Timing Analysis of Rate Constrained Traffic for the TTEthernet Communication Protocol

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DTU Compute
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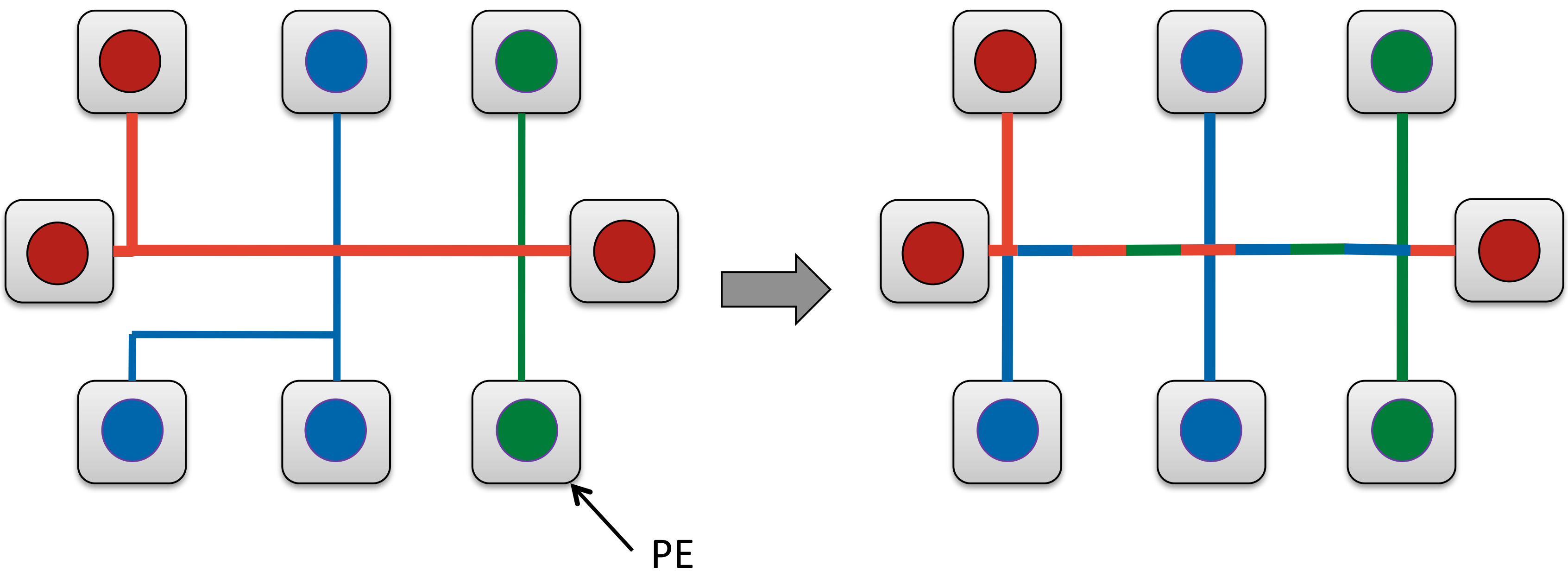
Motivation

- Real time applications implemented using distributed systems

Point-to-point connection

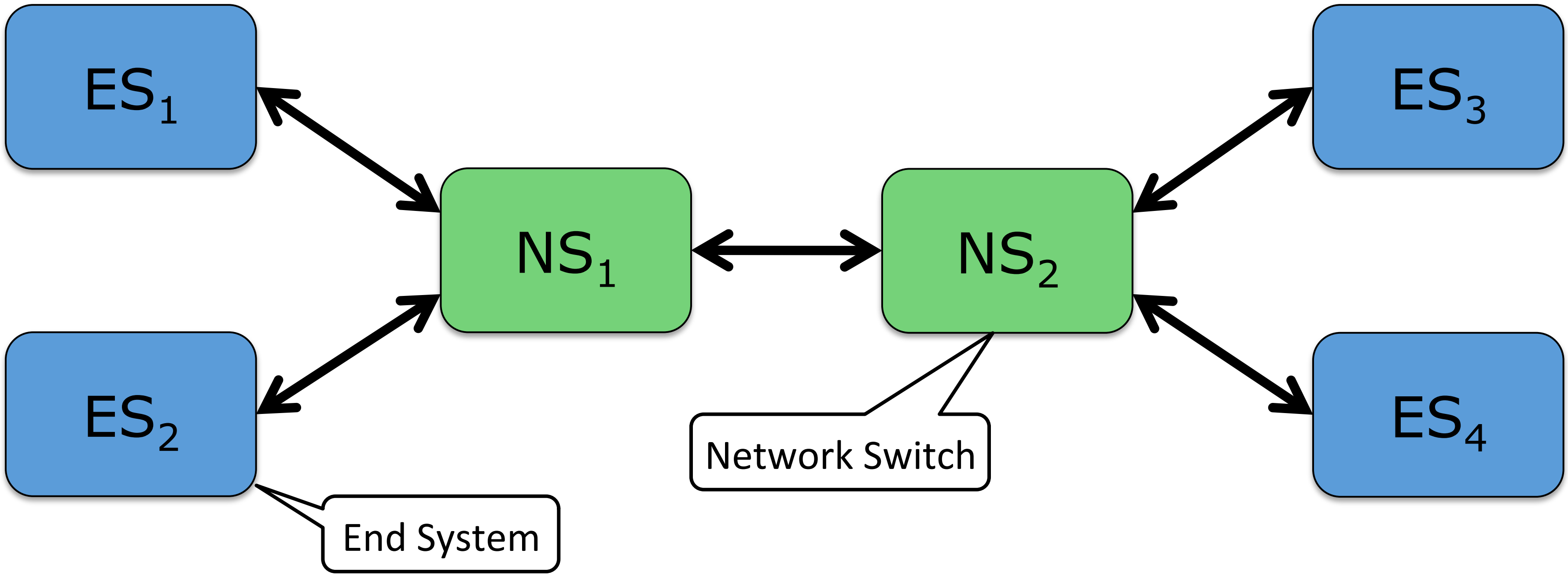
Bus connection



- Application $\mathcal{A}_1$ -- highly critical
- Application $\mathcal{A}_2$ -- critical
- Application $\mathcal{A}_3$ -- non-critical

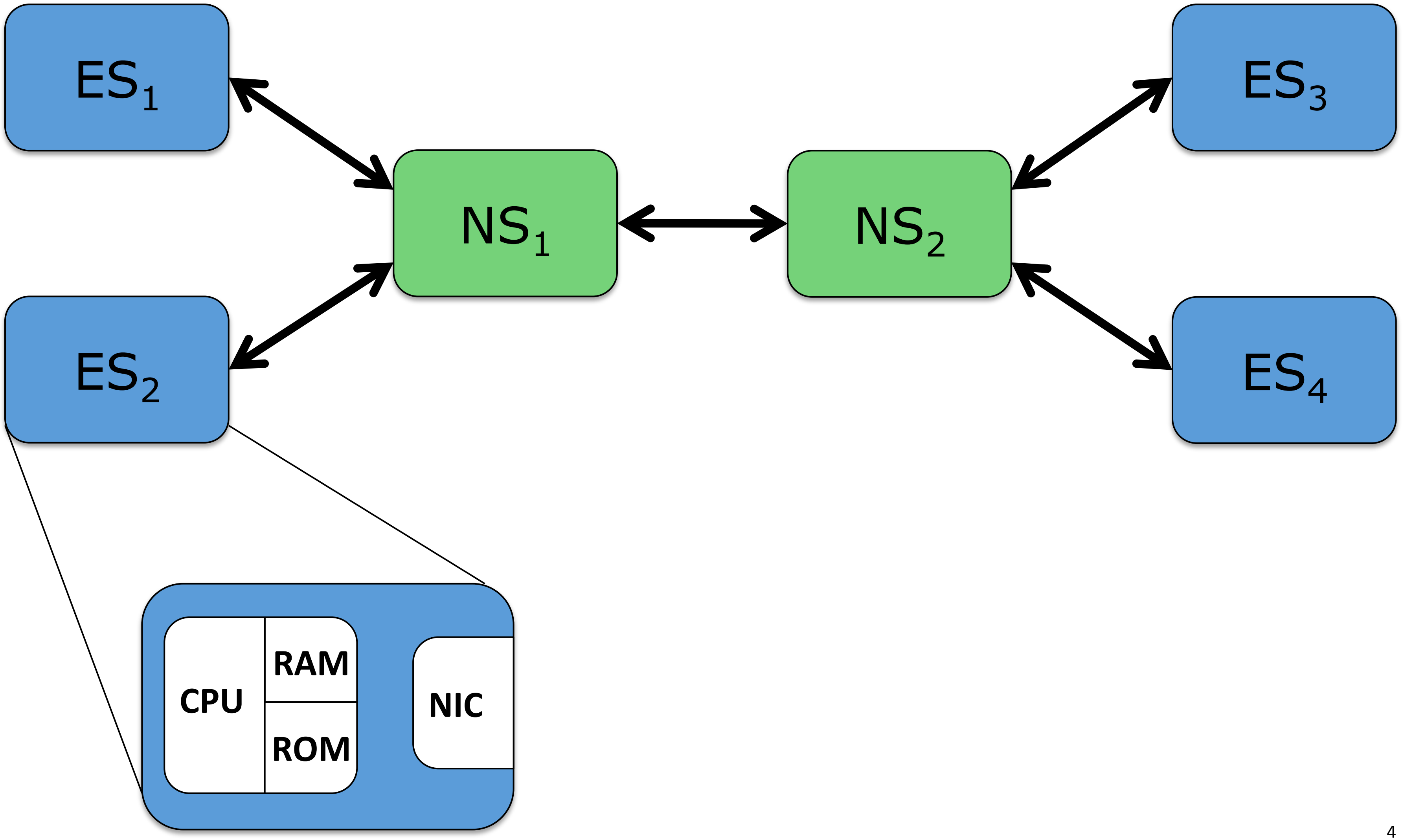
- Reduces wiring and weight
- Mixed-criticality applications share the same network

ARINC 664 p7 "Aircraft Data Network"



- Full-Duplex Ethernet-based data network for safety-critical applications

ARINC 664 p7 "Aircraft Data Network"



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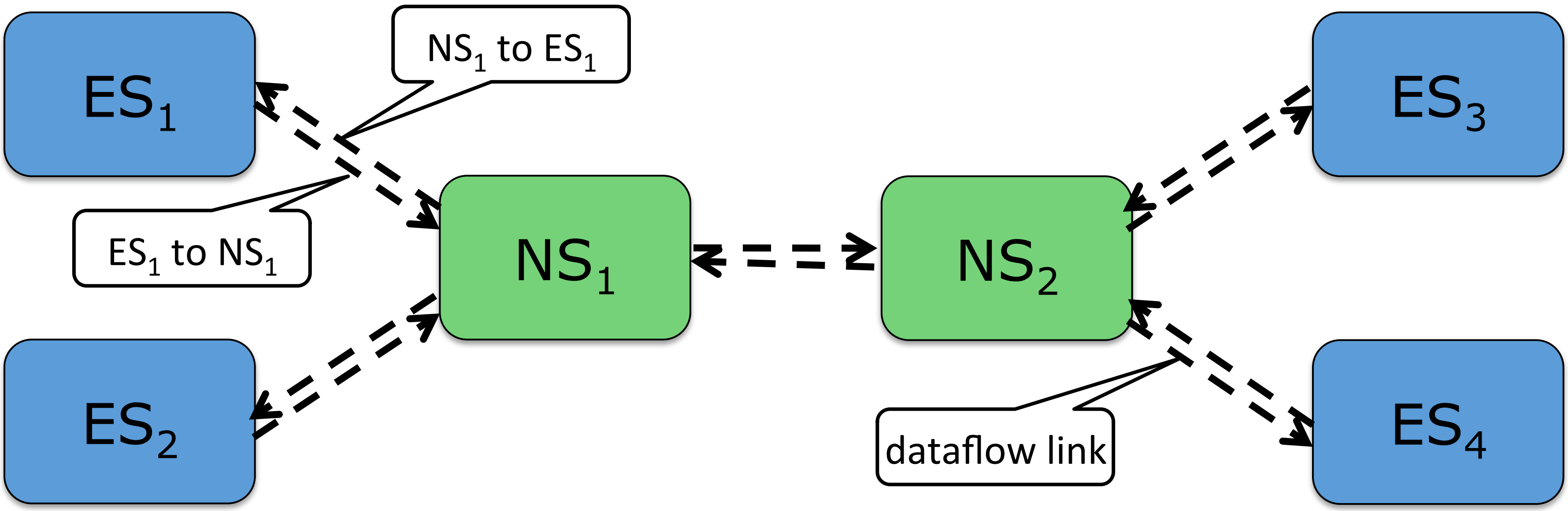

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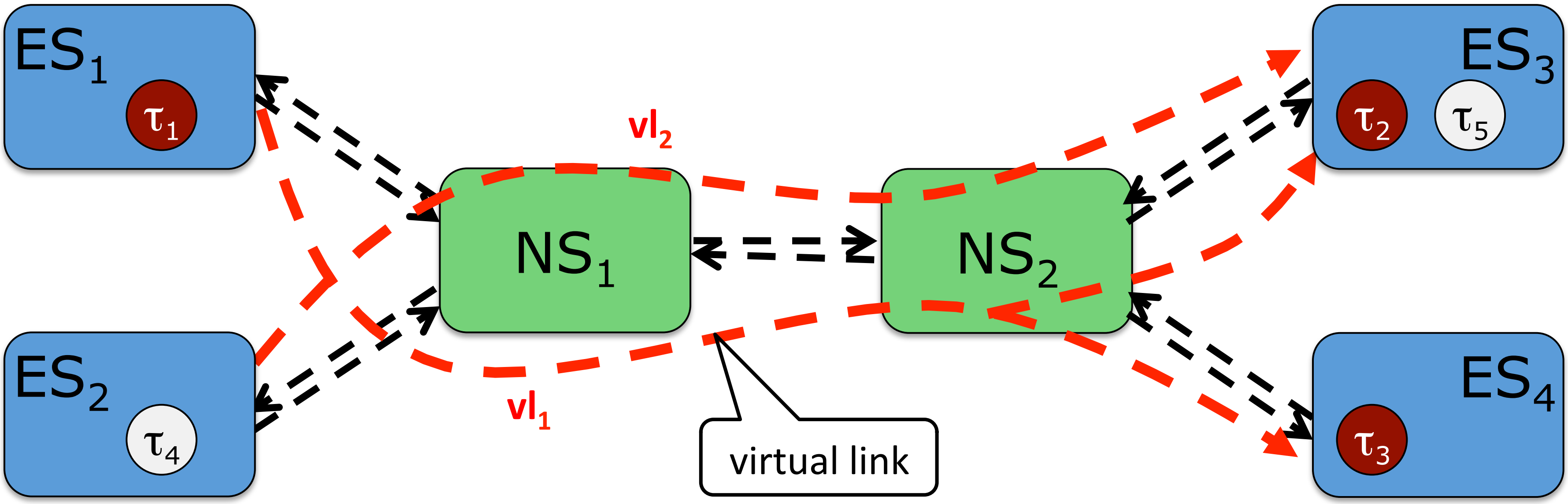

- Highly critical application $\mathcal{A}_1$: τ_1, τ_2 and τ_3
  - τ_1 sends message m_1 to τ_2 and τ_3
- Non-critical application $\mathcal{A}_2$: τ_4 and τ_5
  - τ_4 sends message m_2 to τ_5

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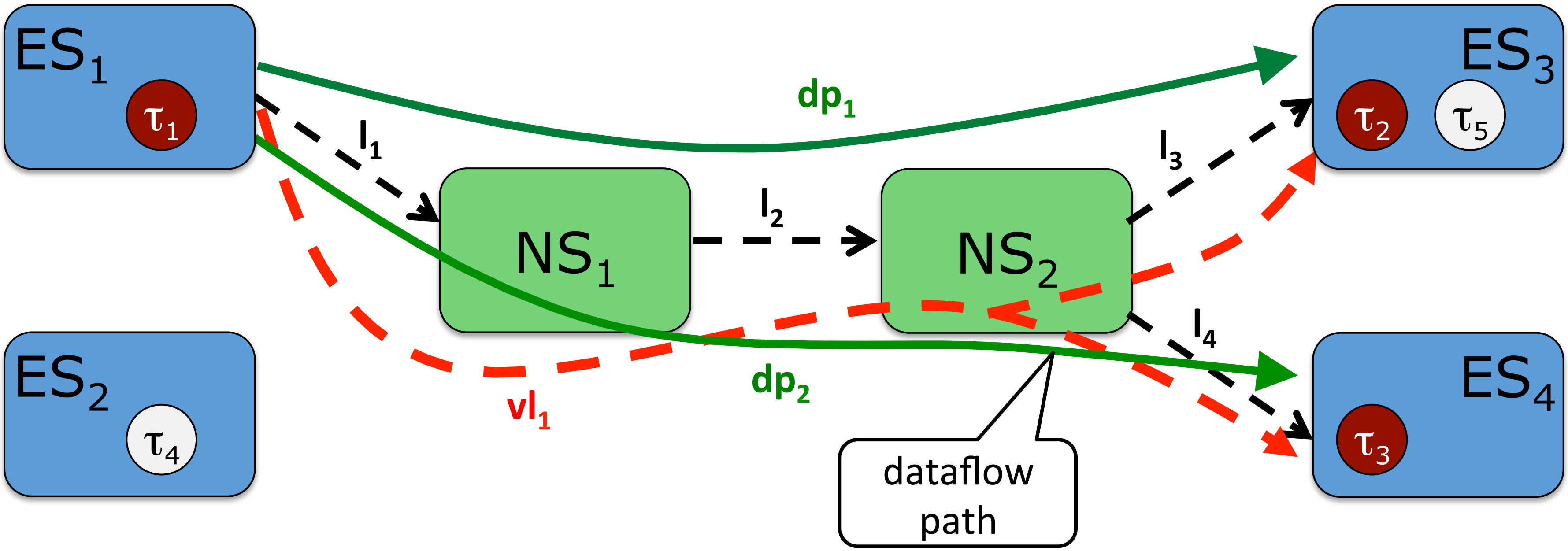

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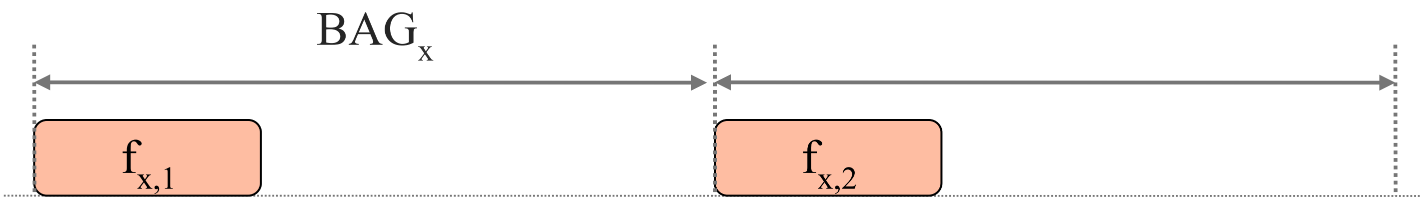
ARINC 664 p7 “Aircraft Data Network”

- Deterministic Event Triggered communication
- Separation of traffic enforced through “bandwidth allocation”
- Bandwidth Allocation Gap (BAG) – minimum time interval between two consecutive instances of a frame on a virtual link



- Maximum bandwidth assigned to virtual link vl_i

$$BW(vl_i) = f_i\,.size/BAG_i$$

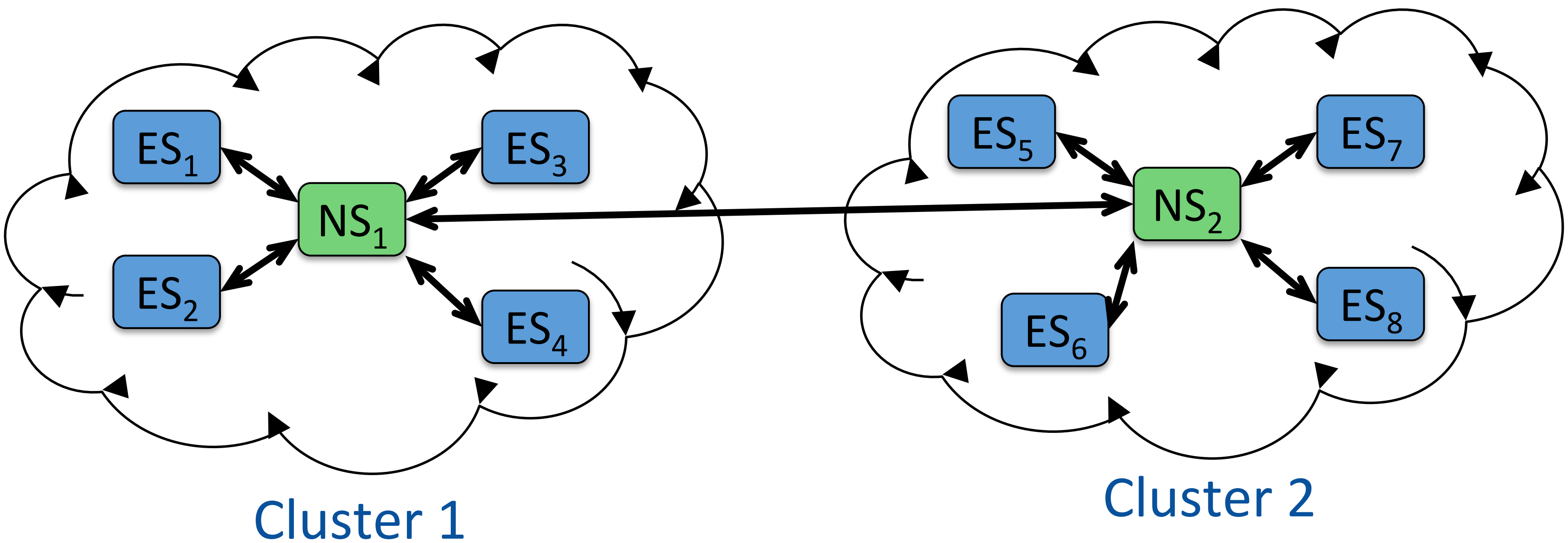
TTEthernet

- ARINC 664p7 compliant
- Traffic classes:
  - synchronized communication
    - Time Triggered (TT)
  - unsynchronized communication
    - Rate Constrained (RC) – ARINC 664p7 traffic class
    - Best Effort (BE) – no timing guarantees

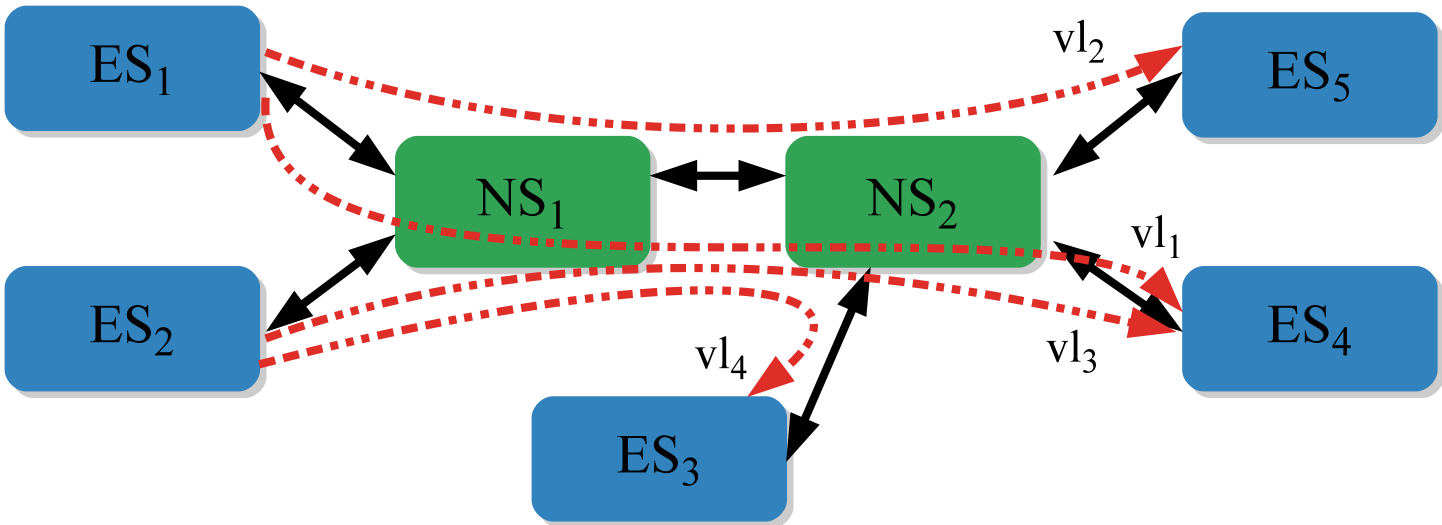
- Standardized as SAE AS 6802
- Marketed by TTTech Computertechnik AG
- Implemented by Honeywell on the NASA Orion Constellation

TTEthernet

- Composed of clusters
- Each cluster has a clock synchronization domain
- Inter-cluster communication using RC traffic



Motivation



Frame	period (ms)	deadline (ms)	size (B)	C_i (ms)	Source	Dest
$f_1 \in \mathcal{F}^{TT}$	32	32	683	3	ES_1	ES_4
$f_2 \in \mathcal{F}^{TT}$	32	32	555	2.5	ES_1	ES_5
$f_3 \in \mathcal{F}^{TT}$	32	32	808	3.5	ES_2	ES_3
$f_{10} \in \mathcal{F}^{RC}$	32	32	308	1.5	ES_1	ES_5
$f_{11} \in \mathcal{F}^{RC}$	32	32	555	2.5	ES_1	ES_5
$f_{12} \in \mathcal{F}^{RC}$	32	32	433	2	ES_2	ES_4
$f_{13} \in \mathcal{F}^{RC}$	32	32	433	2	ES_1	ES_4
$f_{14} \in \mathcal{F}^{RC}$	32	32	308	1.5	ES_2	ES_3

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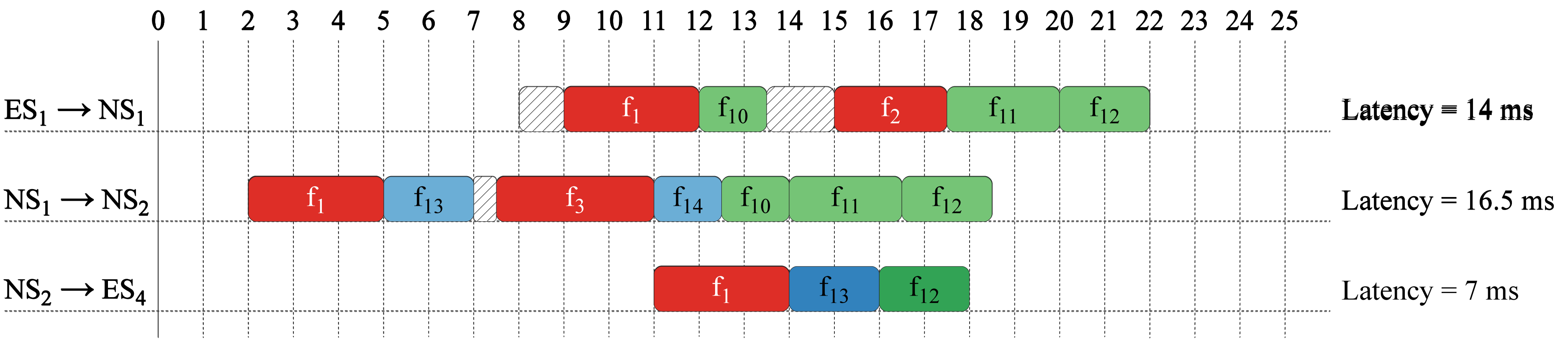
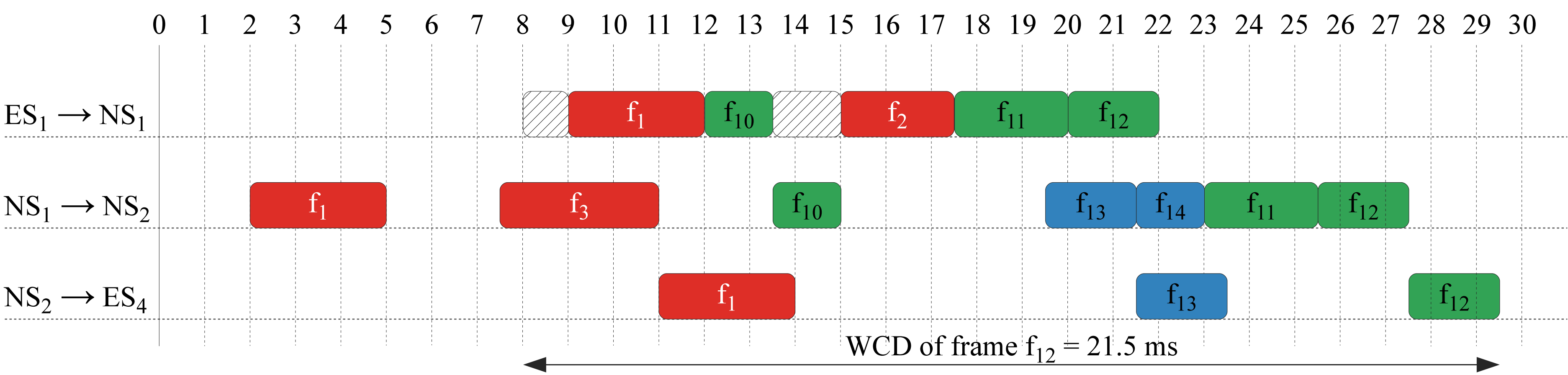
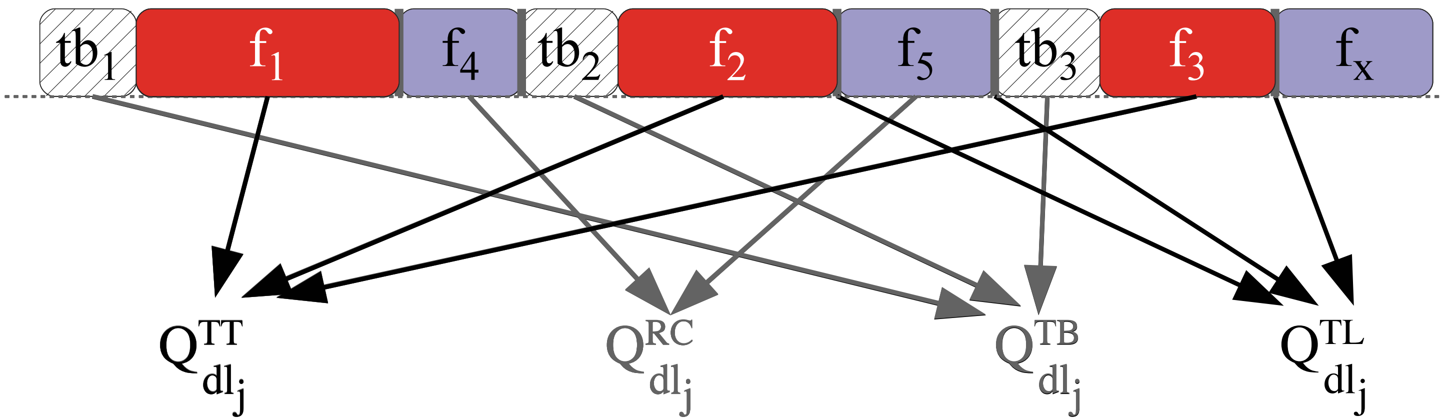


WCD = 37.5 ms



Sources of delay



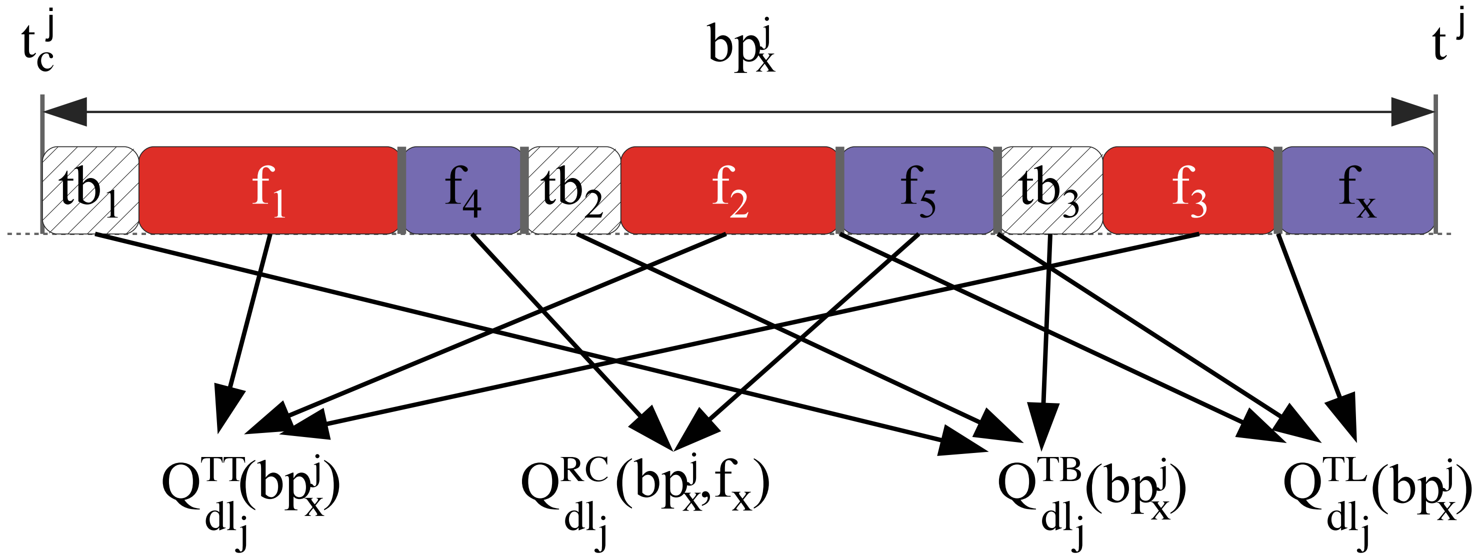
$Q^{TT}_{dl_j}$ Delays from scheduled TT frames on dl_j

$Q^{RC}_{dl_j}$ Delays from other RC frames transmitted on dl_j

$Q^{TB}_{dl_j}$ TT and RC traffic integration-induced delays

$Q^{TL}_{dl_j}$ Technical latencies introduced by the network nodes

Busy Period



- To compute the size:
  - Demand

$$H_x^j(bp_x^j) = Q_{dl_j}^{RC}(bp_x^j, f_x) + C_x^j$$

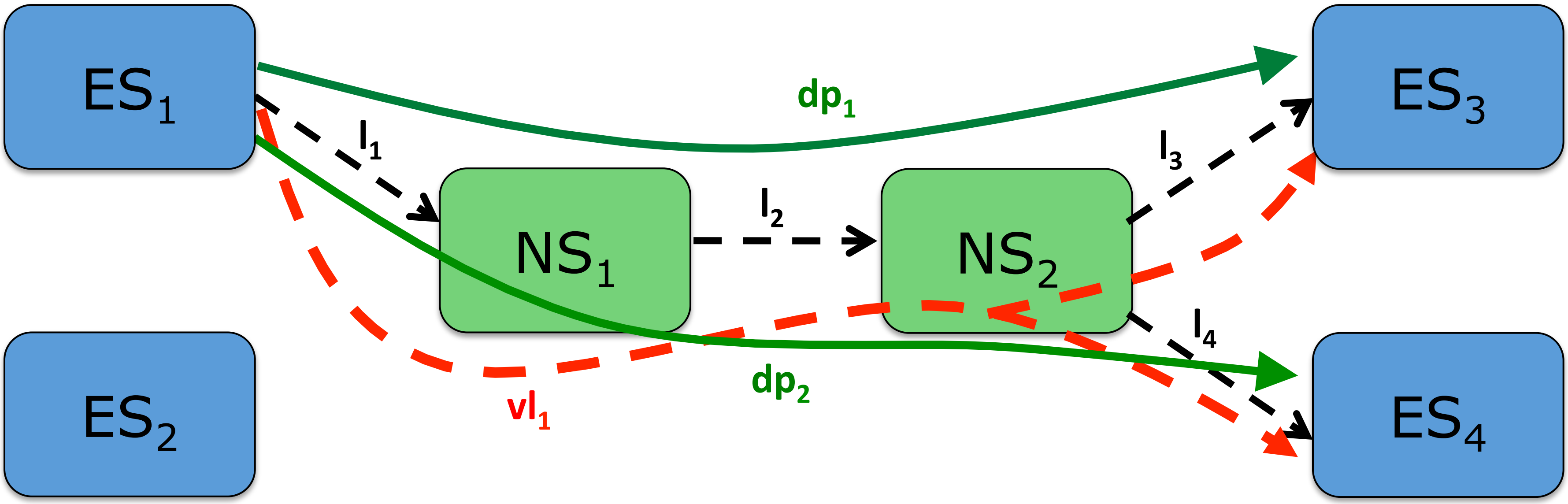
  - Availability

$$A_x^j(bp_x^j) = \overline{bp_x^j} - (Q_{dl_j}^{TT}(bp_x^j) + Q_{dl_j}^{TB}(bp_x^j) + Q_{dl_j}^{TL}(bp_x^j))$$

Worst-case end-to-end delay

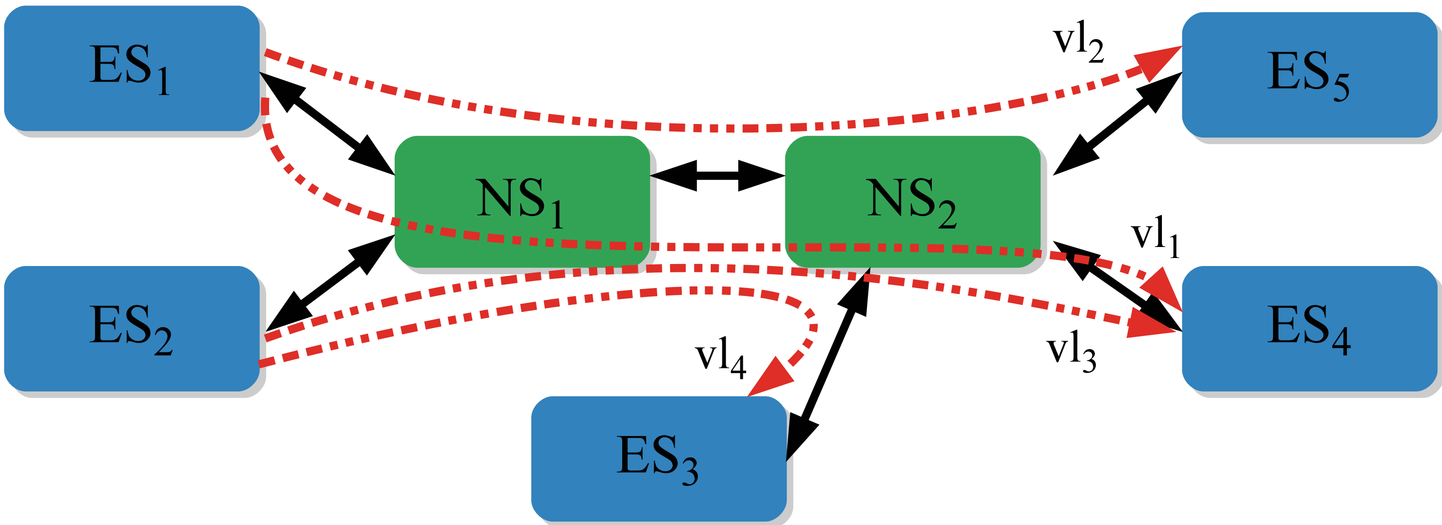
- For each dataflow path dp_i, the end-to-end delay is the time difference between start of the busy period on the first dl_0 and the end of the busy period on the last dl_n
  - The start of the busy period on dl_j is obtained by subtracting from the end of the busy period on dl_{j-1} all the RC frames transmitted on both dl_j and dl_{j-1}
- The longest delay among all the dp_i is the WCD

Worst-case end-to-end delay



- WCD: the longest end-to-end delay for all dp_i
- The end-to-end delay on dp_i: $t^n - t_c^0$
- Consider only possible scenarios: t_c^j depends on t^{j-1}

Example



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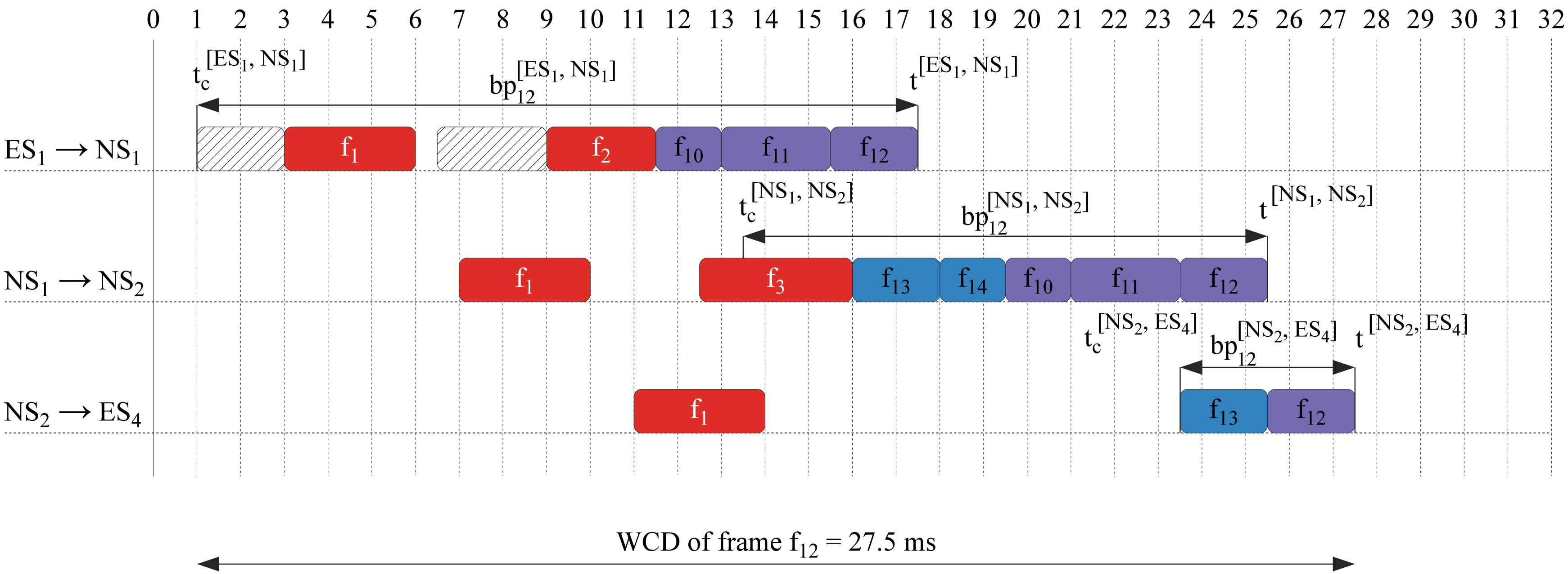
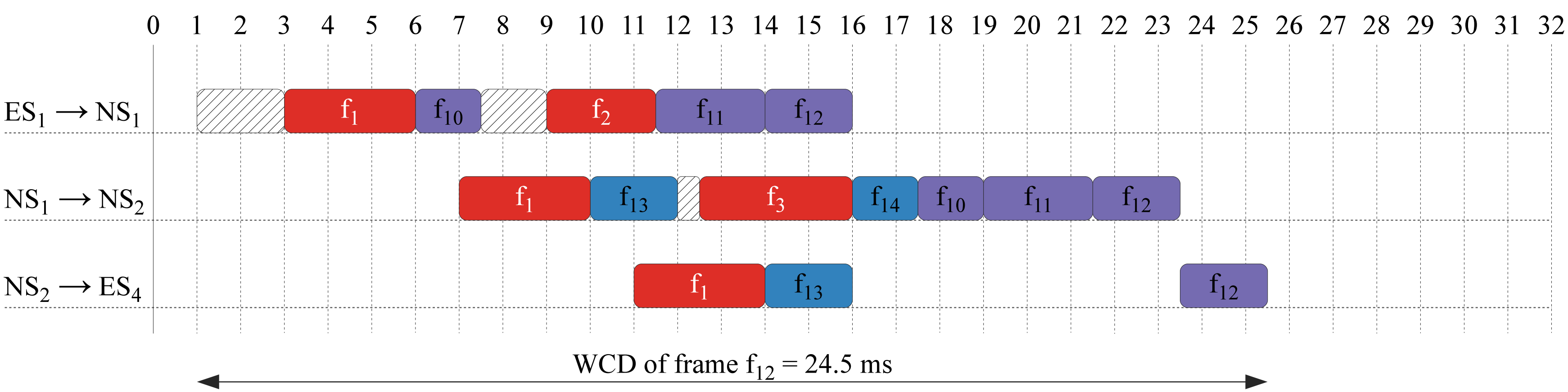


- Exact WCD:



Experimental Results

- 3 synthetic benchmarks:
  - 12 ESes and 4 NSes, 20 TT and 26 RC
  - 10 ESes and 5 NSes, 58 TT and 51 RC
  - 35 ESes and 8 NSes, 91 TT and 81 RC

- The analysis is compared to the analysis from:
  - W. Steiner. Synthesis of Static Communication Schedules for Mixed-Criticality Systems. In *Proceedings of the International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing Workshops*, pages 11–18, 2011.

Experimental Results

Frame	Size (B)	Period (ms)	WCD using [17] (ms)	Our WCD (ms)	Difference (ms)
rc_1	1021	4	4.44	0.77	3.66
rc_2	1395	16	19.94	1.81	18.12
rc_3	134	4	20.68	1.10	19.57
rc_4	1078	2	10.16	1.53	8.62
rc_5	590	8	13.04	1.35	11.69
rc_6	946	2	14.62	1.68	12.93
rc_7	784	16	3.12	0.79	2.33
rc_8	1120	2	14.09	1.22	12.86
rc_9	1361	8	8.43	1.38	7.04
rc_{10}	20	4	17.81	1.48	16.33
rc_{11}	1262	8	11.30	1.34	9.96
rc_{12}	926	4	15.30	1.17	14.13
rc_{13}	879	4	12.86	1.43	11.43
rc_{14}	1360	16	16.69	1.80	14.89
rc_{15}	1332	8	14.62	1.60	13.01
rc_{16}	728	16	13.67	1.61	12.05
rc_{17}	1127	16	18.52	1.70	16.81
rc_{18}	156	4	5.57	0.86	4.71
rc_{19}	378	8	20.73	1.08	19.65
rc_{20}	1443	2	20.07	1.75	18.31
rc_{21}	1367	2	20.52	1.85	18.67
rc_{22}	519	16	13.24	1.32	11.91
rc_{23}	522	2	19.74	1.33	18.41
rc_{24}	308	16	11.15	1.23	9.91
rc_{25}	411	2	11.11	0.65	10.46
rc_{26}	406	16	7.47	1.35	6.11

Conclusions

- TTEthernet is very well suited for mixed-criticality applications
  - Predictability is achieved using three classes of traffic: TT, RC and BE
  - Spatial separation is achieved trough virtual links
  - Temporal separation is enforced by schedule tables for TT traffic and bandwidth allocation for RC traffic
- We proposed a timing analysis for the TTEthernet protocol
  - Compared to other analyses, our analysis is much closer to the exact worst-case end-to-end delay, while requiring more time to obtain a result
- Future work:
  - Optimize the analysis to reduce the computation time
  - Provide a more formal complexity analysis