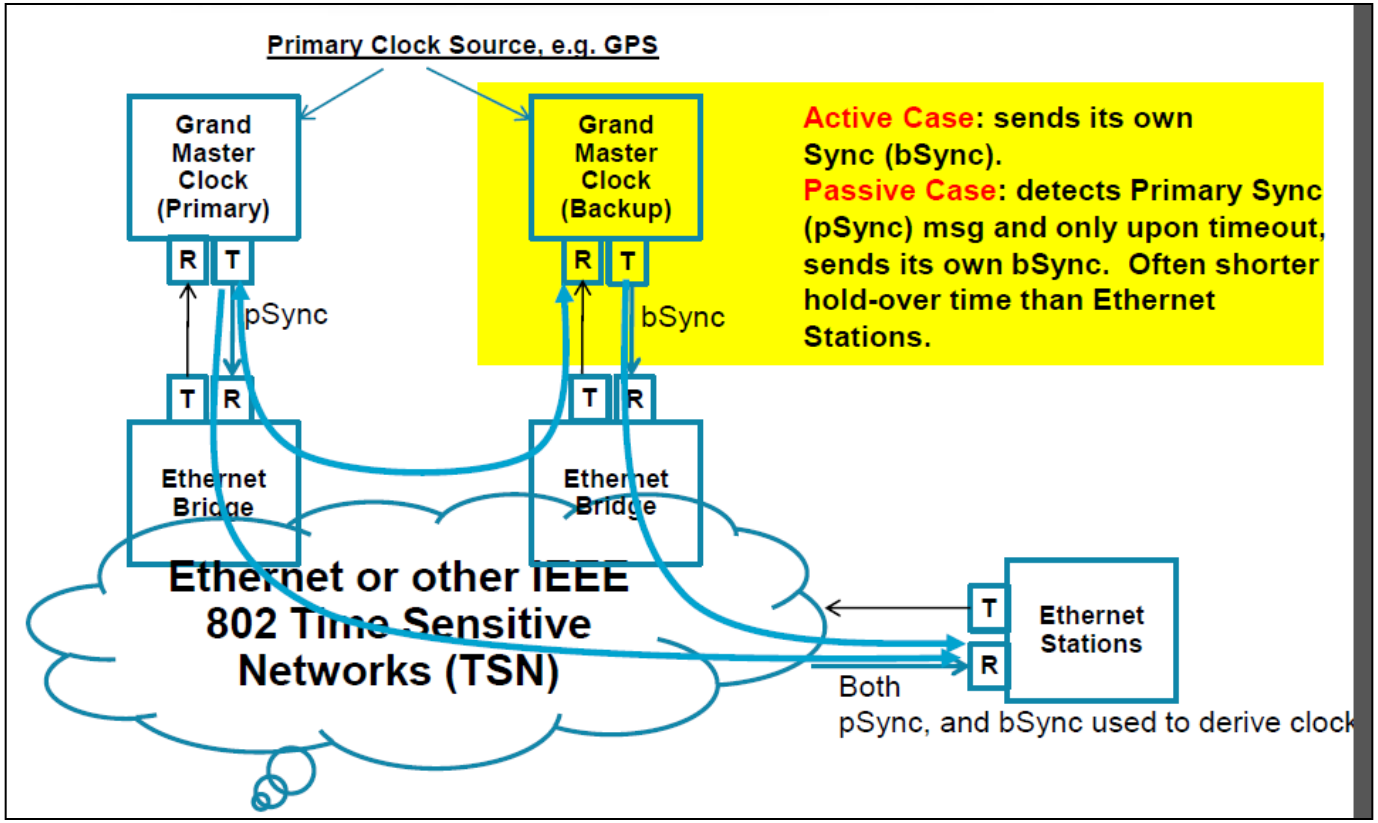
IEEE 802.1AS
Clock Synchronization

Ensuring Reliable Networks TTTech



The clock synchronization protocol is a classical master-slave protocol.
The master is called the “grandmaster”.
When the grandmaster fails, then a new grandmaster is elected.
Issues with this mechanism have been reported by industry.

802.1ASbt Clock Synchronization Proposals for Improvements



http://www.ieee802.org/1/files/public/docs2013/ASbt-Spada-Kim-Fault-tolerant-grand-master-proposal-0513-v1.pdf

SAE AS6802 – Fault-Tolerant Clock Synchronization

Ensuring Reliable Networks TTTech

TTEthernet Executable Formal Specification

- Using symbolic and bounded model checkers *sal-smc* and *sal-bmc*
- Focus on Interoperation of Synchronization Services (Startup, Restart, Clique Detection, Clique Resolution, abstract Clock Synchronization)

Verification of Lower-Level Synchronization Functions

- Permanence Function (*sal-inf-bmc* + k-induction)
- Compression Function *(sal-inf-bmc + k-induction)*

Formal Verification of Clock Synchronization Algorithm

- First time by means of Model Checking (*sal-inf-bmc* + k-induction)

Re-use of the Formal Models to prove:

- Layered clock-rate correction algorithm (*sal-inf-bmc* + k-induction)
- Layered clock-diagnosis algorithm (*sal-inf-bmc* + k-induction)

Verification and minor corrections of the "Sparse Timebase" Concept

- Distributed computations without explicit coordination (PVS)

Work has mostly been done in the context of the Marie Curie CoMMiCS project
FP7 (FP7/2007-2013) project no. 236701

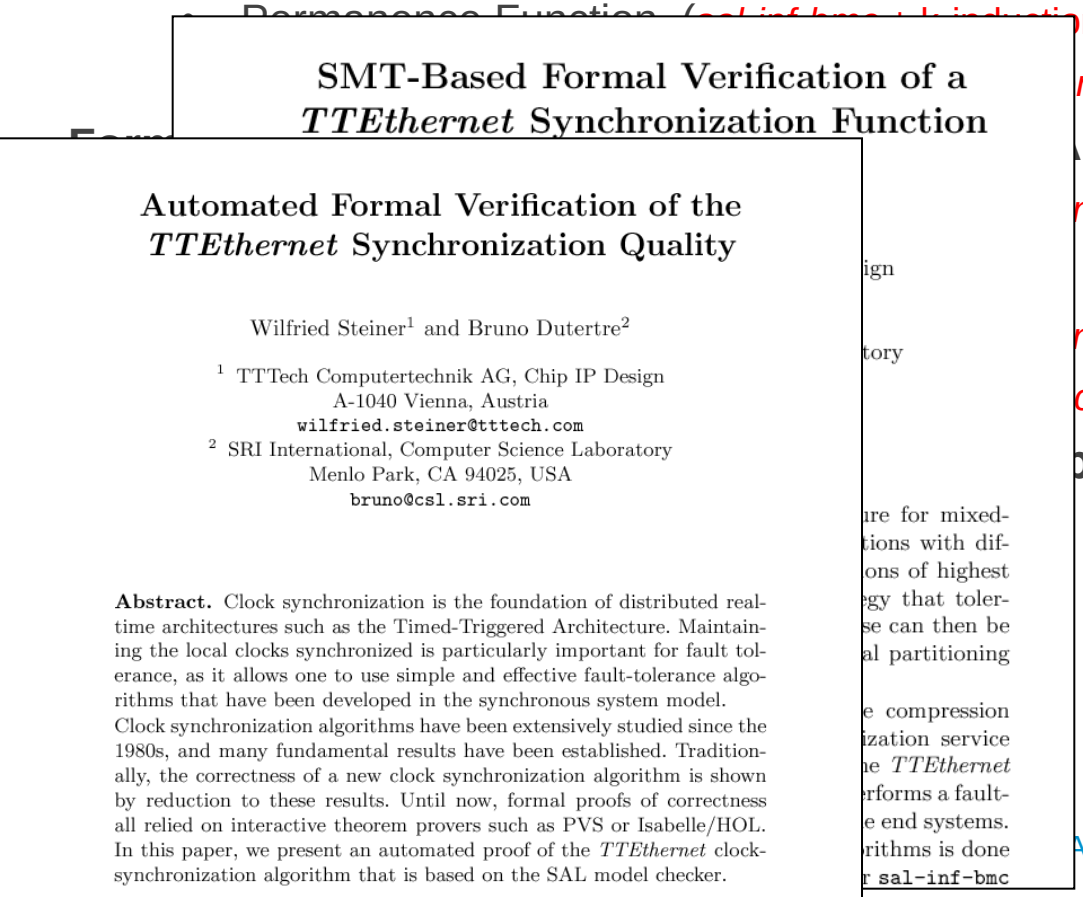
SAE AS6802 – Fault-Tolerant Clock Synchronization

TTEthernet Executable Formal Specification

- Using symbolic and bounded model checkers *sal-smc* and
- Focus on Interoperation of Synchronization Services (Start
  Detection, Clique Resolution, abstract Clock Synchro

Verification of Lower-Level Synchronization Functions

- Permanence Function (*sal-inf-bmc* + k-induction)



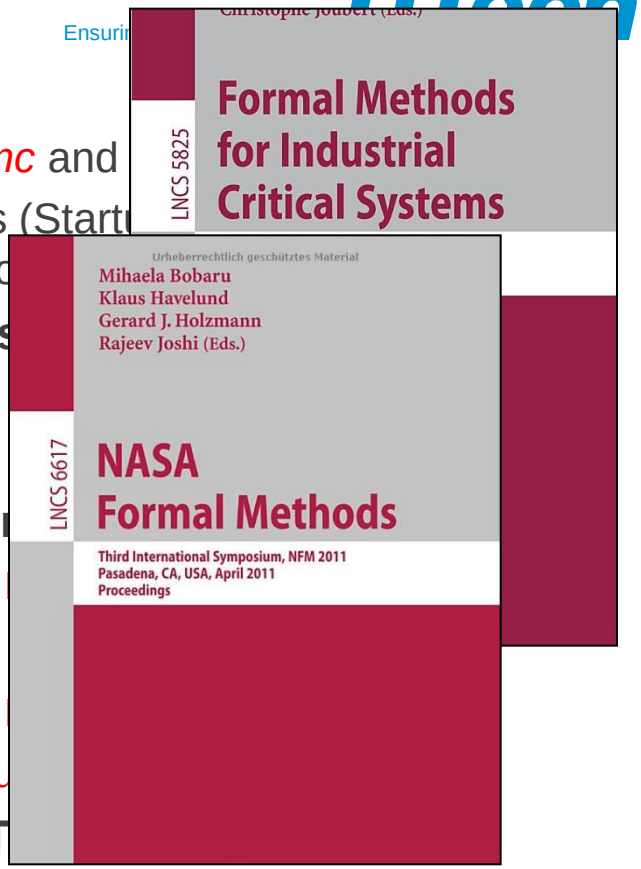
SMT-Based Formal Verification of a *TTEthernet* Synchronization Function

Automated Formal Verification of the *TTEthernet* Synchronization Quality

Wilfried Steiner[1] and Bruno Dutertre[2]

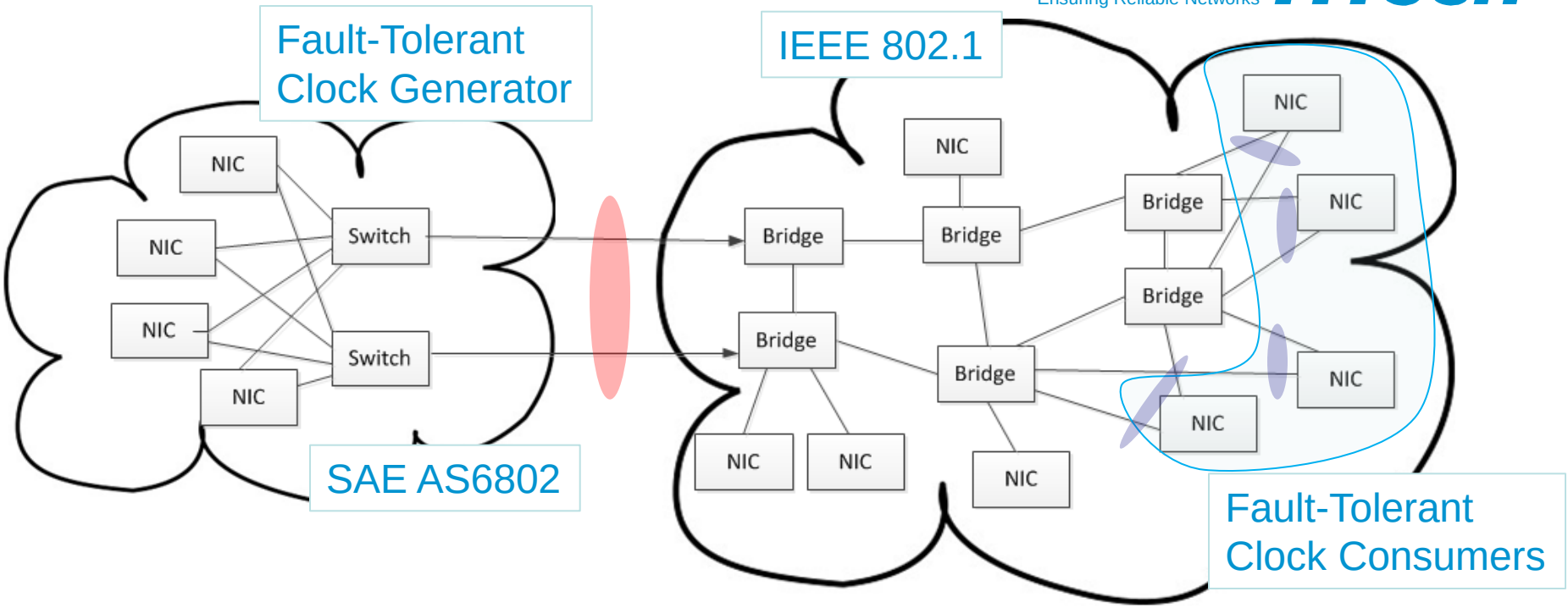
[1] TTTech Computertechnik AG, Chip IP Design
A-1040 Vienna, Austria
wilfried.steiner@tttech.com
[2] SRI International, Computer Science Laboratory
Menlo Park, CA 94025, USA
bruno@csl.sri.com

Abstract. Clock synchronization is the foundation of distributed real-time architectures such as the Timed-Triggered Architecture. Maintaining the local clocks synchronized is particularly important for fault tolerance, as it allows one to use simple and effective fault-tolerance algorithms that have been developed in the synchronous system model. Clock synchronization algorithms have been extensively studied since the 1980s, and many fundamental results have been established. Traditionally, the correctness of a new clock synchronization algorithm is shown by reduction to these results. Until now, formal proofs of correctness all relied on interactive theorem provers such as PVS or Isabelle/HOL. In this paper, we present an automated proof of the *TTEthernet* clock-synchronization algorithm that is based on the SAL model checker.



CoMMiCS

Interface Design i



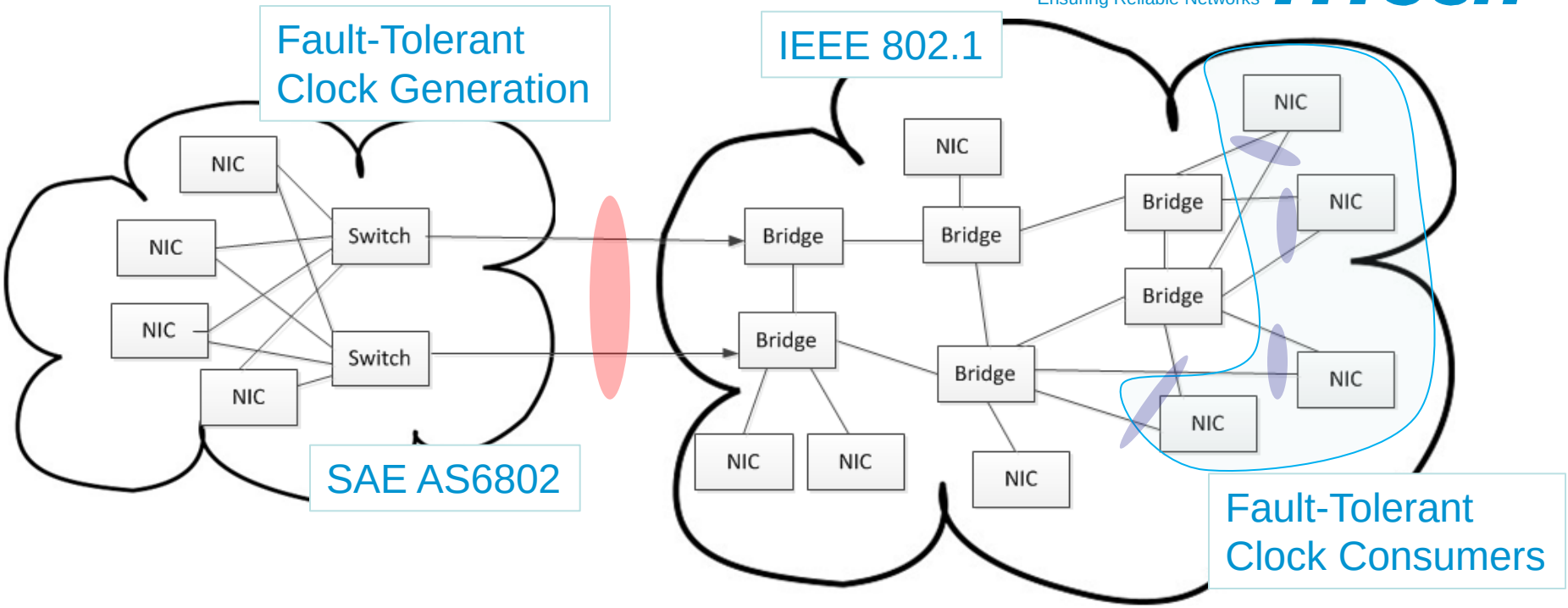
"Architecture Design is Interface Design" [Kopetz]

Red Interface specifies the behavior of the FT Clock Generator *as observed by the connecting bridges of the IEEE 802.1 network*.

Internal behavior of the FT Clock Generator may (and most likely will) *be much more complex* than as observed at the interface.

Blue Interface specifies the behavior of the FT Clock Generator *as observed by the FT Clock Consumers.*

Interface Design ii



The red interface is different from the blue interfaces, because there *is additional behavior introduced by the IEEE 802.1 network* connecting the FT Clock Generator to the FT Clock Consumers.

Both, red and blue, interfaces need to be specified to enable the usage of a fault-tolerant timebase.

SUMMARY AND OUTLOOK

Summary

Our daily life more and more depends on dependable systems.

The interconnection and networking of these systems is a main aspect.

We see a cross-industry trend towards the use of Ethernet in time-critical, safety-related, and also safety-critical systems, for example in the automotive industry.

Plain Ethernet as of today does not provide all functions to allow building distributed dependable systems.

Hence, Ethernet variants have been developed, for example TTEthernet (standardized as SAE AS6802) that defines a time-triggered paradigm and mixed time-triggered event-triggered paradigm for Ethernet.

Currently, the IEEE is improving native Ethernet with real-time and dependability functions.

Summary

In particular, IEEE 802.3 develops and maintains the Ethernet PHY (e.g., the Reduced Twisted Pair Gigabit Ethernet – RTGBE for automotive use) and MAC standards, IEEE 802.1 develops and maintains bridging (aka switching) standards.

With AVB, the IEEE has moved Ethernet into the real-time applications domain.

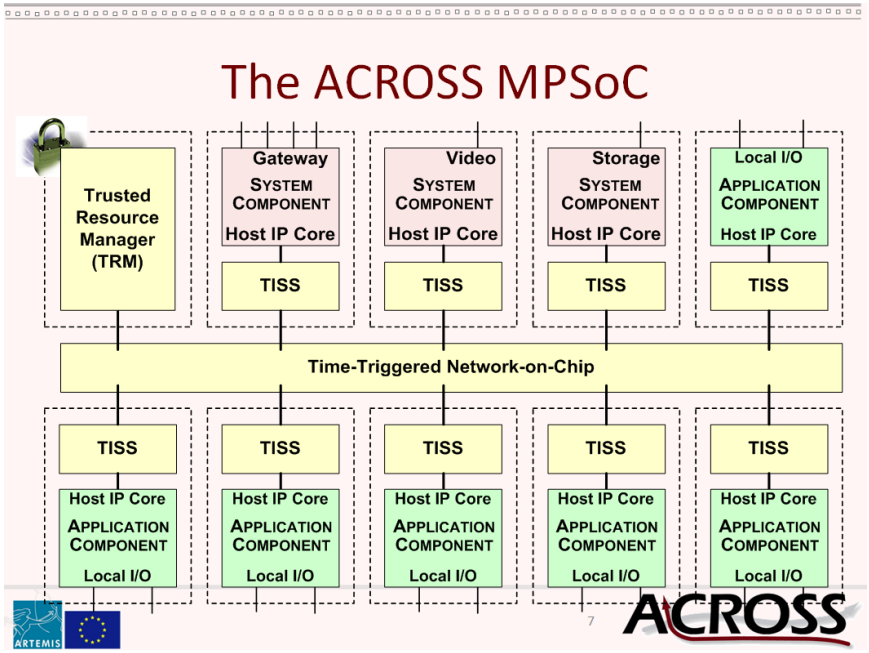
With TSN, the IEEE currently moves Ethernet into the hard real-time applications domain and improves Ethernet's robustness.

With the growing competences in the IEEE standards, products built on these standards increase their market potential.

Well-defined interfaces allow to re-use existing fault-tolerant clock-synchronization protocols.

Outlook:
Networks are everywhere

In the European-funded ACROSS project we investigated Network-on-Chip technologies and developed a Time-Triggered Network-on-Chip (TTNoC)



http://www.across-project.eu/

Outlook:
Networks are everywhere

Ensuring Reliable Networks TTTech

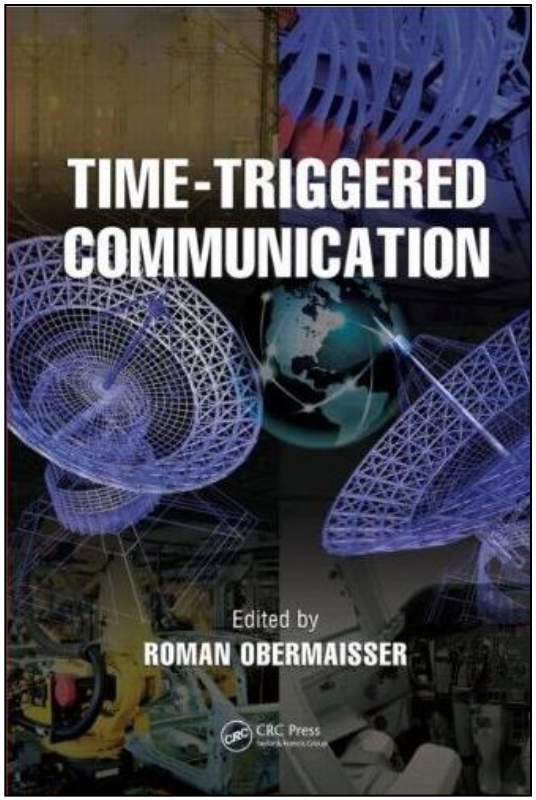
In the recently started and European-funded DREAMS project we are taking a holistic view on distributed dependable system as a system-of-systems.

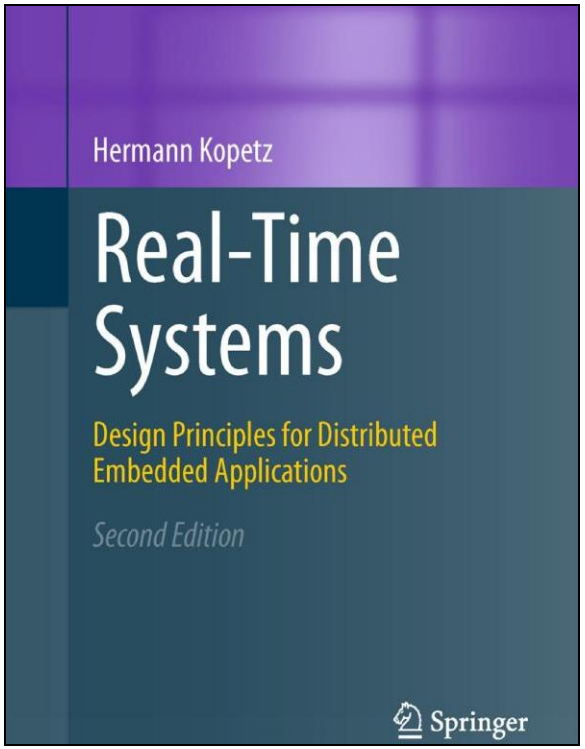
Thereby, we research networks on different levels: on-chip, on-board (e.g., on a PCB), within a box, and “local area” network.

In particular we are interested on emerging benefits that come with the realization of the time-triggered paradigm on all these different hierarchical levels.

http://www.dreams-project.eu/

Recent Book on Time-Triggered Technology





Recent Book on Real-Time Systems

Ensuring Reliable Networks

www.tttech.com