Switched Ethernet solutions for embedded real time networks

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1 Context
   - Avionics network architecture
   - Automotive network architecture

2 Ethernet
   - Ethernet Evolution
   - AFDX
   - Ethernet-AVB
   - TTEthernet

3 Some open issues
Agenda

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3. Some open issues
Historical evolution of embedded networks

- Early days: one single computer for all embedded functions
- Then distribution of the functions on computing nodes
  - Transmission of data between these functions
  - Dedicated point-to-point links for deterministic transmissions
- Two many links $\Rightarrow$ shared communication medium
  - Timing constraints have to be insured
  - Specific technologies have been defined, e.g. CAN
  - Timing analysis have been developed
- More and more functions $\Rightarrow$ huge increase of communication needs
  - Specific technologies are no more sufficient
  - Ethernet technologies are candidate
    - Pros: large bandwidth, mature technology
    - Cons: Ethernet is not deterministic
- Real-time Ethernet widely used for industrial communications, e.g. Profinet
- Candidates for embedded communications: AFDX, Ethernet-AVB, TTEthernet, ...
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Civilian aircraft communications

Avionics
ARINC 429 - 664

A/C Ops & CABIN
ARINC 429- Ethernet

IFE

HF/VHF/SATCOM

Ground Information System (Airlines, Airbus, …)
Avionics systems characteristics

- **Avionics**: electronic systems installed in an aircraft
  - Calculators and their software, sensors and actuators
  - Communication links between these elements

- **Example of avionic systems**: autopilot, navigation, flight control, . . .

- **Constraints on the avionics systems**
  - Volume and weight limitations
  - Correct behavior in severe conditions: heat, vibrations, electromagnetic interferences, . . .
  - Safety level required, depending on the system (ARP 4754):
    - catastrophic (failure = loss of the aircraft), hazardous, major, minor, no effect
  - Segregation between critical functions

- **Aeronautical Radio INCorporated (ARINC)**: leadership in the development of specifications and standards for avionics equipment

- **Airlines Electronic Engineering Committee (AEEC)**: development and maintenance of specifications and standards (airlines, governments, ARINC)

- **ADN**: Aircraft Data Network
Avionics systems evolution

- In the 1950’s
  - Very simple standalone systems
  - One single calculator for the execution of all the functions

- In the 1960’s
  - The beginning of modern avionics
  - Replacement of analog devices by their digital equivalent

- Since then
  - Huge increase in the complexity of avionics
  - More and more digital equipments for existing or new functions
  - New needs inherent to the evolution of civil aviation or better answers to existing problems (e.g. fly-by-wire command system)

- Increase in the number of embedded systems and functions ⇒ increase in communication needs

- Integrated Modular Avionics (IMA) in the 1990’s: better sharing of execution and communication resources
  - First implementation of IMA for the Boeing 777, based on the ARINC 629 multiplexed data bus
  - IMA in the Airbus A380, based on the ARINC 664 (switched Ethernet)
Classical avionics architecture (up to A340)

- Each equipment (LRU) dedicated to a system function (braking, flight computers, ...): sensors, actuators, calculators ...
- Natural segregation between the equipments
Data transmission in classical avionics

- A network of equipments

Each data is transmitted from its source to every equipment that needs the data

- One dedicated line for each data

- Repetitive transmission of the data on each line

- Each line: a mono-emitter ARINC 429 data bus

- Each data individually identified by a label

- Low bit rate: 12 Kbits/s to 100 Kbits/s

- At most 20 receivers per line
Classic avionics evolution

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Avionic Volume</td>
<td>745 litres</td>
<td>760 litres</td>
<td>830 litres</td>
<td></td>
</tr>
<tr>
<td>Number of equipment</td>
<td>77</td>
<td>102</td>
<td>115</td>
<td>147</td>
</tr>
<tr>
<td>Embedding Software</td>
<td>4 Mo</td>
<td>10 Mo</td>
<td>20 Mo</td>
<td>100 Mo</td>
</tr>
<tr>
<td>Number of ARINC 429</td>
<td>136</td>
<td>253</td>
<td>368</td>
<td>1000 (AFDX)</td>
</tr>
<tr>
<td>Computing Power</td>
<td>60 Mips</td>
<td>160 Mips</td>
<td>250 Mips</td>
<td></td>
</tr>
</tbody>
</table>

Avionic repartition

90% of the avionic
IMA characteristics

- Hardware components
  - LRM (Line Replaceable modules): resources in common cabinets
    - Core modules for the execution of the applications
    - Input/output modules for communications with non-IMA equipments
    - Gateway modules for communications between cabinets
  - LRU (Line Replaceable Unit): existing non-IMA equipments
  - Backplane databus: ARINC 659

- Sharing of execution resources
  - An avionics subsystem: a partition with an assigned time window to execute its application on a shared module
  - Guarantee isolation between subsystems ⇒ robust partitioning concept
    - Spatial isolation: limitation and protection of the address space of each partition, e.g. by a MMU
    - Temporal isolation: static allocation of a time slice for the execution of each partition, based on WCET
  - Communications between partitions via ports (APEX: APplication EXecutive)
    - Sampling ports: only the last value of data is stored
    - Queueing ports: all the values of data are stored
  - Logical channel: multicast link between ports, independent of the communication technology
The reasons for Ethernet in avionics

- ARINC 429 is no more sufficient: too many buses are needed
- ARINC 629 is too expensive
- Why Ethernet technology?
  - High throughput offered to the connected units (100 Mbits/s)
  - High connectivity offered by the network structure
  - A mature industrial standard
  - Low connection cost
- But Ethernet CSMA/CD is not deterministic
  - Potential collision on the physical medium
  - Binary Exponential Back off retransmission algorithm
- The solution adopted for ARINC 664
  - switched Ethernet technology: units directly connected by point-to-point links to Ethernet switches ⇒ possible collision domain = single link between two elements
  - Full duplex links ⇒ no more collisions
- The problem is shifted to the switch level
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From point-to-point to multiplexed communications

- Before 1970, mechanical and hydraulic systems for engine control, brake system, gear system, . . .
- After 1970, huge increase in the number of electronic systems
- Performance and reliability of hardware components + software technologies ⇒ implementation of complex functions that improve the comfort and safety (Antilock Braking System, Electronic Stability Program, active suspension, GPS, doors, entertainment, . . .)
- Early days of automotive electronics: 1 function = 1 Electronic Control Unit (ECU: a microcontroller and sensors and actuators)
- Exchanges of data between functions via dedicated links (e.g. speed estimated by the engine control and used by the suspension control)
From point-to-point to multiplexed communications

- A function is either too complex or too small for a single ECU \(\Rightarrow\) functions distributed over several ECUs or several functions on the same ECU
- Too many information exchanges \(\Rightarrow\) need for a shared communication medium.
  - Reduces the weight of the electronic systems: reduction of 15 Kg with the replacement of the dedicated links by a shared bus for the control of the doors of a BMW
  - Necessary to guarantee that the communication delays can be bounded
- First automotive bus: Controller Area Network (Bosch, 1980s)
- First embedded CAN bus: Mercedes class S (1991)
- Today: a complex architecture with several communication technologies
Automotive functional domains

- Different applications with different domains

**Powertrain**
- Control of engine and transmission
- Complex control laws implemented in microcontrollers with high computing power
- Stringent time constraints
- Frequent data exchanges with other car domains
- Closed-loop control systems ⇒ implementation is moving toward a time-triggered approach

**Chassis**
- Control of the vehicle’s according to steering, braking and driving conditions
- Part of the vehicle active safety systems (Antilock Braking System, Adaptive Cruise Control, ...)
- Communication requirements similar to those for the powertrain, more emphasis on safety
Automotive functional domains

- **Body and comfort**
  - Software-based systems that control dashboard, wipers, lights, doors, windows, seats, mirrors, air conditioning
  - Many exchanges of small pieces of information
  - Activation of body functions triggered by occupants’ solicitations ⇒ event-triggered communication

- **Multimedia/infotainment**
  - Audio CD, DVD players, rear seat entertainment
  - Hand-free phones, in-car navigation systems, traffic information systems, remote vehicle diagnostic, vehicle tracking, fleet management, ...
  - Large amounts of data to be exchanged within the vehicle and with the external world
  - QoS of multimedia data stream, bandwidth, security
Automotive network architecture in 2006
Vision for future in-car networks
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Shared Ethernet

- A set of stations share a single communication channel
- A frame from a station is received by all the other stations (eventually through hubs)
- Collisions may occur => CSMA/CD
  - CSMA (Carrier Sense Multiple Access): listen to the medium, send only when medium is detected idle
  - CD (Collision Detection): if a collision is detected during transmission
    - Transmission is stopped
    - Station waits a random delay (exponential backoff)
    - Station tries to transmit again
- At least 64 bytes in order to detect a collision
- Number of collisions: major impact on Ethernet performance
  - Performance decreases very quickly when number of collisions increases
  - Collision domain: the whole network
Switched Ethernet

- Division of the network with separate collision domains ⇒ more than one frame being transmitted at a given time without collision
- A switch:
  - A set of input and output ports with buffers for pending frames
  - A switch fabric which “moves” each frame from its input port to its destination output ports
  - A service discipline for the scheduling of frames in output ports
- Two modes for a switch
  - Store and forward: reception and verification of the whole frame before it is forwarded to its output port(s)
  - Cut through: frame is transferred as soon as destination is decoded
    - Smaller latency
    - Invalid frame might be transferred
Shared Ethernet Vs switched Ethernet

- Full duplex links ⇒ no more collisions
Full duplex switched Ethernet is not deterministic

- Temporary congestion on an output port
  - Increase of the waiting delay of frames in the Tx buffer
  - Frame loss by overflow of the Tx buffer

- An illustrative example

- Five frames at the same time ⇒ one frame waits until the transmission of the four other ones
- More than five frames at the same time ⇒ at least one frame is lost

- Addition of dedicated mechanisms to classical full duplex switched Ethernet in order to guarantee the determinism of transmissions
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The AFDX key characteristics

- Static full duplex Switched Ethernet: no CSMA/CD, no spanning tree, static 802.1D tables
- Two FIFO buffers per output port (high and low priorities)
- Traffic characterization based on the Virtual Link (VL) concept
  - Static definition of the flows which enter the network
  - Multicast path with deterministic routing
  - Mono transmitter assumption
  - Sporadic flows (\(BAG\): Bandwidth Allocation Gap)
    - Discrete values: 1, 2, 4, 8, 16, 32, 64, 128 ms
    - Traffic shaping on each emitting end system
  - Minimum \((S_{\text{min}})\) and maximum \((S_{\text{max}})\) frame lengths for each VL
  - \(BAG\) and \(S_{\text{max}}\) define the maximum bandwidth allocated to a VL
    - Example: \(BAG = 16\) ms and \(S_{\text{max}} = 128\) bytes \(\Rightarrow 64000\) bits/s
  - Scheduling of VLs on end systems \(\Rightarrow\) (bounded) jitter
Worst-case end-to-end delay on an AFDX network

- Three parts in the delay
  - Transmission times on links (known): link bandwidth, frame size
  - Switching latency (known)
  - Waiting time in FIFO queues (unknown)

- Upper bound on the waiting time in FIFO queues
  - Network calculus
    - based on modelling with arrival curves and service curves
    - Certification of AFDX on board A380 and A350
  - Trajectory approach
    - Maximum workload of interfering frames on the considered path
An industrial AFDX configuration
An industrial AFDX configuration

- 2 redundant networks, 9 switches per network, 24 ports per switch, 123 end systems
- 984 VLs, 6412 paths
- 100 Mbits data rate
- BAG and maximum frame length

<table>
<thead>
<tr>
<th>Bag (ms)</th>
<th>Number of VL</th>
</tr>
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<tbody>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>8</td>
<td>78</td>
</tr>
<tr>
<td>16</td>
<td>142</td>
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<tr>
<td>32</td>
<td>229</td>
</tr>
<tr>
<td>64</td>
<td>220</td>
</tr>
<tr>
<td>128</td>
<td>255</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$S_{\text{max}}$ (bytes)</th>
<th>Number of VL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-150</td>
<td>561</td>
</tr>
<tr>
<td>151-300</td>
<td>202</td>
</tr>
<tr>
<td>301-600</td>
<td>114</td>
</tr>
<tr>
<td>601-900</td>
<td>57</td>
</tr>
<tr>
<td>901-1200</td>
<td>12</td>
</tr>
<tr>
<td>1201-1500</td>
<td>35</td>
</tr>
<tr>
<td>&gt; 1500</td>
<td>3</td>
</tr>
</tbody>
</table>
An industrial AFDX configuration

- Length of VL paths

<table>
<thead>
<tr>
<th>Number of crossed switches</th>
<th>Number of paths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1797</td>
</tr>
<tr>
<td>2</td>
<td>2787</td>
</tr>
<tr>
<td>3</td>
<td>1537</td>
</tr>
<tr>
<td>4</td>
<td>291</td>
</tr>
</tbody>
</table>

- Load of the links

![Load of the links diagram]
Need for QoS support in embedded networks

- In the context of avionics
  - AFDX is purely event-triggered with no global synchronization
  - AFDX only support two priority levels which are not significantly used
  - AFDX is lightly loaded ⇒ share the network with non avionic flows ⇒ non avionic flows should not disturb avionic ones

- In the context of automotive
  - Heterogeneous flows with heterogeneous constraints ⇒ needs for differentiated service disciplines
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Ethernet AVB (IEEE Audio Video Bridging)

- Set of standards that provide the specification for time-synchronized low latency streaming services through IEEE 802.1 networks
  - IEEE 802.1AS: timing and synchronization for time-sensitive applications
    - Variation of IEEE 1588
    - Precise time synchronization with an accuracy better than 1 \( \mu s \)
  - IEEE 802.1Qat: stream Reservation protocol
    - Reservation of resources along the path between the talker and the listener
  - IEEE 802.1Qav: forwarding and queueing enhancements for time-sensitive streams
    - Different classes for time-critical and non-time-critical traffic
    - Two Stream Reservation classes for time-critical traffic: SR-A and SR-B
    - Credit-Based Shaper (CBS) to prevent traffic bursts
    - SR-A and SR-B can start transmission only if their credit is not negative
Ethernet-AVB Credit-Based Shaper

- Credit decreases at sendslope rate during the transmission of frames of the associated class.
- Credit increases at idleslope rate when frames of the associated class are waiting or no frame of the associated class is waiting, but credit is negative.
- Credit reset to 0 when credit greater than 0 and no frame of the associated class is waiting.
Scheduled traffic over AVB

- Ongoing project within the Time Sensitive Networking Task Group
  - Procedures to suspend the transmission of a non-time critical frame and allows for one or multiple critical frames to be transmitted
  - Policies to support scheduled traffic
- Scheduled traffic is a traffic class that
  - Requires to schedule frame transmission based on time
  - Is time-sensitive and requires a bounded latency
    - Ex: delay-sensitive command and control traffic which requires deterministic and very small delays
Latency assessments for time-sensitive traffic

- Without interfering traffic
  - Maximum latency of a time-sensitive frame mainly depends on
    - Transmission time of the time-sensitive frame on links (computed from the frame size)

Good news since time-sensitive flows typically feature small frames
Latency assessments for time-sensitive traffic

- With interfering traffic
  - Maximum latency of a time-sensitive frame also depends on
    - Maximum size of the interfering frames, due to non-preemptive scheduling at the egress port of each network device

Bad news since non time-sensitive frames might be large
Time-Aware Shapers (TAS)

- Time-Aware Shapers have been defined to deal with interfering frames.
- Based on the knowledge of the next arrival time for scheduled time-sensitive frames.
  - Synchronization is provided by IEEE 802.1AS.
  - Time-sensitive traffic typically follows a regular pattern.
- TAS blocks any lower priority frame that would interfere with an upcoming time-sensitive frame.
  - Time-sensitive traffic mapped onto SR Class A.

\[\text{TS latency}\]

\[\text{S1} \rightarrow \text{S2} \rightarrow \text{ES2} \]

\[\text{TS latency}\]
An alternative solution to support scheduled traffic

- TAS alone are not enough to support scheduled traffic
  - Only two real-time traffic classes (A and B) ⇒ time-sensitive control traffic often has to share Class A with other real-time traffic
  - It might interfere significantly with time-sensitive frames
  - Increased effect due to credit-based shaping

- AVB-ST (Scheduled Traffic) approach
  - A new ST on top of AVB SR class A and B
  - ST traffic is handled in a separate queue
  - ST traffic does not undergo credit-based shaping
  - Offline scheduling of ST frames (a priori known periods and frame sizes)
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TTEthernet very short summary

- Time is shared between time-triggered and event-triggered traffic
- Three types of traffic
  - TT flows: scheduled flows, possible thanks to the clock synchronization
  - Rate Constrained flows (RC): very similar to AFDX VLs
  - Best Effort flows (BE)
- Priority order: TT, then RC, then BE
- RC and BE frames might interfere with TT frames
- Three solutions when a RC or BE frame is ready before a TT slot
  - RC or BE frame starts transmission and might delay TT frame
  - RC or BE frame starts transmission and is preempted if TT frame is ready
  - RC or BE frame starts transmission only if there is enough time before TT slot
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Some open issues

- Comparative analysis of candidate switched Ethernet solutions
- Design and analysis of heterogeneous network architectures
  - Interconnection of fieldbuses through an Ethernet backbone
- Probabilistic analysis
  - Up to now, certification process based on guaranteed delay upper bound
  - Worst-case delay scenario: very rare event
  - Leads to over-dimensioning of the network
  - Do we really need a guaranteed upper bound?
  - Is it ok if the probability to exceed the deadline is $10^{12}$?
  - Avionics functions designed to behave correctly even if some (rare) frames are lost $\Rightarrow$ computing a probabilistic upper bound makes sense
Thank you for your attention