Bus Systems

Automotive Bus Systems – TT Ethernet

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Automotive Bus Systems

Learning objectives

- Understand operation of standard ethernet
  - Bus arbitration
  - MAC Frame formats
- Understand shortcomings of standard ethernet for embedded systems
  - Predictbability
- Understand TTEthernet history and approach

Ethernet

- Local Area Network
  - Developed for the connection of computers
  - Servers, Terminals, Workstations
  - Personal computers (later)

- History
  - 1983, 802.3 CSMA/CD Standard was initially published
    - Basic Medium Access Control and frame formats
    - Foundation of modern ethernet networks
    - Based on collision detection and collision resolution

- Physical layers
  - Shared medium
  - 10Base5 („Thick Ethernet“) – 9.5 mm Diameter coaxial cable (~1982)
  - 10Base2 („Thin Ethernet“) – thinner „Antenna style“ coaxial cable (~1985)
  - Twisted Pair (~1990-Today, 10BASE-T (1990), 100BASE-TX (1995), 1000BASE-T (1999), 10GBASE-T (2006))

Ethernet – Physical Layer

10-BaseT

- Requires two twisted pair wires
- Category 3 or category 5 cable types are used for realizing network
  - Category 3:
    - Unshielded twisted pair cable
    - Supports bandwidth up to 16 Mhz
    - Used e.g. for telephone wiring
  - Category 5:
    - Unshielded twisted pair cables
    - Supportds bandwidth up to 100 Mhz
    - 4 Pairs are common, more pairs are possible
- Uses Manchester coding

Ethernet – Physical Layer

100-BaseTX

- Requires two twisted pair wires
  - Category 5 cable types are used for realizing network
- Uses 4B5B coding followed by MLT-3 encoding on copper wires
  - DC equalization and optimizes transmission spectrum
  - Maps 4 data bits to 5 code bits
  - Efficient with respect to required signal spectrum

Ethernet – Physical Layer

100-BaseTX

- 4B5B Coding
  - Maps 4 Bit data to 5 Bit code
  - Avoids long 1 and 0 sequences by ensuring at least two level transitions per code sequence

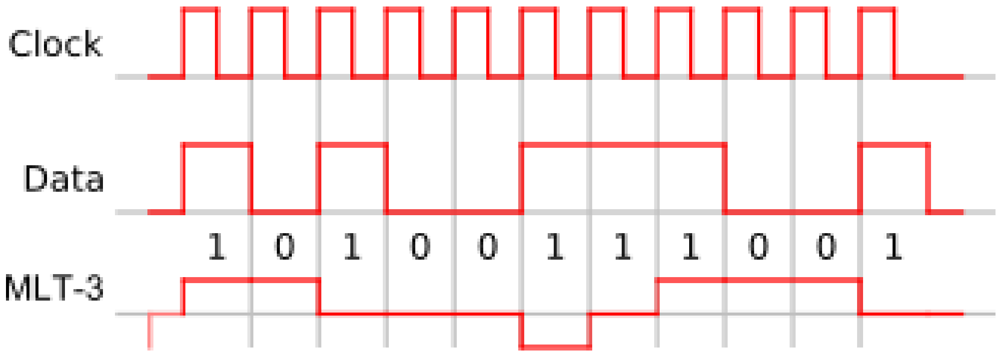
- Additional code sequences are used for control words
  - Two consecutive 5-Byte sequences ensure proper level transitions

Data value	4B	5B
0	0000	11110
1	0001	01001
2	0010	10100
3	0011	10101
4	0100	01010
5	0101	01011
6	0110	01110
7	0111	01111
8	1000	10010
9	1001	10011
A	1010	10110
B	1011	10111
C	1100	11010
D	1101	11011
E	1110	11100
F	1111	11101

Ethernet – Physical Layer

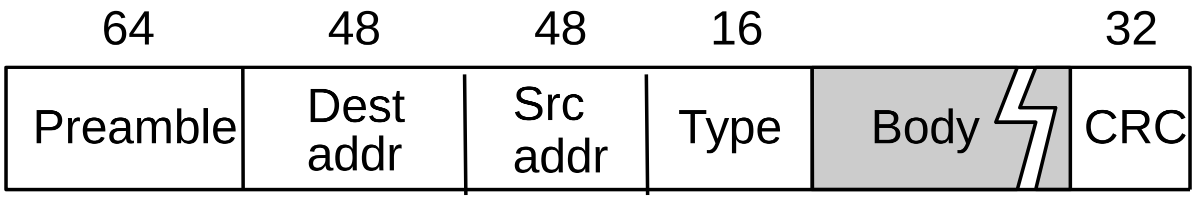
100-BaseTX

- MLT-3 Coding
  - Cycles three voltage levels sequentially: -1, 0, +1
  - 1-Bit: Moves to next level in cycle, 0-Bit stays at current level
  - Coding efficiency of 1 Bit per Baud
  - Requires four cycles for transition through full cycle



Ethernet – Medium Access Control (MAC)

- Ethernet frame format
  - 8 Byte Preamble (7 Bytes Preamble, 1 Byte Start of Frame)
  - 6 Byte destination address
  - 6 Byte source address
  - 2 Byte type
  - 60-1514 Bytes body (payload data)
  - 4 Byte CRC checksum (CRC-32)



Ethernet – Medium Access Control (MAC)

Ethernet is an address based protocol

- Source and destination nodes are explicitly addresed
- Addresses are unique and pre-programmed into Ethernet controllers
  - 6-Byte MAC-Address
  - Manufracturers receive blocks of MAC addresses for their controllers
  - No two controllers with same MAC address must appear in same network
- Broadcast address (FF:FF:FF:FF:FF:FF) supports communication with all nodes
  - In the same physical network (OSI-Layer 2 – do you remember?)
  - These frames are not routed to other networks

Ethernet – Medium Access Control (MAC)

CSMA/CD Medium access – Rationale

- Shared medium – the same transmission medium us used by all stations
- CSMA/CD detects collisions, but unlike CSMA/CA does not avoid them

- CSMA/CD rationale
  - Send only if medium is idle
    - Carrier Sensing (CS)
  - Enable multiple stations to access the same medium
    - Multiple Access (MA)
  - Stop sending immediately if collision (concurrent transmitters) is detected
    - Collision Detection (CD)

- IEEE 802.3 implements fair and decentral CSMA/CD medium access algorithm
  - All stations have similar chance of accessing the medium

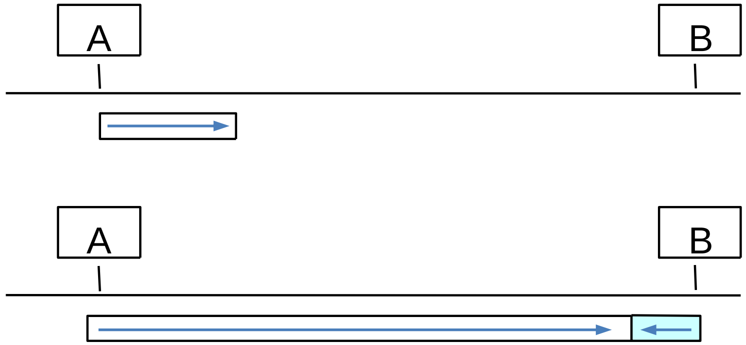
Ethernet – Medium Access Control (MAC)

CSMA/CD Medium access – Collisions

- Collisions are caused when two adaptors transmit at the same time
  - Adaptors sense collision based on voltage differences

- Example

A transmits at time 0



Message almost there at time T when B starts – collision!

Ethernet – Medium Access Control (MAC)

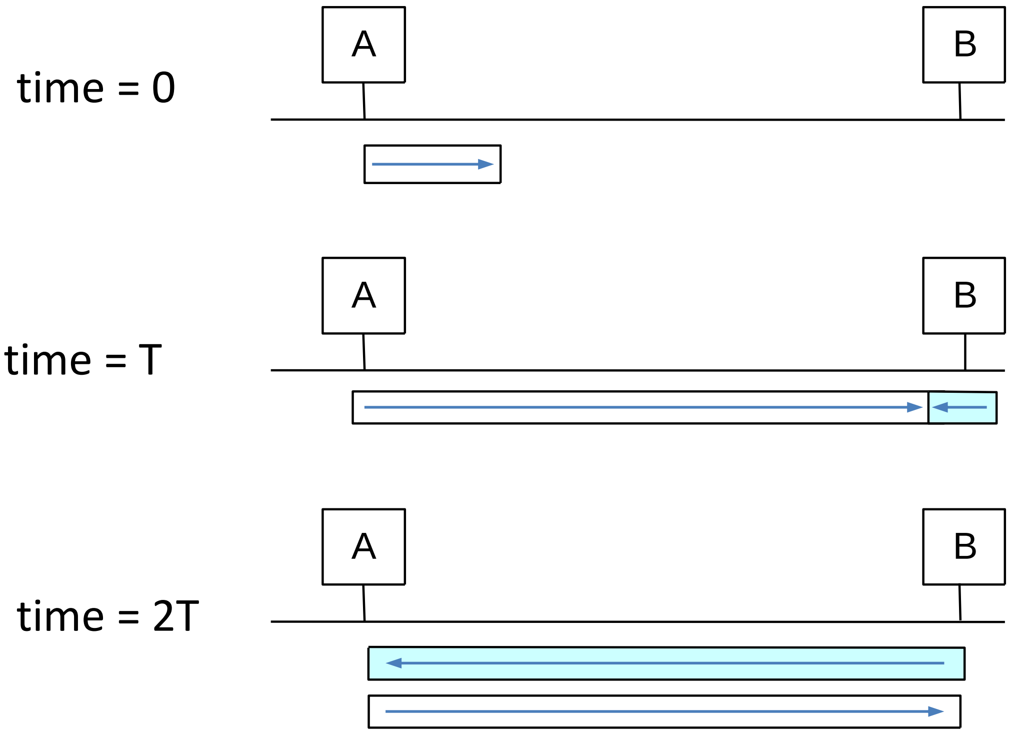
CSMA/CD Medium access – Collisions

- Frame transmission is invalidated
  - All nodes must be able to sense that collision

- How can A know that a collision has taken place?
  - There must be a mechanism to ensure retransmission on collision
  - A's message reaches B at time T
  - B's message reaches A at time 2T
  - So, A must still be transmitting at 2T

- IEEE 802.3 specifies maximum value of 2T to be 51.2µs
  - This relates to maximum distance of 2500m between hosts
  - At 10Mbps it takes 0.1µs to transmit one bit, 512 bits (64B) take 51.2µs
  - Ethernet frames must be at least 64B long
    - 14B header, 46B data, 4B CRC. Padding is used if data is less than 46B
    - Send 48 Bit jamming signal after collision is detected to ensure all hosts see collision

Ethernet – Medium Access Control (MAC)



Ethernet – Medium Access Control (MAC)

CSMA/CD Medium access – Collisions

- If a collision is detected, delay and try again
  - Delay time is selected using binary exponential backoff delay
    - 1st time: choose K from {0,1} then delay = K * 51.2us
    - 2nd time: choose K from {0,1,2,3} then delay = K * 51.2us
    - nth time: delay = K x 51.2us, for K=0..2n – 1
  - Maximum value for k is 1023
    - Transmitting node gives up after several tries (usually 16)
    - Reports transmit error to host

- If backoff delays are not random, transmitters will re-start transmission at same time
  - Size of set 'k' is balanced between network size and waiting times
  - Smaller maximum value of 'k' yields less waiting times but larger probability of collisions

Ethernet – Medium Access Control (MAC)

CSMA/CD Medium access – Implications

- Ethernet works best under light loads
  - Higher networks loads imply higher probability of collisions
- Ethernet is not predictable
  - Repeated collisions could cause a frame to be not transmitted at all
  - No worst case transmission delays can be estimated
    - Worst case = no transmission
- Ethernet is fast, cheap, and easy to administer

Ethernet – Medium Access Control (MAC)

Ethernet - Topologies

- Line Topology
  - One broadcasting and collision domain

- Star topology (Hub)
  - Hub forwards incoming signals to all ports
  - Less error prone to errors in cables
  - Same broadcasting and collision domain as line topology

Ethernet – Medium Access Control (MAC)

Ethernet - Topologies

- Star topology (switched – store and forward)
  - Switch transmits signal to receiver port or broadcasts if receiver port is unknown
    - Forwards frame after it has been fully received
    - Bidirectional communication is used
    - Enables hierarchical topologies
    - Switch only as limited storage space, if storage space is exceeded it defaults to broadcasting
  - Switch decouples collision domains – collisions are not propagated to other ports
    - Enables multiple concurrent transmissions between independent pairs of nodes
    - Prevents collisions between switched nodes if no additional line topology is used
  - Broadcasts are propagated to all nodes
    - Special measures need to be taken to avoid loops between switches

Ethernet – Medium Access Control (MAC)

Ethernet - Topologies

- Star topology (switched – wormhole routing)
  - Frame is forwarded after destination address has been evaluated
  - Faster, but more likely affected by transmission errors (why?)

TTEthernet

- Development and standardization
  - Originated as academic research project (TT-Ethernet)
  - Development was continued by TTTech as TTEthernet
  - One out of many real-time Ethernet standards

- TTEthernet extends standard Ethernet frames
  - Time triggered messages
    - Sent at defined times
    - Take precedence over all other messages
  - Rate constrained messages
    - Guaranteed bandwidth and maximum bounds for delay
  - Best effort messages
    - Regular 802.3 frames
    - Least important in TT Ethernet topologies

TTEthernet

- Application areas
  - Time triggered messages
    - Shared control loops
    - X-by-wire applications
    - Safety relevant communication
    - Communication that is sensitive with respect to delay/jitter

  - Rate contrained messages
    - Shared control loops
    - Multi-media traffic
    - Communication that is more tolerant with respect to delay/jitter

  - Best effort traffic
    - Software updates
    - Diagnostic data
    - „App“ downloads
    - Traffic that has no particular / only low real-time requirements

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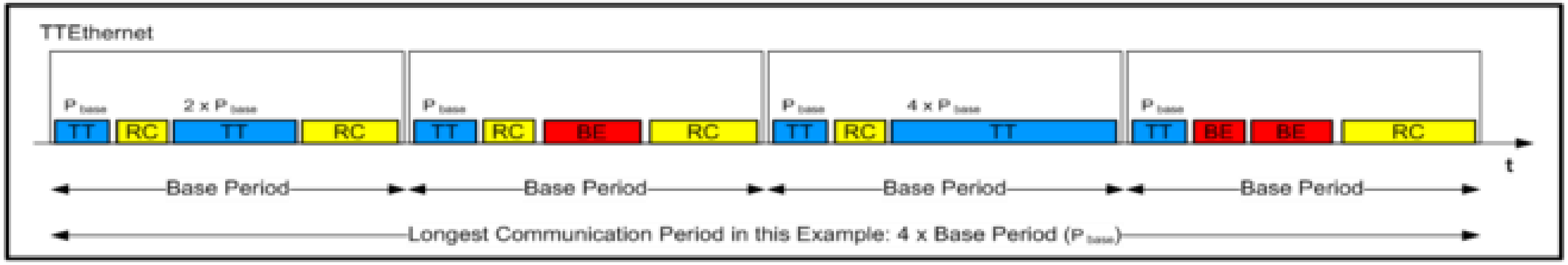
Realization

- Time divided medium
- Medium is time divided into base periods
- Base periods contain fixed time triggered slots
  - Fixed time slots (TT – Time Triggered) used for critical hard real-time traffic
  - Rate constrained traffic for traffic with bitrate/delay requirements
  - Best effort slots for uncritical data
- Predictable delay and jitter possible for:
  - Fixed time slots
  - Rate constrained traffic
- Best effort traffic uses remaining time



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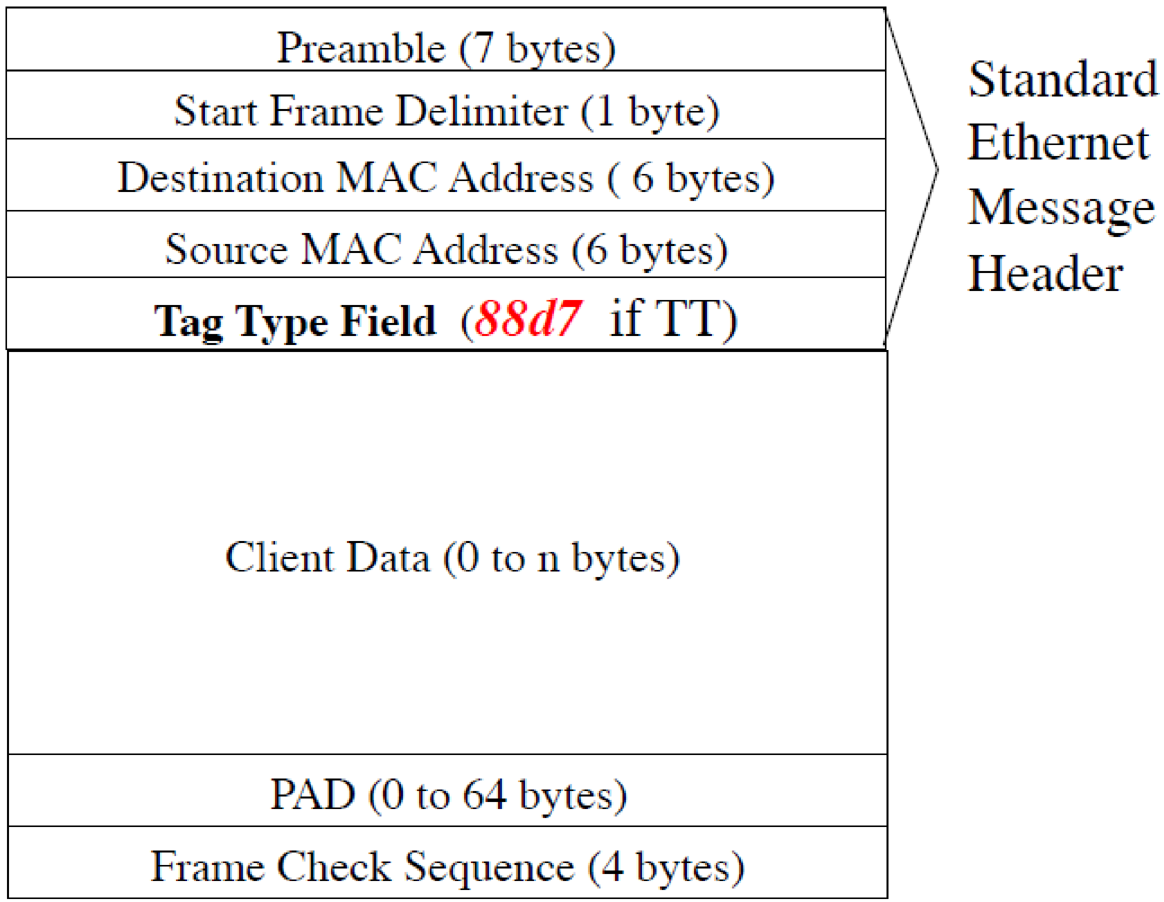
Realization – TT Ethernet is mostly realized on ISO/OSI Layer 2



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TTEthernet Realization

- TT Network segments
  - Switched infrastructure
  - Switches need to be TTEthernet conforming
  - Adapters transmitting TT Data need to be TTEthernet conforming
- Normal nodes may only send best effort messages
- TTEthernet nodes may send all types of messages

TTEthernet switches

- Ensure TT Protocol and bandwidth/delay constraints
  - Regular „Normal“ nodes do not need to implement TT Protocol to communicate via BE frames
- BE/RC frames are delayed in TT slots
  - RC frames are transmitted due to their bandwidth guarantees
- Manage the integration of TTEthernet and standard Ethernet devices

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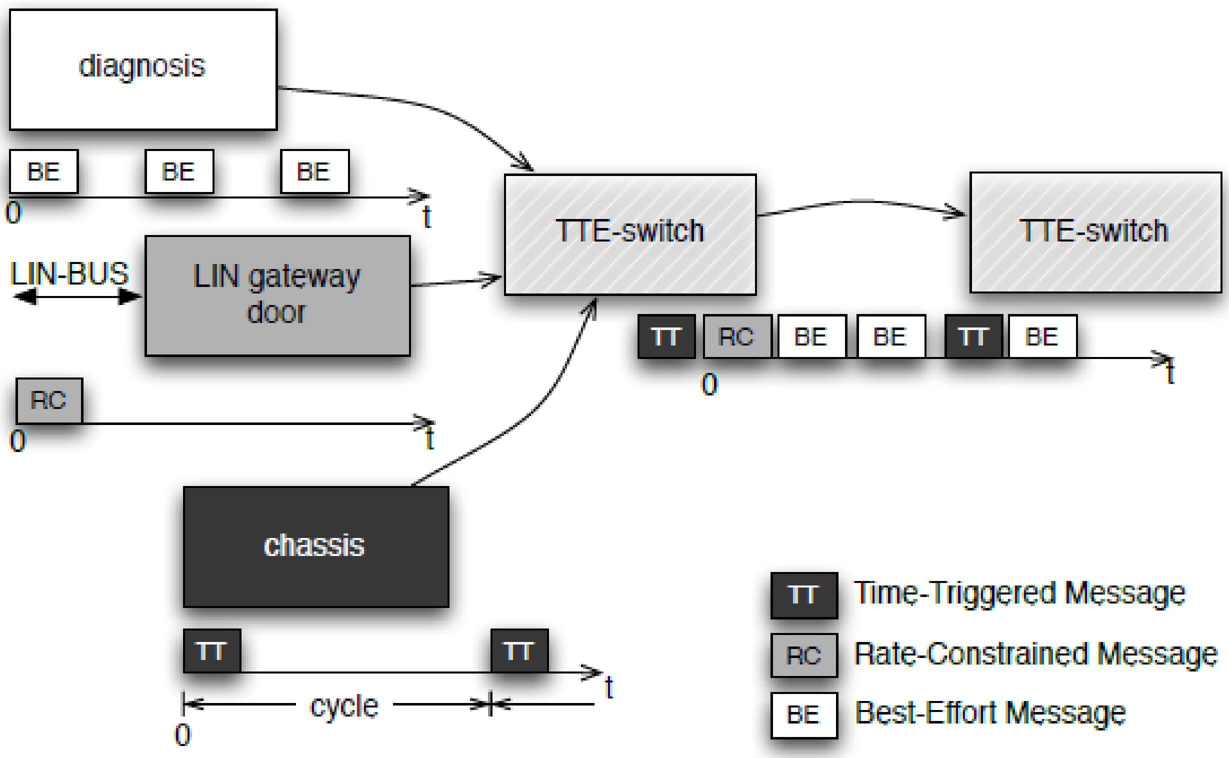
Example TTEthernet topology – Traffic types



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TTEthernet Realization

- TT Network segments
  - Switched infrastructure
  - Switches need to be TTEthernet conforming
  - Adapters transmitting TT Data need to be TTEthernet conforming
- Normal nodes
  - Normal nodes may only send best effort messages
  - TTEthernet nodes may send all types of messages
- Time synchronization
  - TTEthernet nodes maintain time synchronization to create time slots
  - Time synchronization is operational accross multiple hops (switches)
- Redundancy
  - TTEthernet networks may consist of multiple channels
  - Messages may be sent over multiple channels to obtain redundancy

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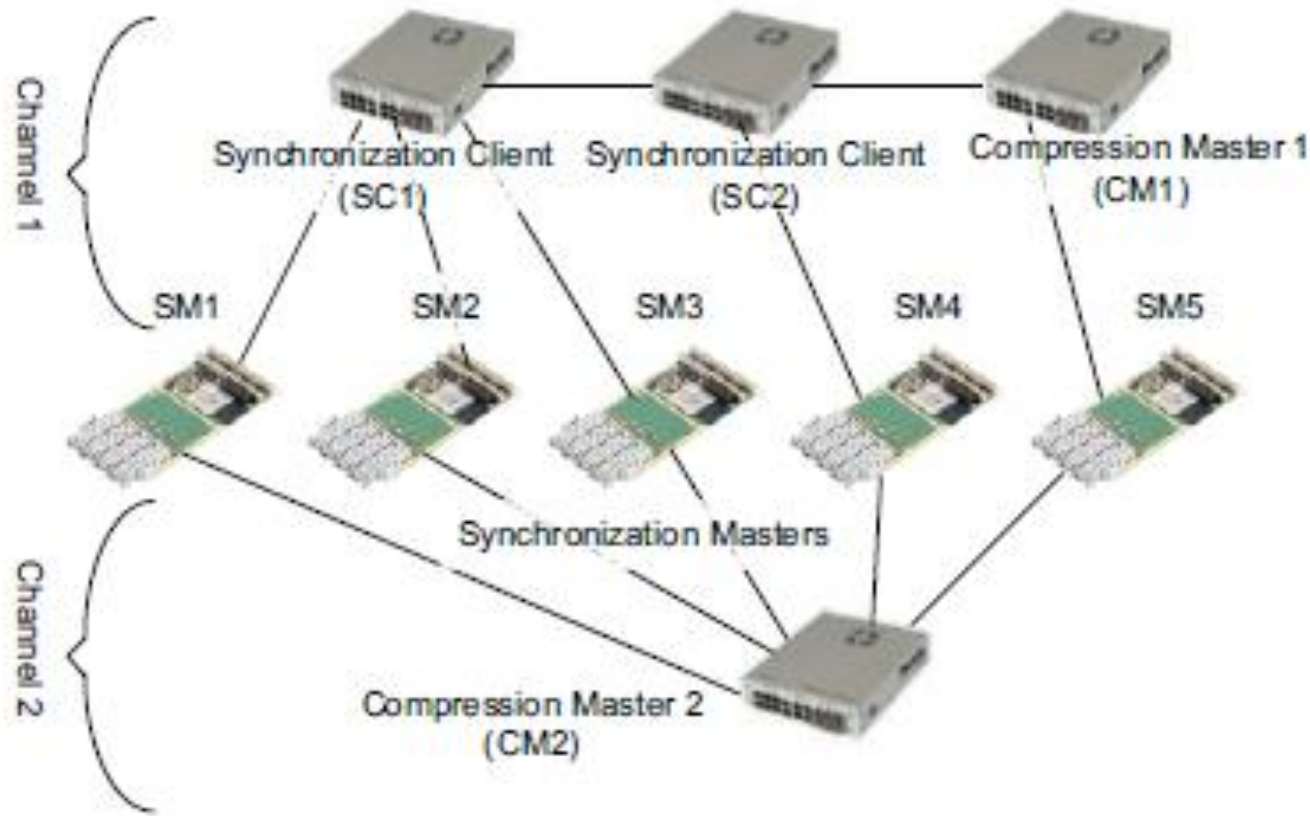
TTEthernet synchronization topology - example



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Synchronization

- Precondition for time triggered approaches (e.g. time slots)

- Node types
  - Synchronization master (SM)
    - Starts synchronization by transmitting synchronization frames
    - Initial and periodic re-synchronization to set and to maintain shared clock
  - Compression master (CM)
    - Receives synchronization frames from SMs
    - Calculates relative delay
    - Transmits aggregates synchronization frame back to SM and SC
  - Synchronization client (SC)
    - Receives synchronization frames and synchronizes to them

- Nodes only synchronize to synchronization frames sent by compression masters (CM)

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Synchronization over multiple devices

- Necessary when devices are not directly connected to synchronization masters

- Synchronization must handle introduced delay
  - Sources of delay
    - Frame propagation t_{prop} – Depends on cable length
    - Transmission time $t_{tx} = t_{bit} * n_{bits}$ – Depends on synchronization frame length
    - Forwarding delay t_{switch} – Depends on switch performance

- Maximum delay times for each network segment are known
  - Delays add up to worst case delay time for link i: $d_{wc}(i)$

- When re-synchronizing, nodes measure transmission delay and wait until worst case delay is reached
  - Accuracy depends on clock drift
  - Reduces jitter during re-synchronization

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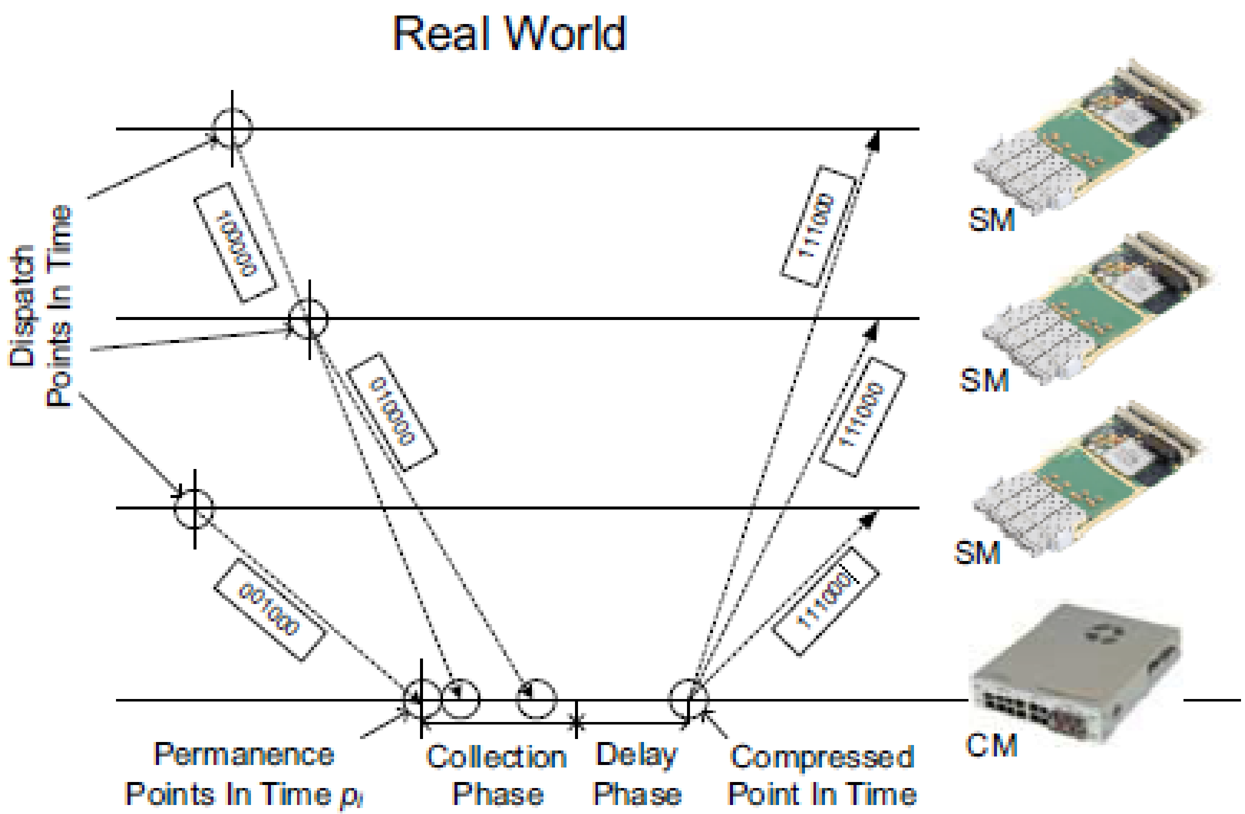
Synchronization process



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Message forwarding in TTEthernet Switches

- TT Ethernet switches use store-and-forward message forwarding
  - Messages are completely received before they are forwarded to output links
  - This enables switches to change the nature of a message, e.g. a TT message could be forwarded as BE message to less significant network segments
  - RC/BE messages that are received at any port during TT slot are stored in the switch and their transmission is deferred
  - Switches assume network to be properly configured, e.g. two TT messages must not be received during the same TT slot

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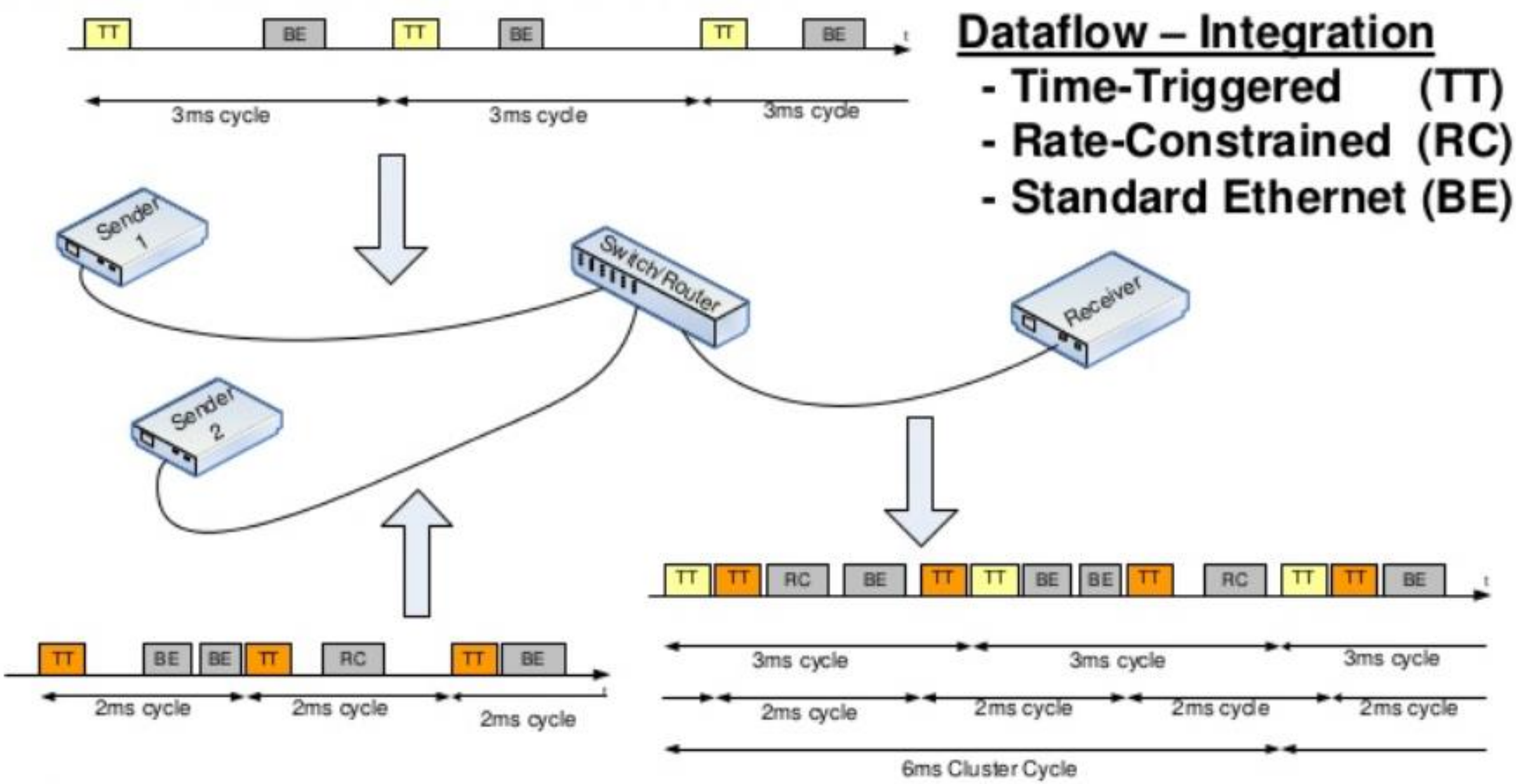
Message forwarding in TTEthernet Switches - Example



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TTEthernet

- Supports synchronous and asynchronous real-time traffic
  - Time triggered communication
  - Rate constraint communication
- Also supports best-effort communication
  - Integration of legacy devices
- Adds redundancy
  - Different physically independent channels
- Fault detection and avoidance
  - Switches act as guards to disconnect „babbling idiots“ from network
  - The same node may be connected to multiple switches for redundancy reasons
  - Cliques of wrongly synchronized nodes are detected through network monitoring
  - Multiple independent synchronization domains (channels) may be created