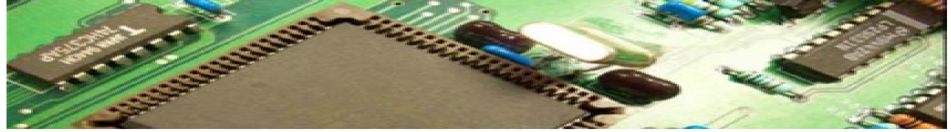

FTT-SE: Towards flexible/open Cyber-Physical Systems

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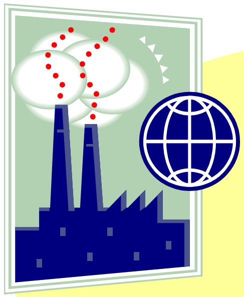
Unifying frameworks



Networked Monitoring and Control

Internet of Things

Vehicular Networks

Cyber-Physical Systems

...

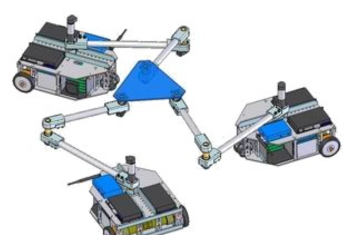
Anything that involves **computer-environment I**

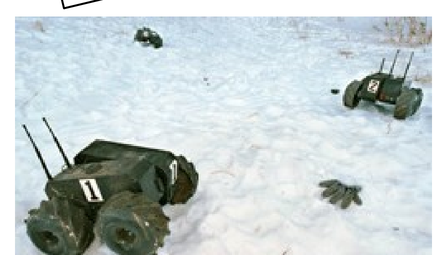
(Distributed) Embedded Systems

Netwo
Embed
System

Focus on

- **Real-time**
- Modeling
- Adaptation
- Control





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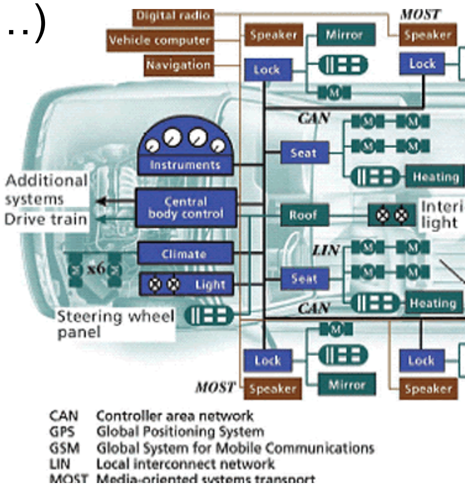
Cyber-Physical Systems

- **Complex structure**
  - **High heterogeneity** (functionality, requirements, resources…)
  - **Variable composition** (versions, modes, connections…)
  - ...



- Need to **be robust** with respect to
  - **Topology changes** (reconfigurations, node crashes, …)
  - **Changes in available resources** (energy, bandwidth…)
  - **Denial-of-service** (malfunctioning nodes, malicious actions…)
  - **Intrusion** (unauthorized accesses or actions…)
  - ...

How to design these systems ??

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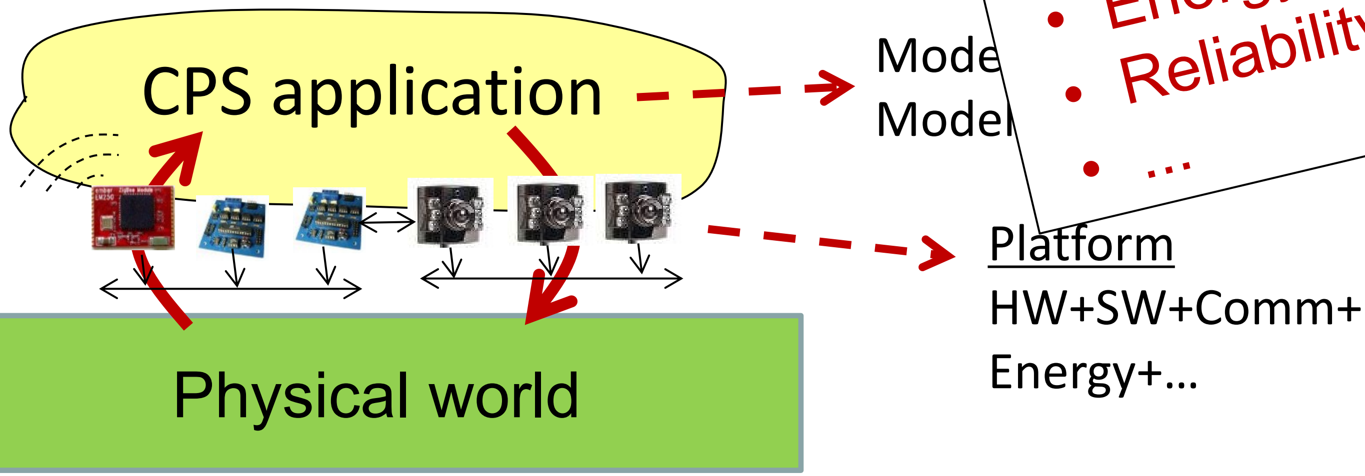
Cyber-Physical Systems: *internals*

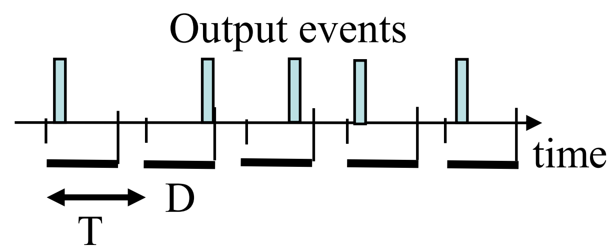
- The **platform determines** the degree of
  - **accuracy** in the knowledge of the physica
  - **control** over the physical world



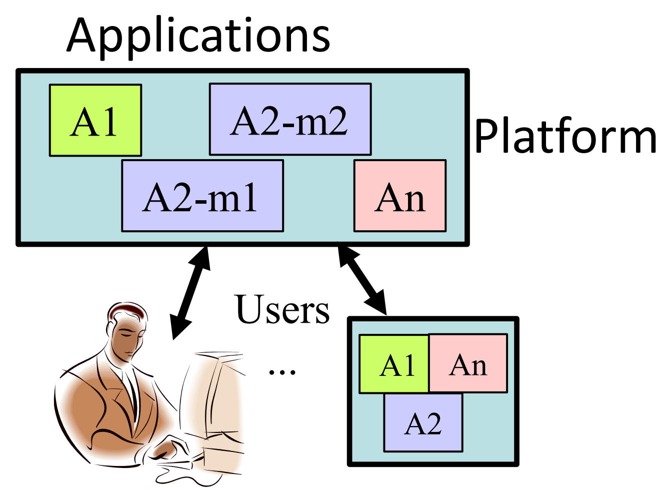
- **Timing**
- Quantization
- Linearity
- Energy
- Reliability
- …

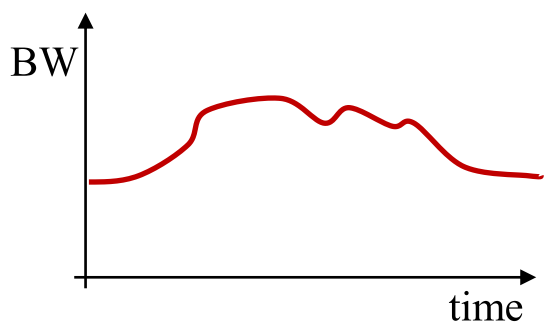
Real-time capable platforms

- Amenable to **modeling of timing behavior**
  - **Bounded** and **computable delays**
    - → **real-time guarantees**



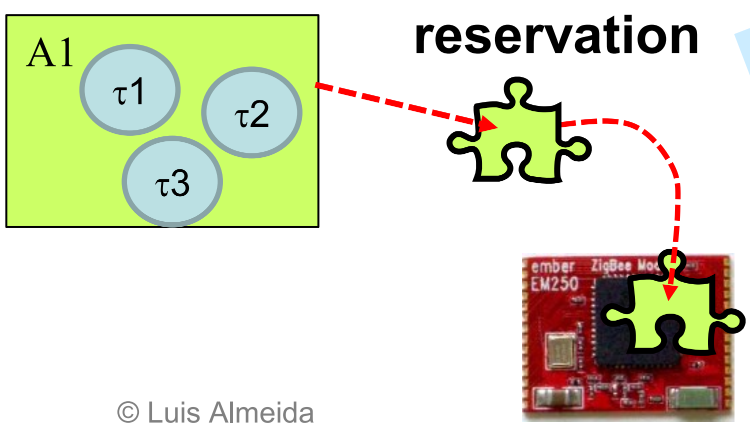
- While supporting **multiple** and **varying**
  - applications, users, operating conditions, ...
- And being **resource efficient**
  - bandwidth, energy





Resource reservation paradigm

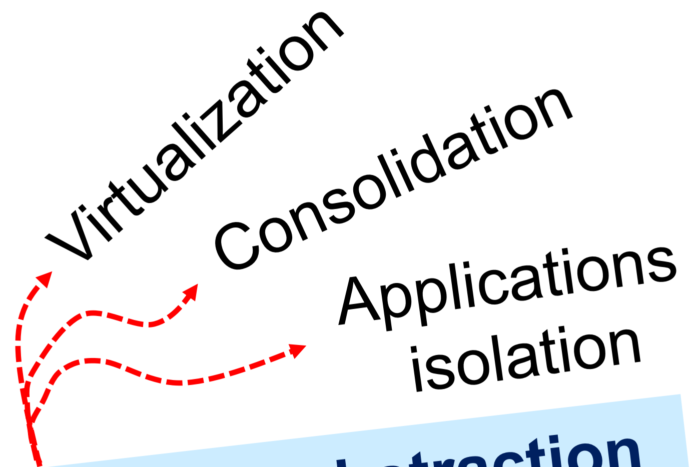
- Define the **application non-functional requirements**
  - Performance & **time behavior** → BW, rate, latency, jitter
  - Possibly with multiple levels of service
- Define **how much** of each **resource is needed**
  - To cover the requirements (**demand**)
  - For each service level
  - Reducing the **application** to an **interface** (or a set)



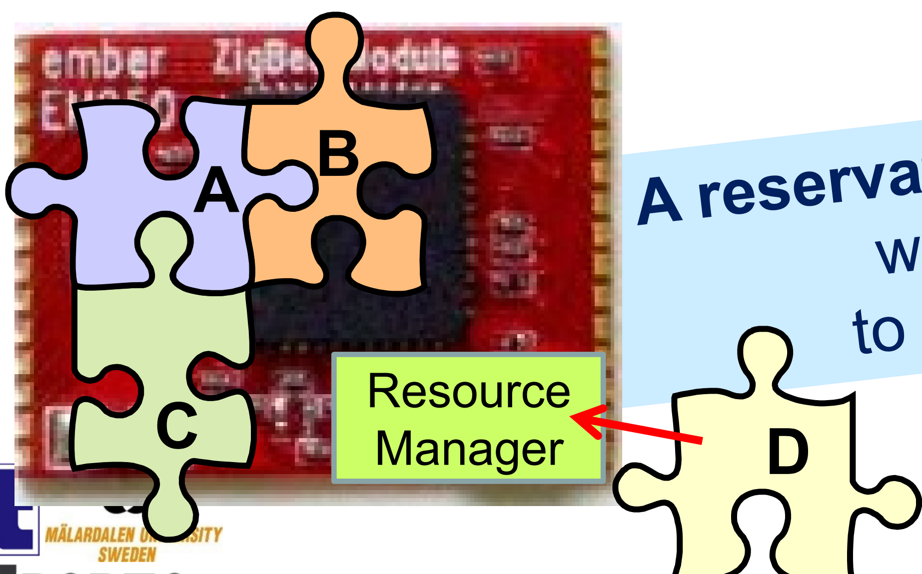
CPU, network, memory, battery…

Resource reservation paradigm

- **Resource Manager** needed
  - **Provide reservations** (partitions...)
    - that **match demand**
  - **Keep track** of accepted reservations
    - to respect **resource capacity**



A reservation is a **platform abstraction** with **fractional capacity** to match a certain demand



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Networks for CPS

- **Are current networks adequate?**
  - **Real-Time communication** technologies
    - well developed for **(static) DES**
    - focused on **latency** and **isolation**
  - **General purpose communication** technlologies
    - well developed for **large networks** (Cloud / Internet)
    - essentially **best-effort** (particularly in access networks)
    - focused on **openness**, **scalability** and **throughput**

CAN EtherCAT
TTEthernet ...
PROFINET-IRT

MPLS
SDN TCP/UDP
RSVP-TE
LTE
5G ...

Unifying effort needed, towards **scalable, open** and **efficient real-time communication**

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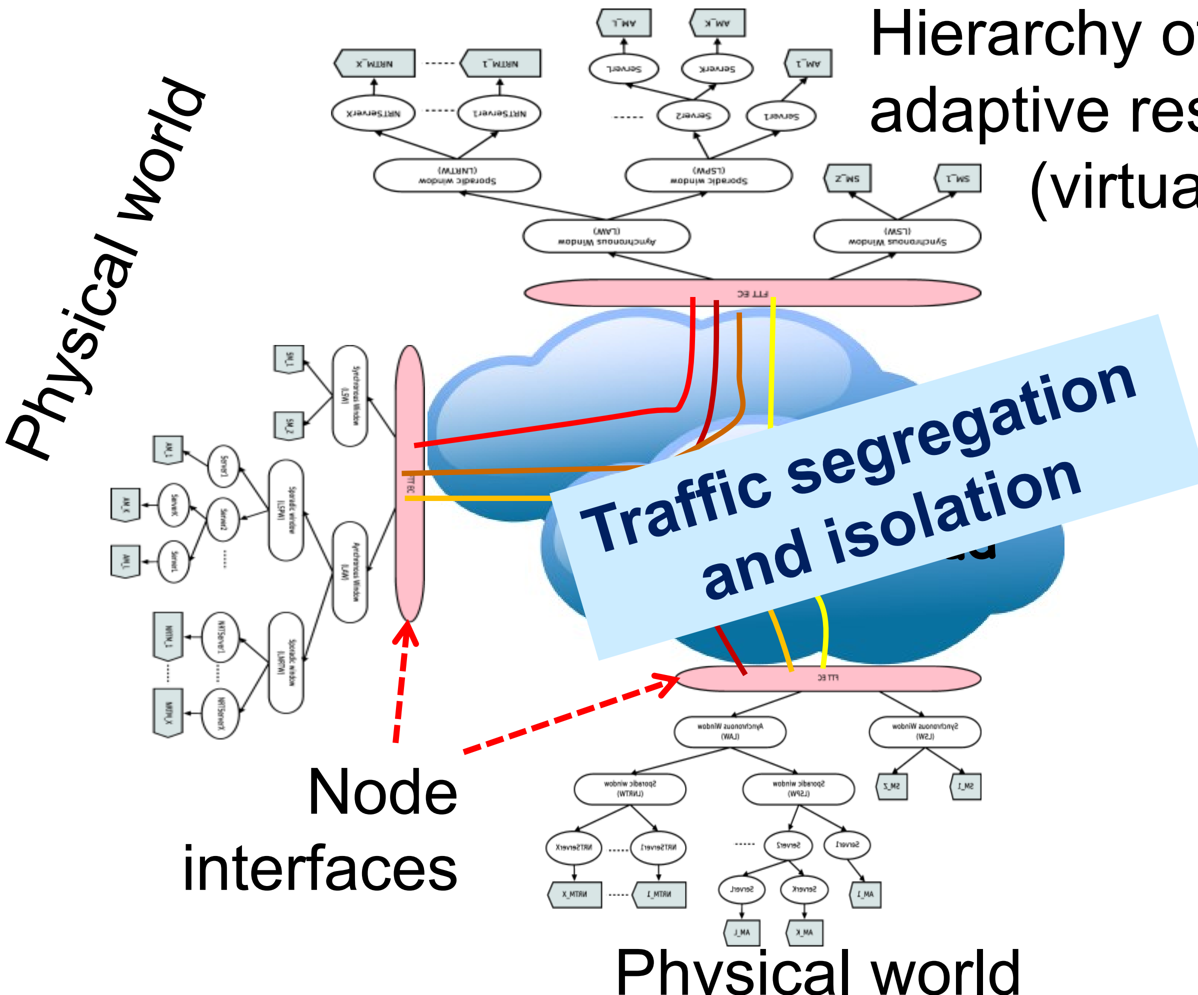
A Network Challenge for CPS

The real-time enabled cloud



Hierarchy of
adaptive reservations
(virtual channels)

Our approaches

- **Centralized resource manager**
  - The **Flexible Time-Triggered** paradigm
    - Isochronous / asynchronous traffic
    - **Any on-line traffic scheduling** supported
  - Building on top of **Linux-TC**
    - Asynchronous traffic, only

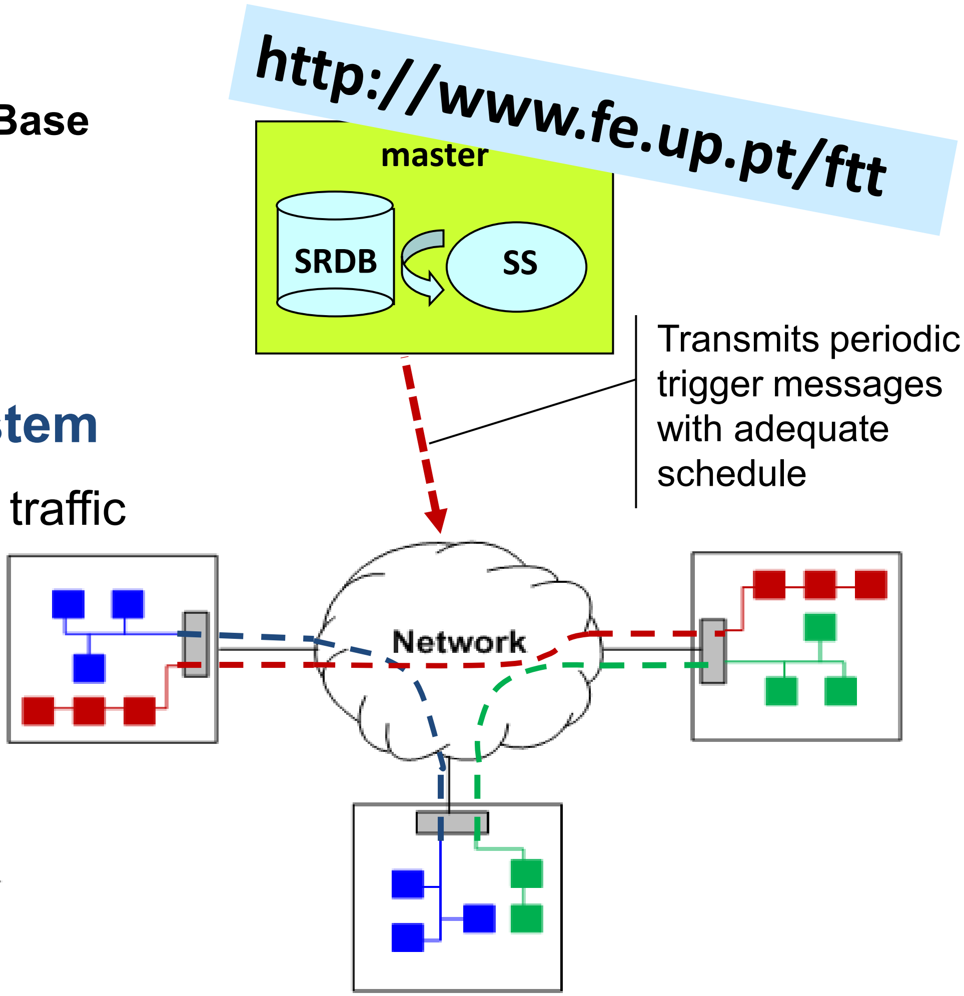
F-T-T-

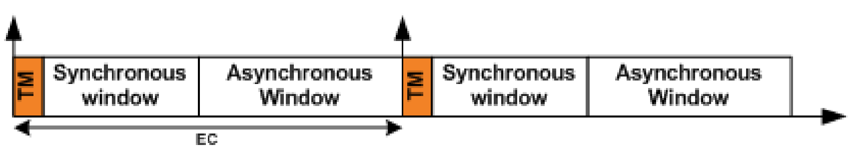
Flexible Time-Triggered architecture

- **Distributed resource manager**
  - The **Reconfigurable and Adaptive TDMA** protocol
    - Used in wireless networks on top of CSMA-CA
    - Isochronous / asynchronous traffic

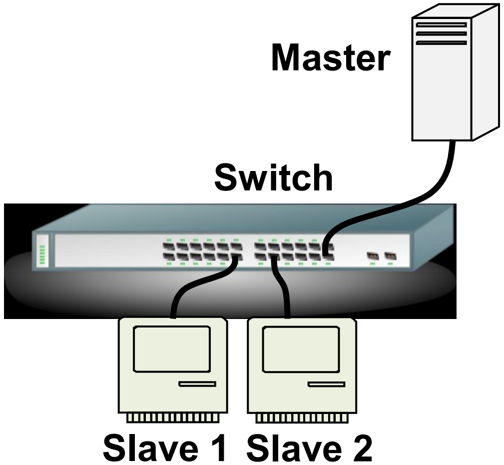
The *Flexible Time-Triggered* paradigm

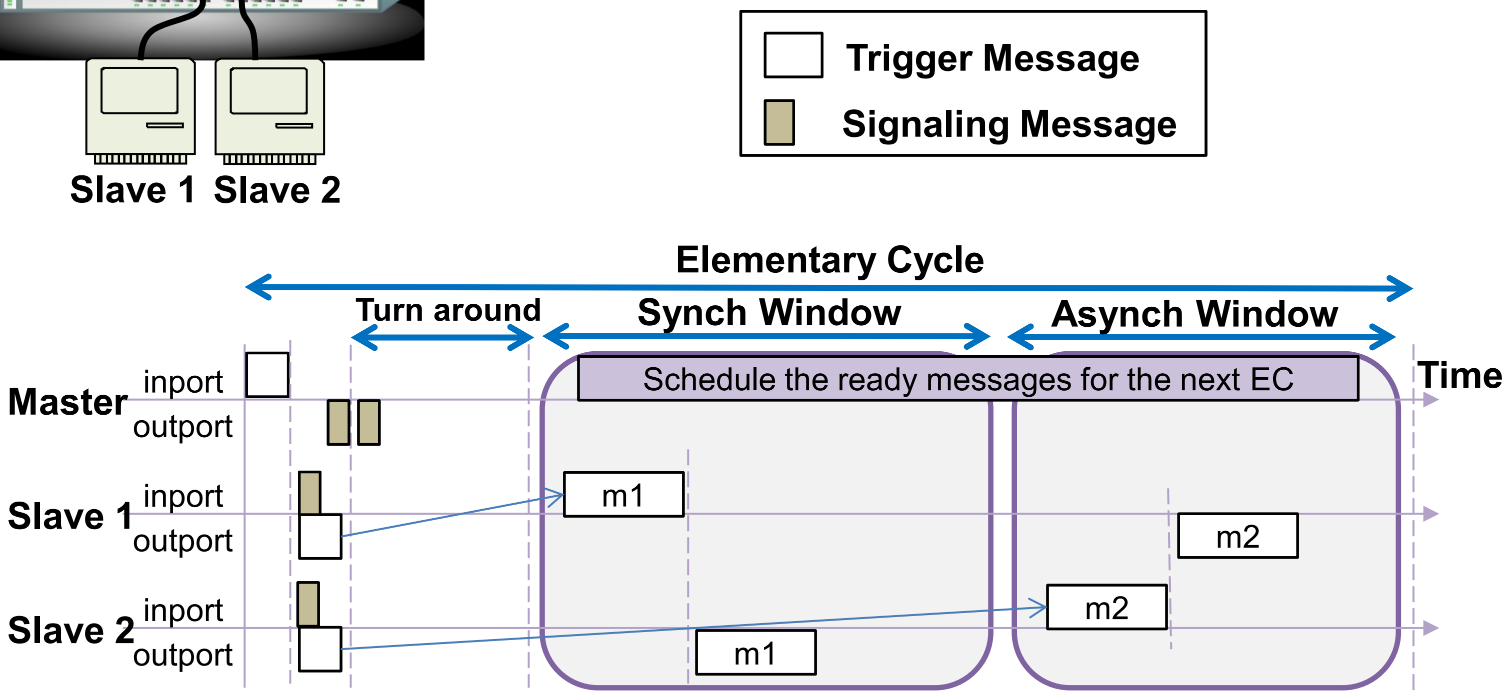
- **Concentration of operational information**
  - **Master node** with
    - **System Requirements Data Base**
    - **Online System Scheduler**
  - **Consistent and prompt** channels management
- **Emanating triggers to the system**
  - **Isochronous / asynchronous** traffic
  - **Any scheduling** policy





FTT-SE: FTT applied to *Switched Ethernet*



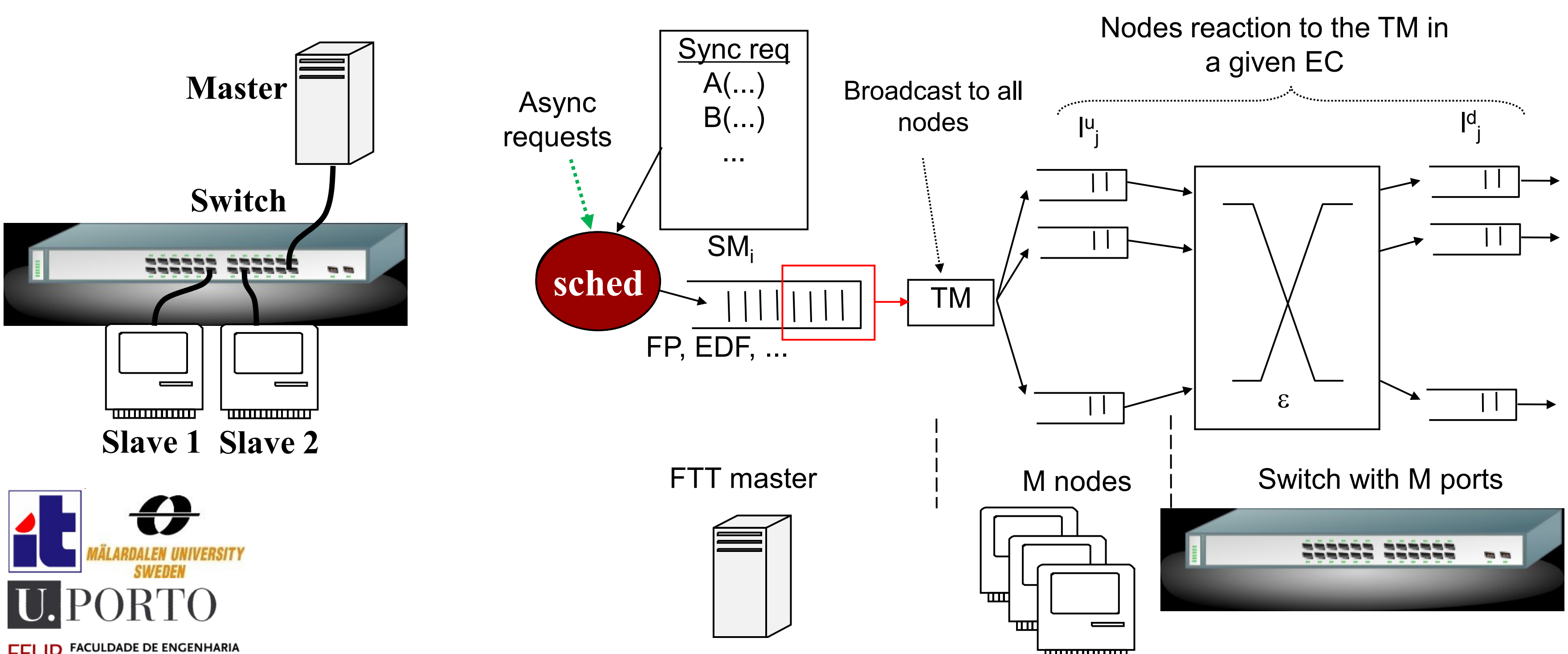


FTT-SE traffic scheduling

- Integrated scheduler for all traffic types

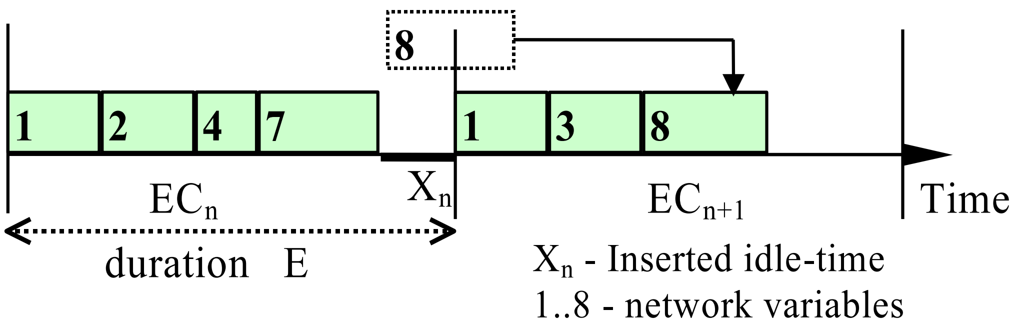
Sync: SRT = $\{SM_i: \mathbf{SM_i(C_i, D_i, T_i, O_i, Pr_i, S_i, \{R^1_i .. R^{ki}_i\})}, i=1..N_S\}$

Async: ART = $\{AM_i: \mathbf{AM_i(C_i, D_i, mit_i, Pr_i, S_i, \{R^1_i .. R^{ki}_i\})}, i=1..N_A\}$



FTT-SE traffic scheduling

- **Basic scheduling model:**
  - **Schedule within partitions** with **strict time bounds**
  - Use **inserted idle-time** (X)
    - There is **no blocking**
    - **Any analysis for preemptive scheduling** can be used with **inflated transmission times** (C')

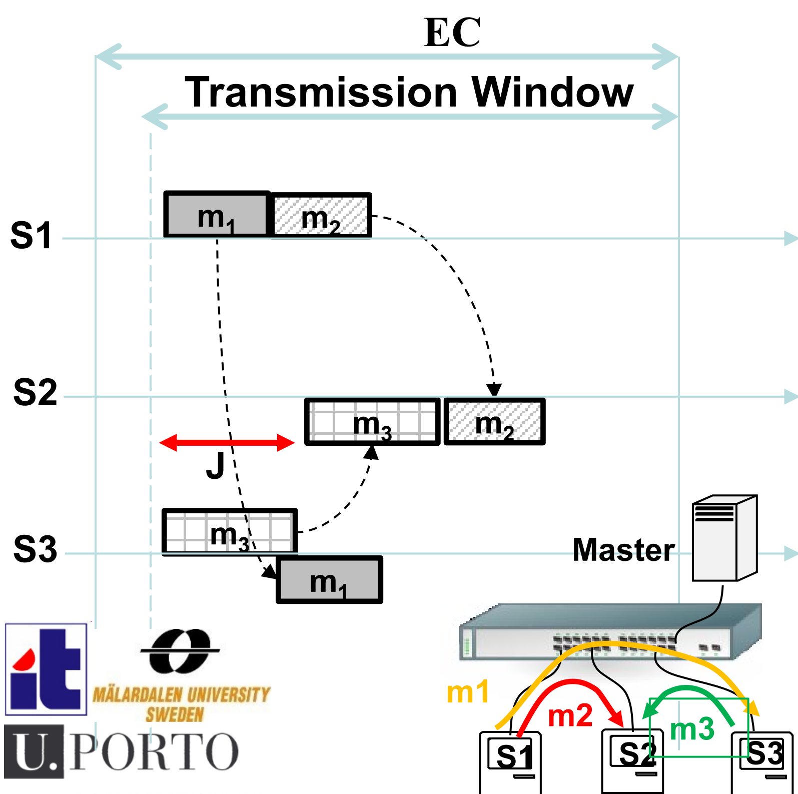


$$C_i' = C_i * \frac{E}{E - X_{max}}$$

Inserted **idle-time** compensation factor

FTT-SE traffic scheduling

- **Utilization bounds for on-line BW management**
  - To be **applied to each link separately**
  - Interference in the uplinks appears at the downlinks as **release jitter** (J)

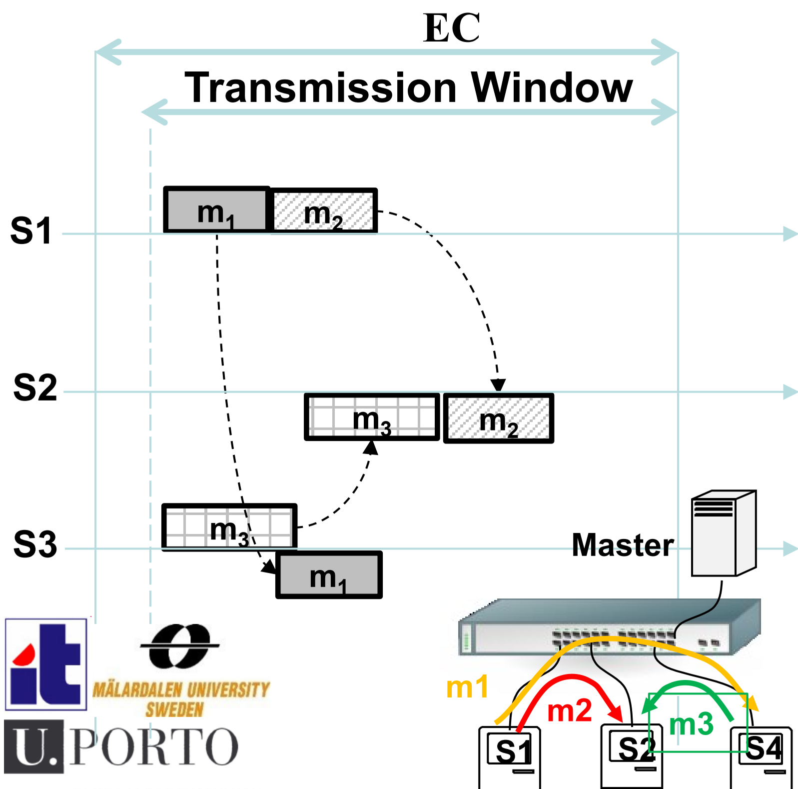


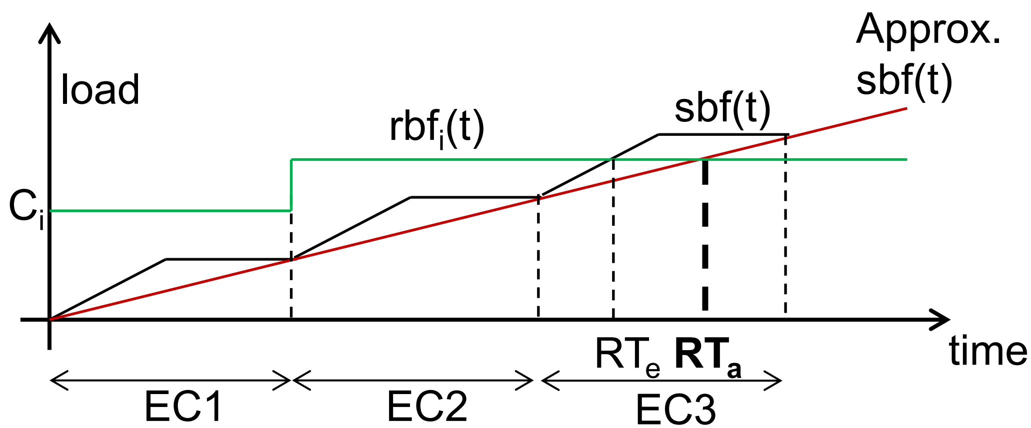
$$\forall_{i=1..n} \sum_{j=1}^{i} \frac{C_j}{T_j} + \frac{\max_{j=1..i} J_j}{T_i} \leq U^{\text{lub}}_{RM,EDF}(i)$$

$$\sum_{i=1}^{n} \frac{C_i}{T_i} + \frac{\max_{i=1..n} J_i}{T_1} \leq U^{\text{lub}}_{RM,EDF}(n)$$

FTT-SE traffic scheduling

- **Response-time analysis**
  - request bound funtion (**rbf**): Max. submitted load & interference
  - supply bound function (**sbf**): Min. effective network capacity





$$RT_i = \min t : rbf_i(t) = sbf(t)$$

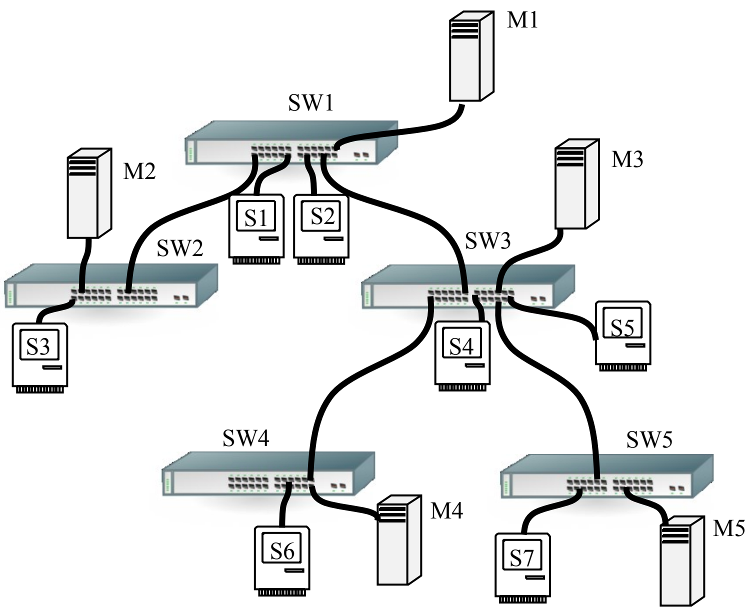
$$rbf_i(t) = C_i + \left(SFD_i + \Delta\right) + WI_i(t)$$

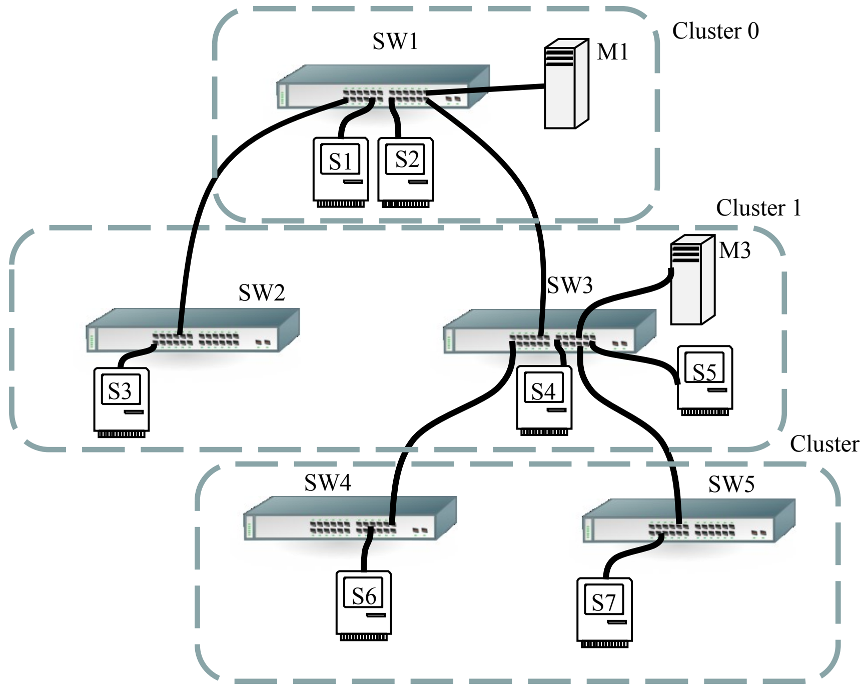
Switching delay

hp(i) interference

Multi-switch FTT-SE architectures

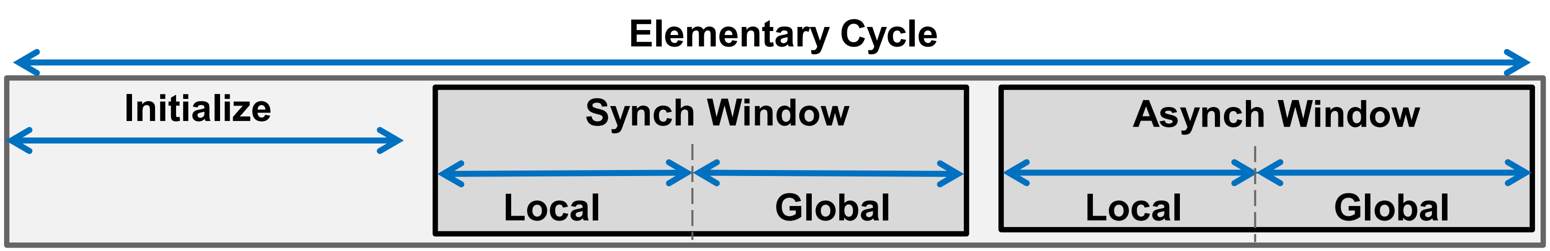
Single-Master





Hybrid

Multi-Master



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Multi-hop Delay Analysis

- request bound function

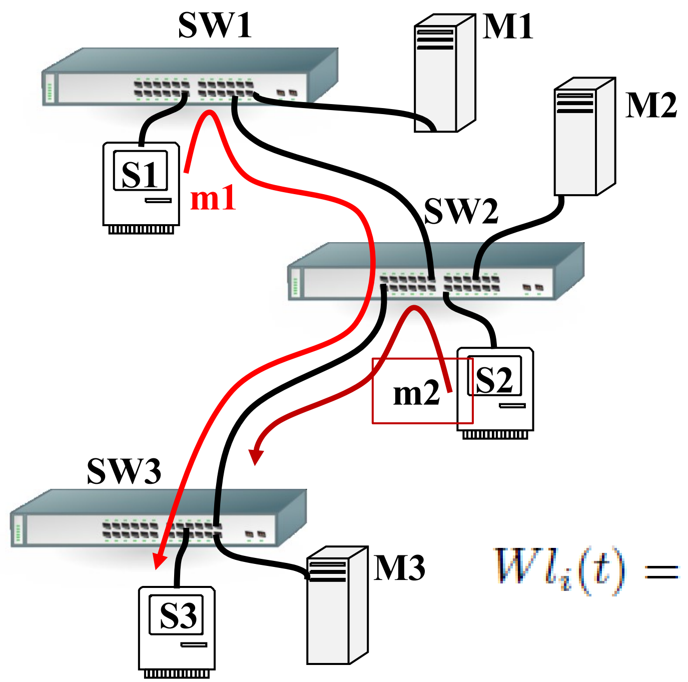
$$rbf_i(t) = \underbrace{C_i + sn_i \times (SFD_i + \Delta)}_{\text{Switching delay}} + \underbrace{Wl_i(t)}_{\text{Shared Link Delay}} + \underbrace{Wr_i(t)}_{\text{Remote Link Delay}}$$

- supply bound function

$$sbf(t) = \left(\frac{\overbrace{BW}^{\text{Window duration}} - \overbrace{I}^{\text{Idle Time}}}{\underbrace{EC}_{\text{EC duration}}}\right) \times t$$

Traffic Delay Analysis

- ## Shared Link Delay



m2 has higher priority than m1, thus causing delay

$$Wl_i(t) = \sum_{\substack{\forall j \in [1,n], j \neq i \\ \wedge\, R_j \cap R_i \neq 0 \\ \wedge\, m_j \in hp(m_i) \\ \wedge\, m_j \in WT(m_i)}} \lceil \frac{t}{T_j} \rceil (C_j + sn_j \times (SFD_j + \Delta))$$

Improved Response-Time Analysis

- ## Revisiting the Shared Link Delay

$$Wl_i(t) = \sum_{\substack{\forall j \in [1,n], j \neq i \\ \wedge R_j \cap R_i \neq 0 \\ \wedge m_j \in hp(m_i) \\ \wedge m_j \in WT(m_i)}} \lceil \frac{t}{T_j} \rceil (C_j + sn_j \times (SFD_j + \Delta))$$

$$Wl_i(t) = \sum_{\substack{\forall j \in [1,n], j \neq i \\ \wedge R_j \cap R_i \neq 0 \\ \wedge m_j \in hp(m_i) \\ \wedge m_j \in WT(m_i)}} \lceil \frac{t}{T_j} \rceil (C_j) + Is_i(t)$$

G contains an upper bound on the number of switching delays from each message that contribute to the Shared Link Delay at time *t*

$$Is_i(t) = \sum_{l=1}^{z(t)} G_i^{sort}(t)[l] \qquad z(t) = \lceil \frac{t}{EC} \rceil$$

We select the first *z(t)* elements (which are the largest) for each *t*

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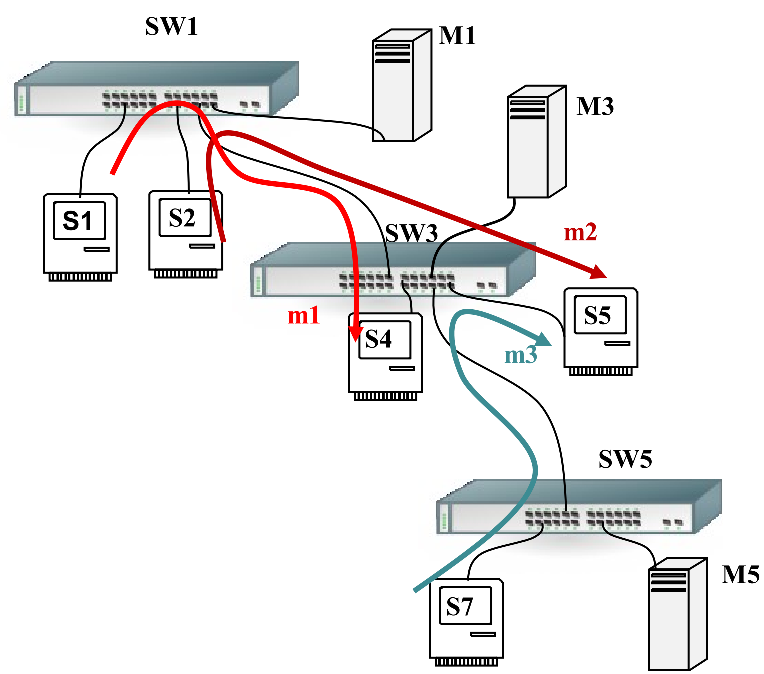
Traffic Delay Analysis

- ## Remote Link Delay

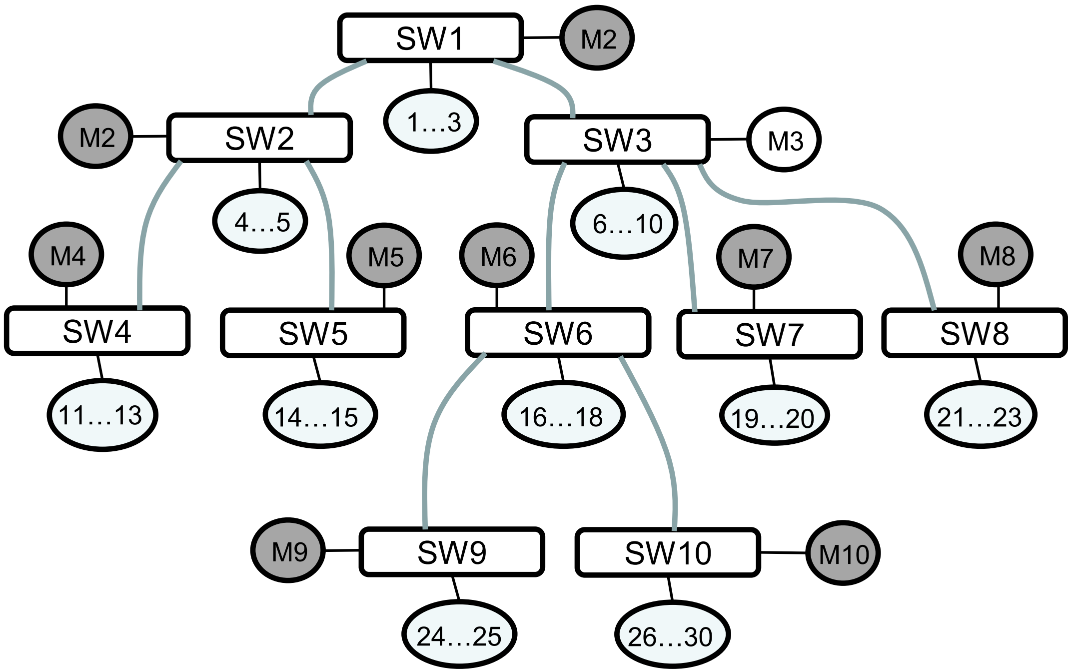


Scheduling of **m1 can push m3 via m2**, despite m1 and m3 not sharing links.

$$Wr_i(t) = \sum_{\substack{\forall k,j\in[1,n],k\neq j\neq i \\ \wedge\ R_k\cap R_j\neq 0 \wedge\ R_k\cap R_i=0 \wedge\ R_j\cap R_i\neq 0 \\ \wedge\ m_k\in hp(m_j) \\ \wedge\ m_k\in WT(m_j)}} \lceil \frac{t}{T_k} \rceil (C_k)$$

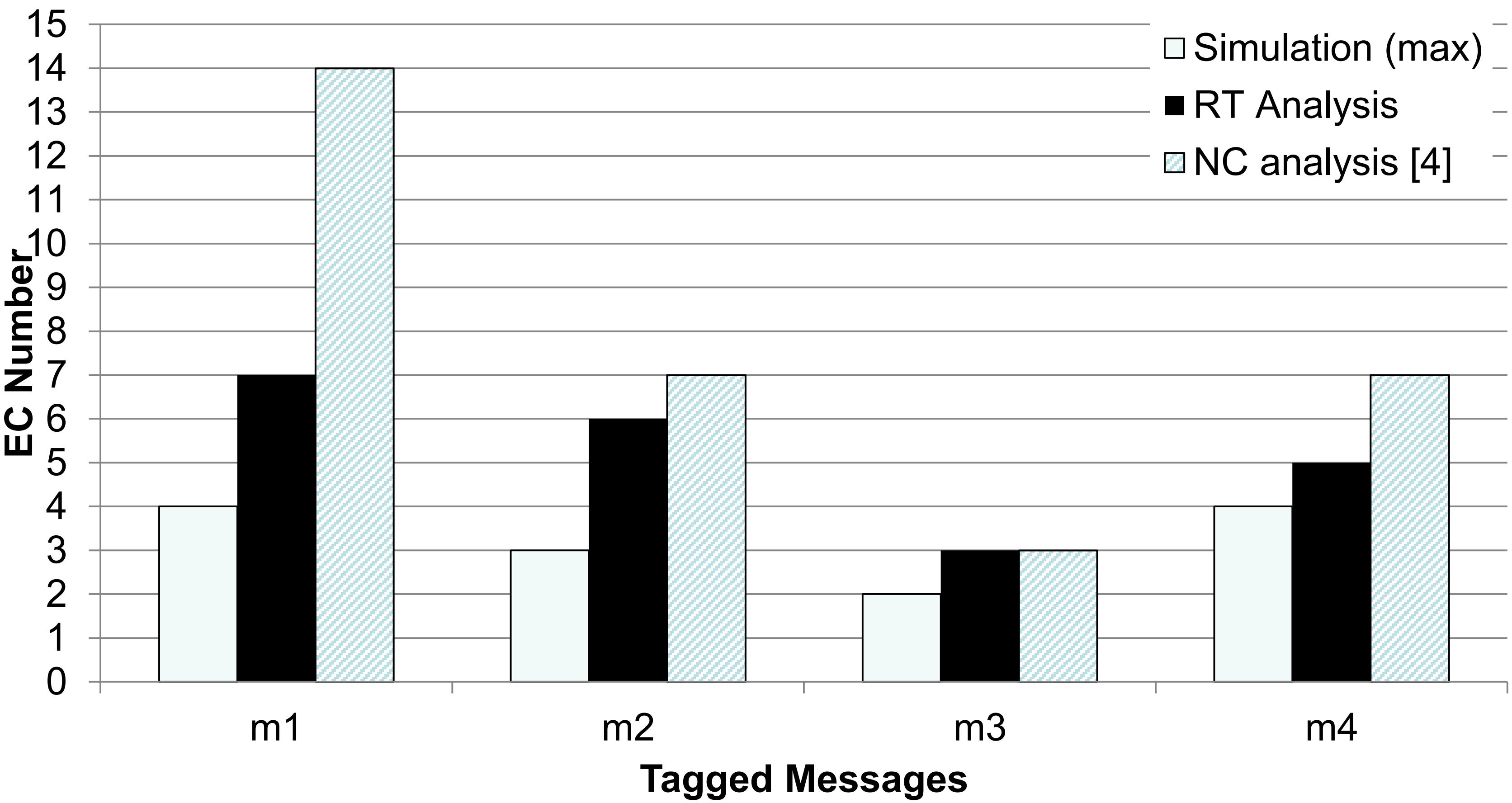
Assessing the Analysis

- 10 switches
- 30 nodes
- EC = 10ms
- C = 100Mbps
- Sync local win = 1.5ms
- Sync global win = 2ms
- Async local win = 1.5ms
- Async global win = 4.4ms
- 4 clusters each 1.1ms



- 90 messages with random parameters
- Worst-case scenario for 4 messages (one per each type)
  - Long route, different activation of interfering messages, priorities

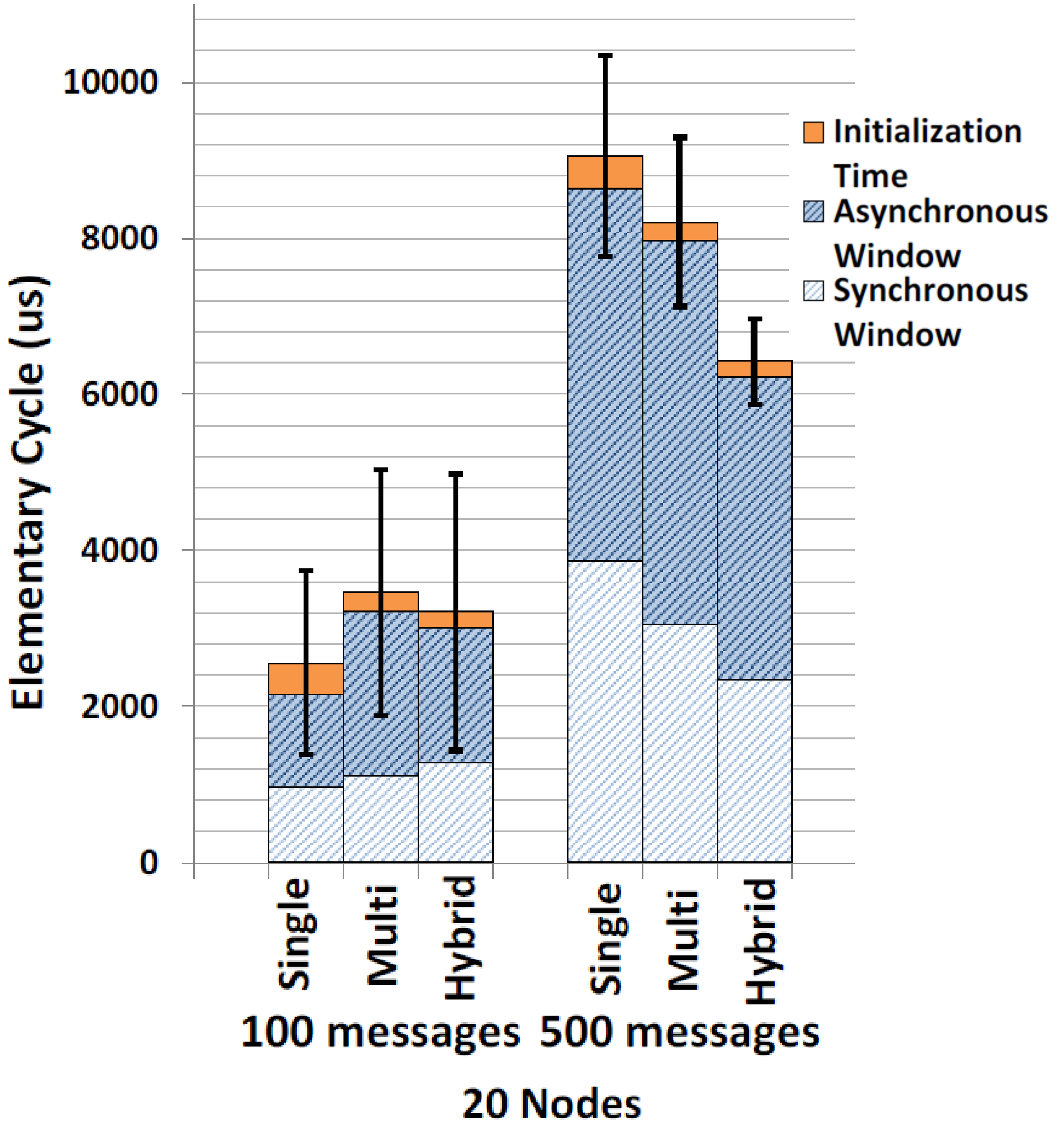
Assessing the Analysis



m1: global sync
m2: global async
m3: local sync
m4: local async

Simulated for 10,000 ECs

Comparing the multi-hop approaches



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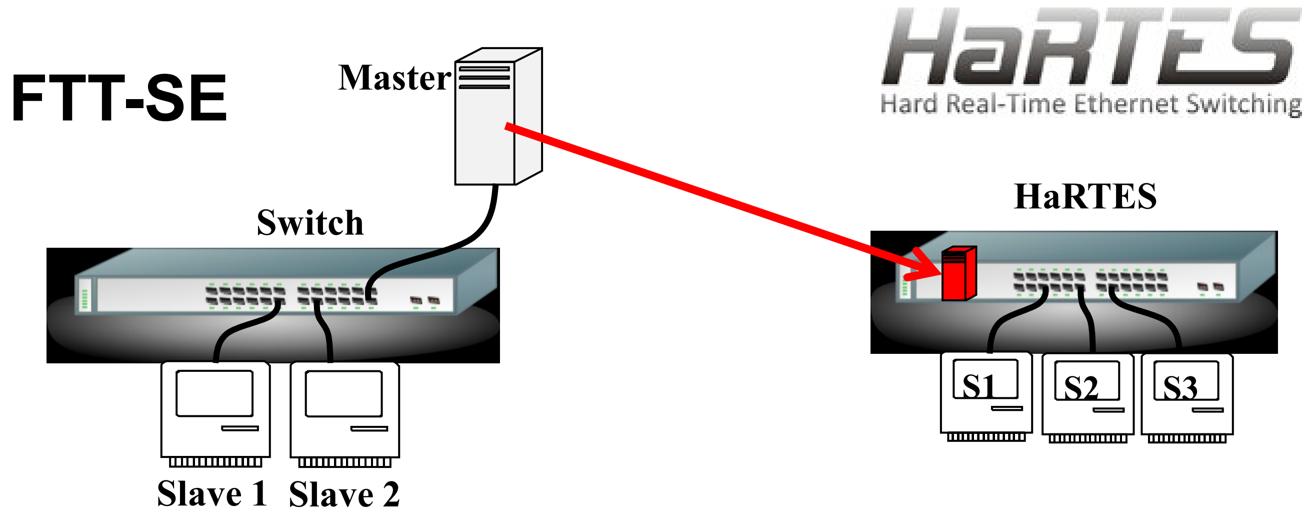
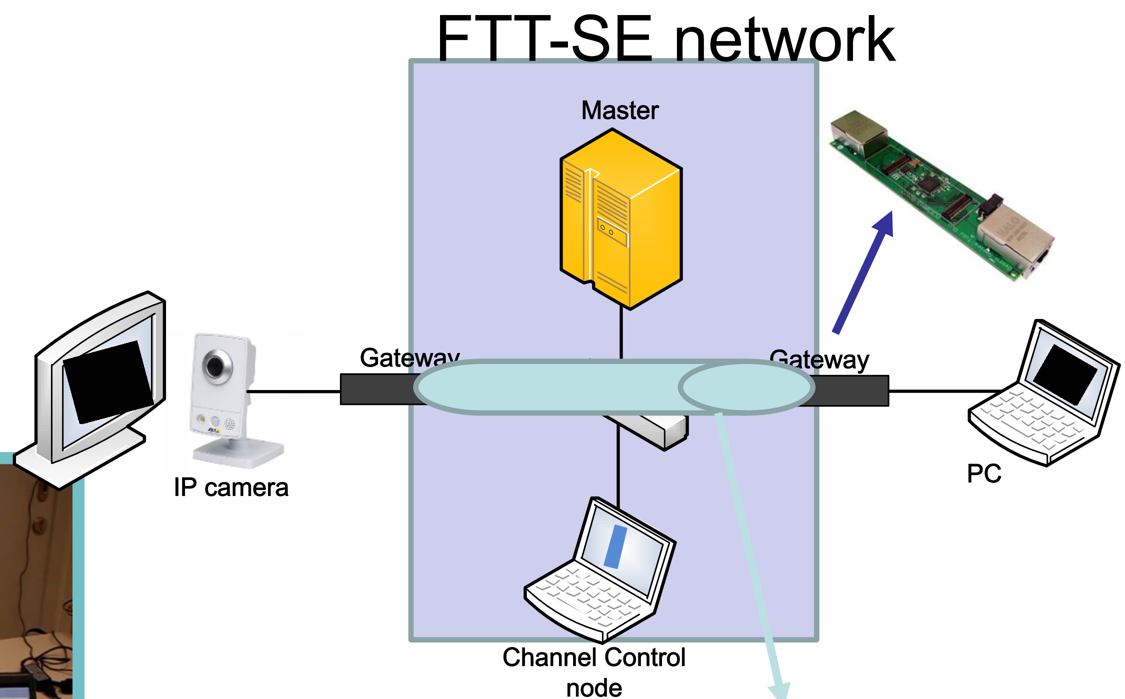
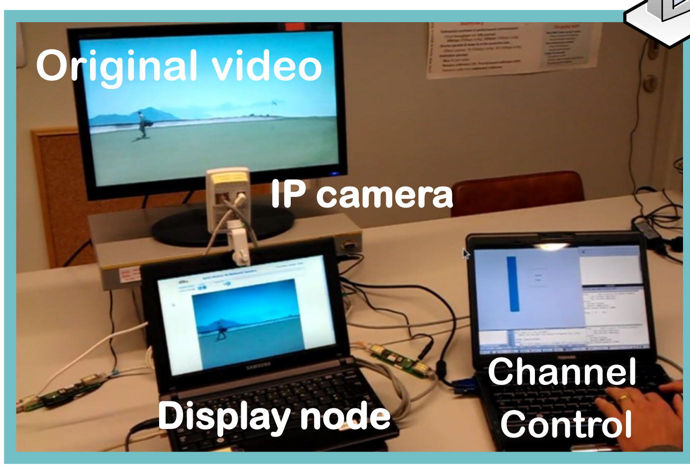
From FTT-SE to HaRTES



- **Master integrated** in the switch
- Asynchronous & NRT traffic **shaped** by the switch
- Allows direct **connection of non-FTT nodes**

Channel control in FTT-SE





Dynamically reconfigurable virtual channel with definable temporal properties
(x bytes every y seconds)

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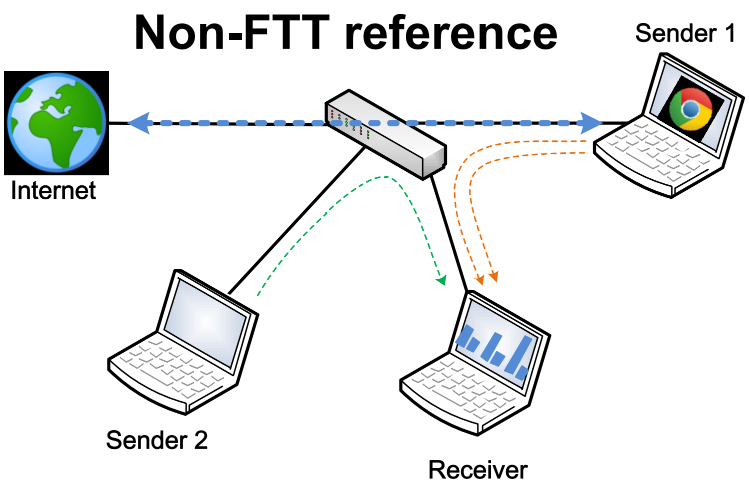
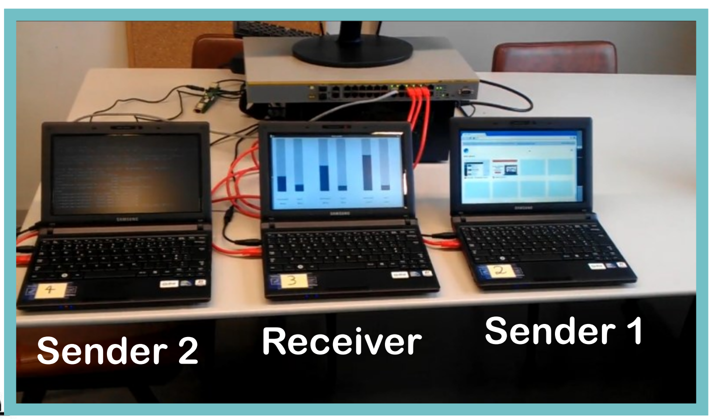
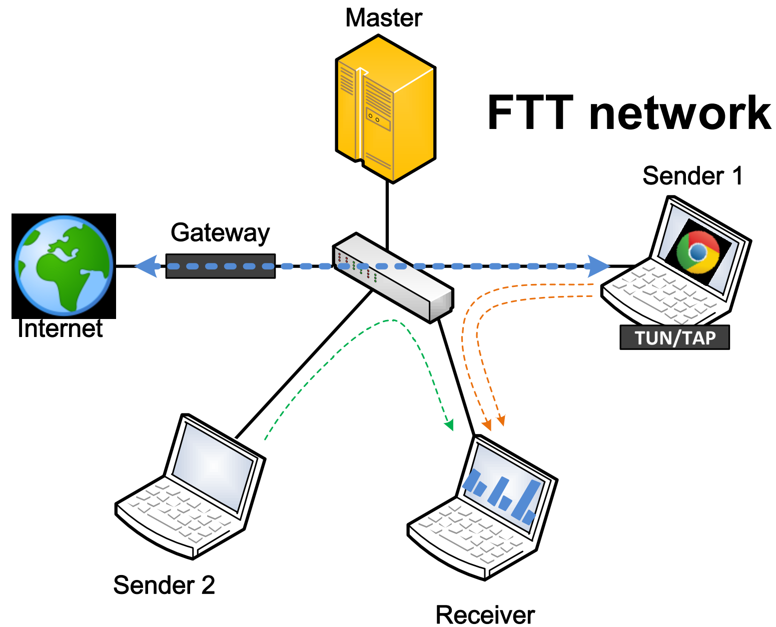
Temporal isolation in FTT-SE







Max interference on FTT-SE channels:

- With graphical interface, < 500µs
- Without graphical interface, < 50µs

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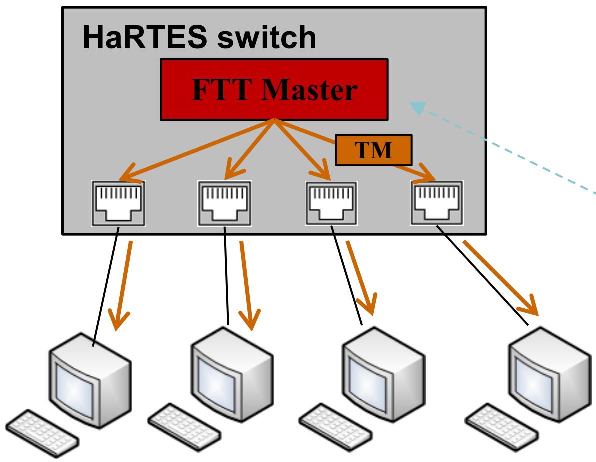
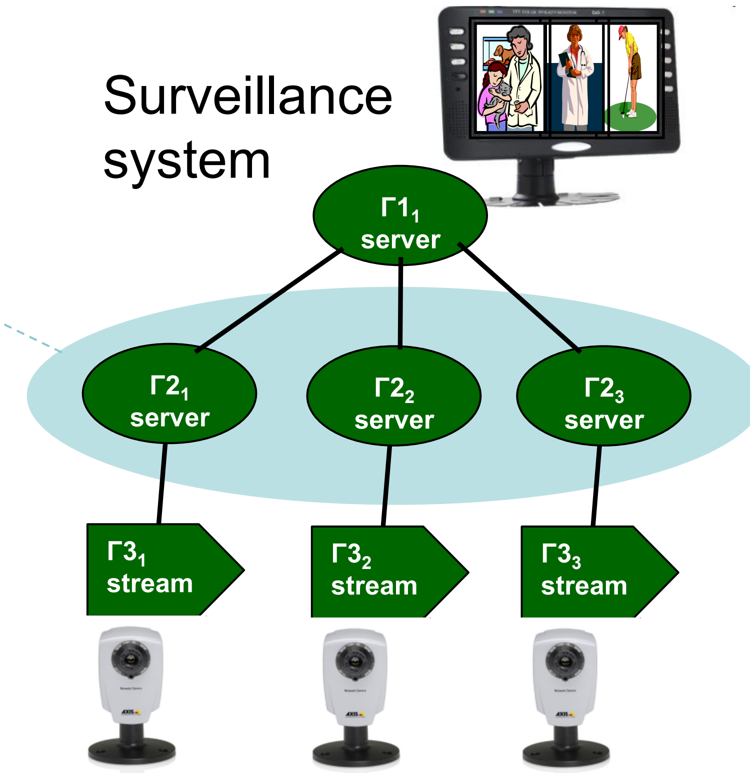
Dynamic QoS management with HaRTES





- **Only 1 server** is allowed with **more BW** at a time. **Constant total BW**

IP cameras programmed with constant frame rate

Insufficient total bandwidth → frame drops w/ TCP/IP sync

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Wrapping up

Communications in CPS

- **Resource reservations** provide **composable virtual channels**
  - Supporting **traffic segregation and isolation**
- **Efficiency requires reconfigurable and adaptive reservations**
  - Adapting channels to **actual use** and **resource availability**

- The **Flexible Time-Triggered** paradigm
  - Provides a **centralized network resource manager**
    - Enforces **reservations** with the desired **operational flexibility**
  - Can **scale to multi-master** topologies using a clustered approach

Some pending issues

- How **strong/robust** and how **relevant** is enforcing proper resource usage (the partitioning) ?
- Control over resources and flexibility management imply **extra resource needs** (BW, CPU, energy ...) !
  - Also imply extra complexity! With potential for lower reliability!
- How to divide free resource capacity among current reservations?
  - Equally, elastic models (weighted), greedy models, ...
    - How much does the application benefit?
- **Global resource reservations management protocols …**
- **New technologies...**
  - **Software Defined Networks** (wired)**, LTE, 5G** (wireless)...

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Questions?

A few acknowledgements:

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