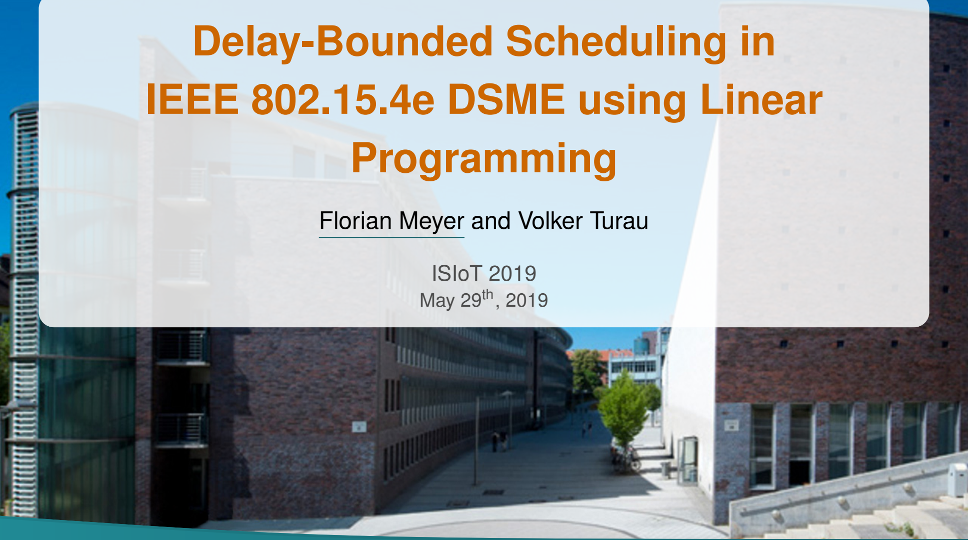
Delay-Bounded Scheduling in IEEE 802.15.4e DSME using Linear Programming

Florian Meyer and Volker Turau

ISIoT 2019
May 29th, 2019



Institute of Telematics
Hamburg University of Technology
TUHH

Motivation

- Wireless sensor networks experience increased adoption in industrial environments (IIoT)
- Many IIoT applications have tight delay constraints
- Existing protocols (CSMA, IEEE 802.15.4, ...) are not suitable
- The Deterministic and Synchronous Multi-Channel Extension (DSME) increases robustness, reliability and scalability:
    - TDMA-based medium access
    - Channel diversity
    - Distributed slot negotiation
    - Adaption to dynamically changing traffic

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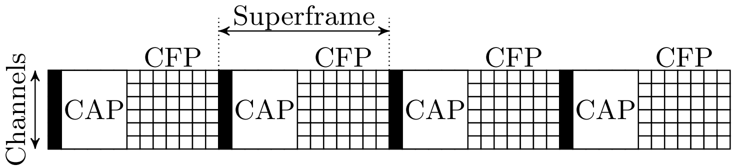
⇒ This work covers different scheduling strategies for DSME and provides results as a reference

Frame Structure



- CAP: Contention access period
- CFP: Contention free period
- GTS: Guaranteed time slot

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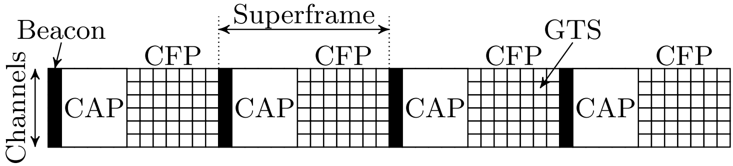

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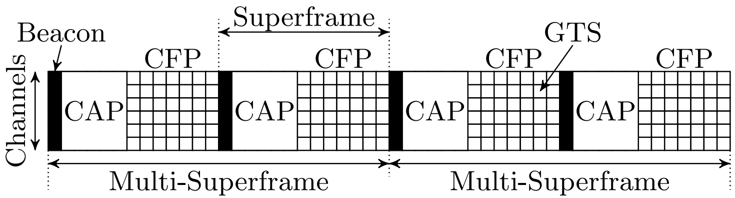

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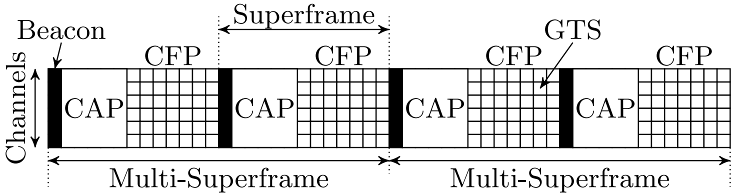

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Parameters:

superframe order (*SO*) - length of a slot / superframe
multi-superframe order (*MO*) - length of a multi-superframe

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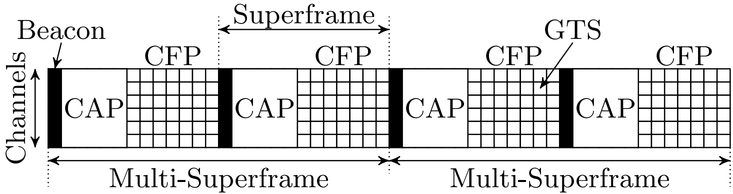

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Parameters:

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time slots per MSF: $7 * 2^{MO-SO}$

Challenges

Challenge 1:

Finding the data throughput limit of DSME for a given convergecast scenario.

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Finding the data throughput limit of DSME for a given convergecast scenario.

Challenge 2:

Many existing scheduling protocols cannot be applied to DSME because of its special frame structure.

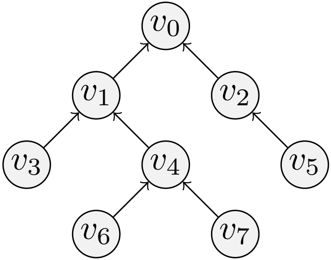
Challenge 3:

There is currently no bound for the worst-case delay in DSME.

Scheduling Requirements

Convergecast scenarios with routing tree:

1. In each slot a node can either send a single packet to its parent or receive a single packet from a child, not both.
2. A node can only receive a packet from a single child in a slot. Several packets from different children collide and are corrupted.
3. If in a slot a node v_i sends a packet, its neighbors can only use different channels of the same time slot.



Maximum Packet Generation Rate ($\mathcal{LP}_1$)

$$x_{ik} = \begin{cases} 1, k \text{ is a transmission slot from } v_i \text{ to its parent} \\ 0, \text{otherwise.} \end{cases}$$

$$\forall_{i,k}: \quad x_{ik} + x_{N_i^+ k} + \sum_{j \in N_i^-} x_{jk} \leq 1$$

$$\forall_i: \quad \gamma_i \times \delta \leq \sum_k x_{ik}$$

$$\forall_{i,k}: \quad \sum_{j \in I_i} x_{jk} \leq |C|$$

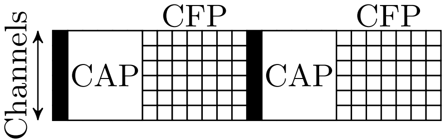
N_i^+ : parent of node v_i
N_i^- : set of children of node v_i
γ_i : number of nodes in subtree with root v_i
δ : number of packets per second
I_i : nodes in interference range of v_i
$|C|$: number of channels

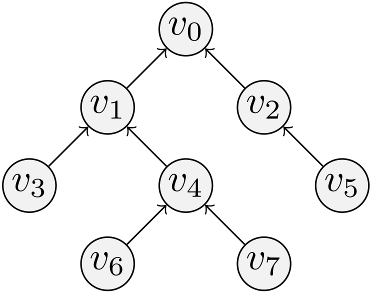
The objective function is

$$O_1: \quad \max\ \delta$$

Alternating Transmission Slots ($\mathcal{LP}_2$)

- Disallow two consecutive transmission slots





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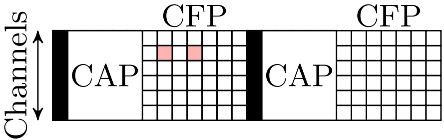

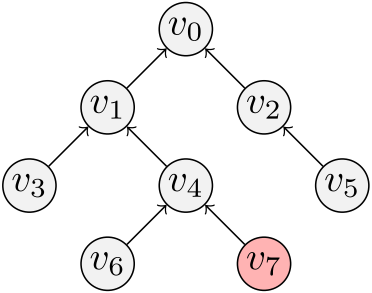

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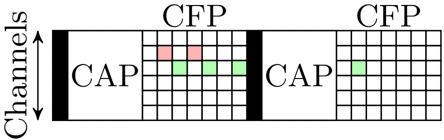

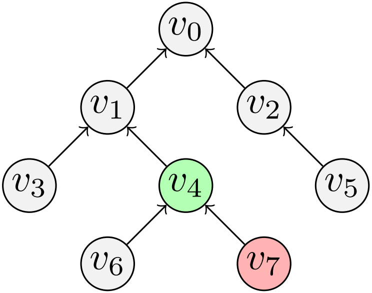

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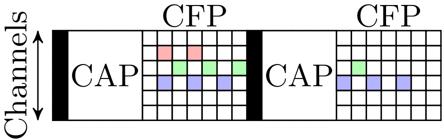

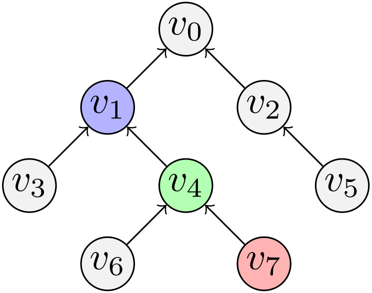

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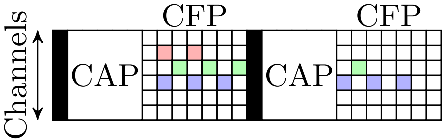

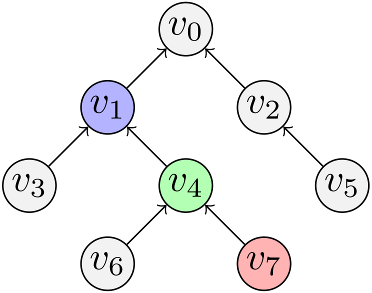

$$\Rightarrow \forall_{i,k} : \quad x_{ik} + x_{i(k+1)\%K} \leq 1$$

K : total number of time slots

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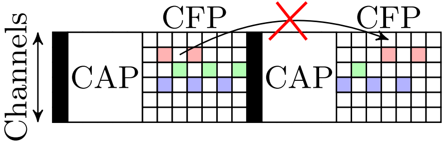

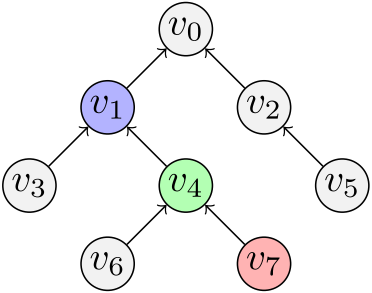

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Slots on Transmission Paths ($\mathcal{LP}_3$)

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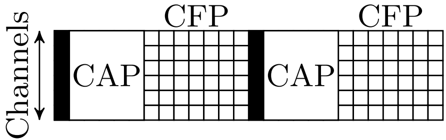

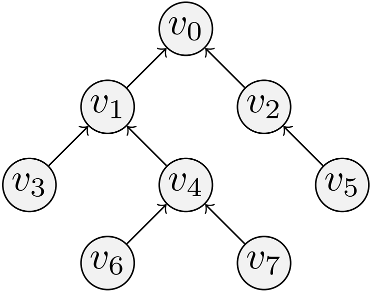

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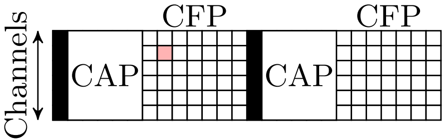

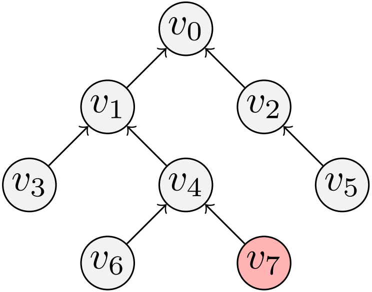

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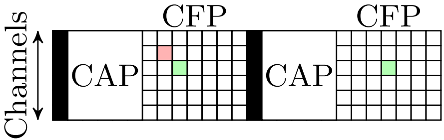

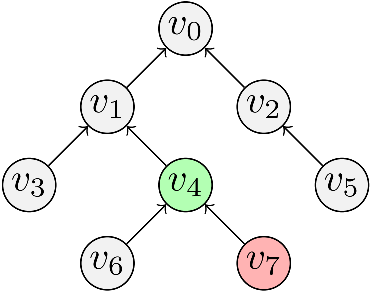

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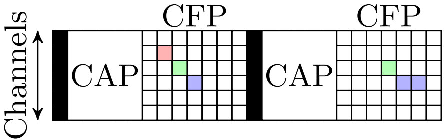

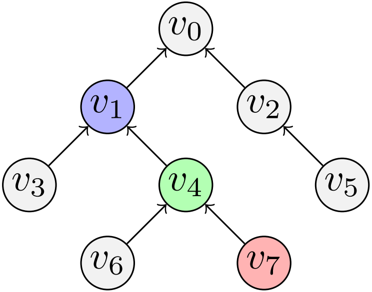

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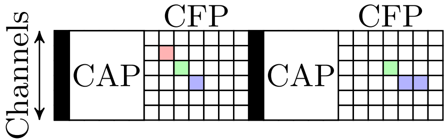

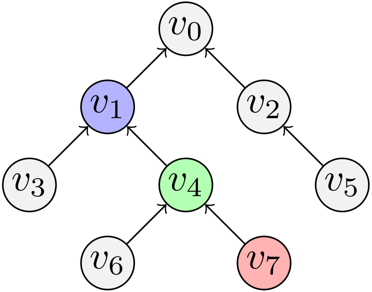

$$\Rightarrow \forall_{i,k}: \quad u_i + x_{i(k+1)} \geq \sum_{j \in N_i^-} x_{jk}$$

$$O_2: \quad \min \sum_i u_i$$

with u_i : binary variable for all $v_i \neq v_0$

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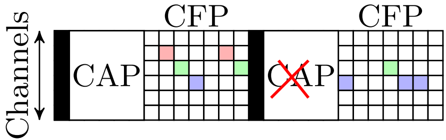

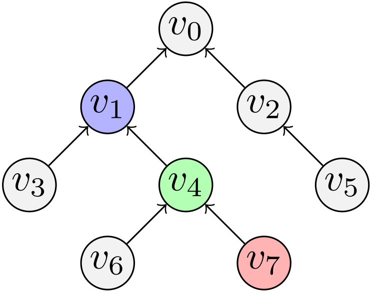

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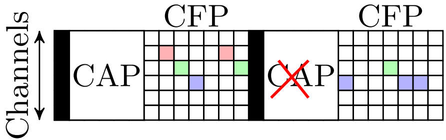
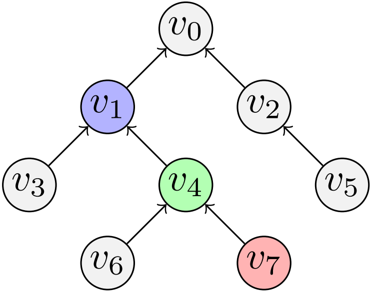
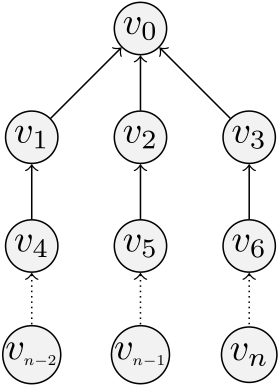




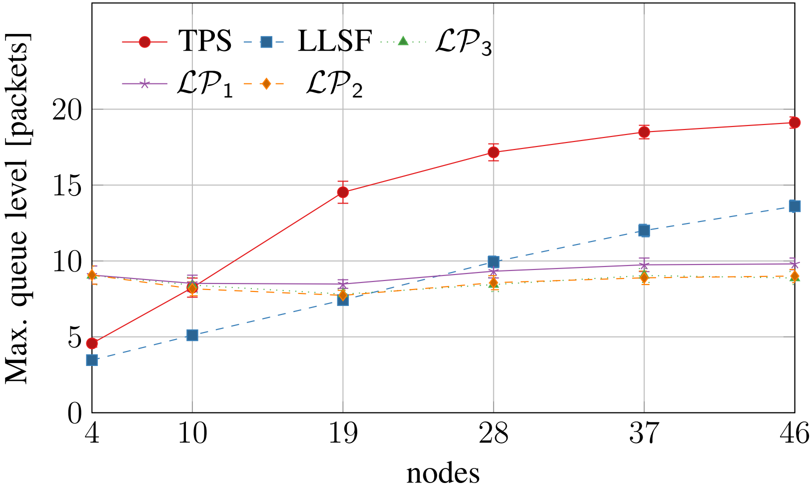
$\Rightarrow$ $\mathcal{LP}_4$ avoids scheduling over CAPs

Experimental Setup

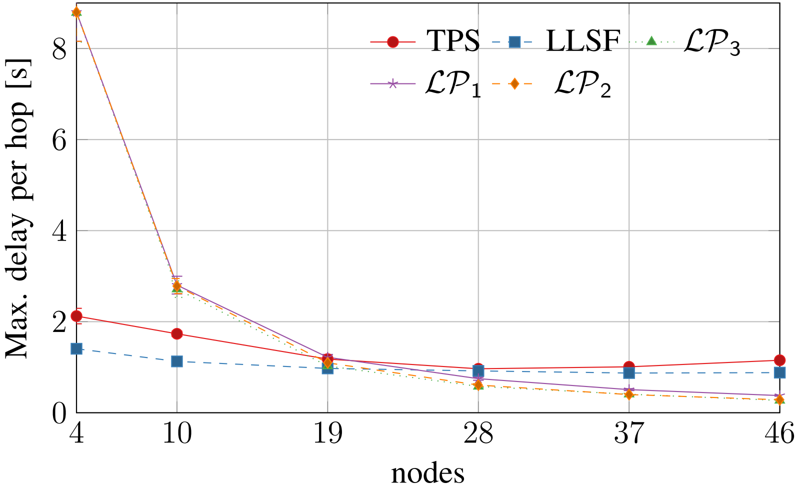
- Multi-line topology without interference between branches
- Poisson-distributed traffic with $\delta = 5/6$, $MO = 6$, $SO = 3$
- Schedules calculated for $\delta = 1$ (over-provisioning)
- Simulations conducted with OMNeT++ and openDSME



Queue Level


TPS
LLSF
$\mathcal{LP}_3$
$\mathcal{LP}_1$
$\mathcal{LP}_2$
Max. queue level [packets]
0
5
10
15
20
4
10
19
28
37
46
nodes

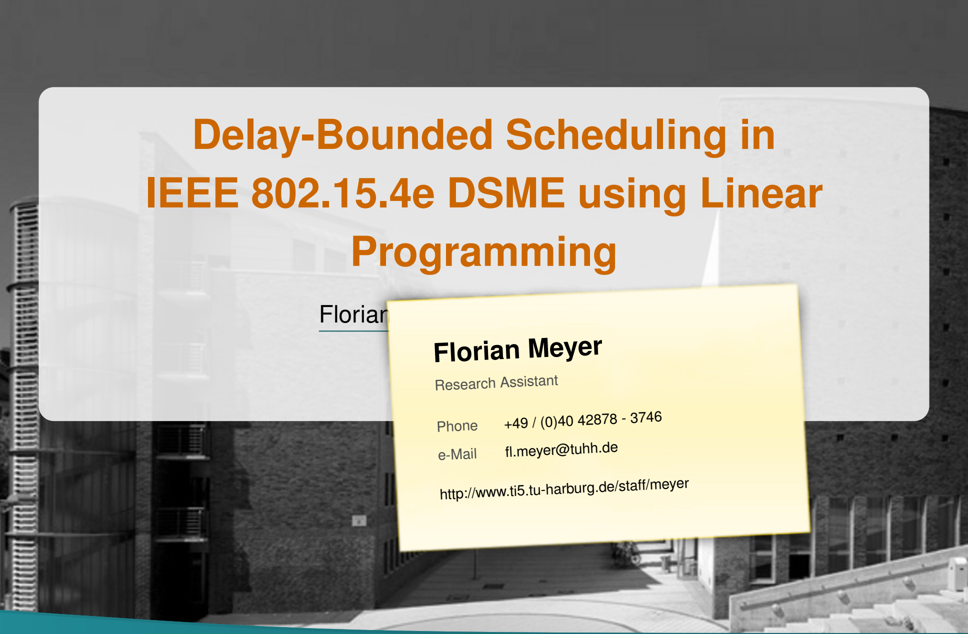
Maximum end-to-end delay



Conclusion & Outlook

- Formulation of different scheduling strategies as linear programs
- Comparison with state-of-the-art scheduling strategies
- Practical tool for the realization of data collection tasks requiring delay bounds, e.g.:
  - For 46 nodes, sampling frequency 1 Hz, sampling resolution 100 bytes: Guaranteed packet delivery in 10.97 seconds

- Future work
  - Hybrid algorithm which performs better at startup
  - More efficient algorithm for scheduling (machine learning?)



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DSME Parameter Selection

	$MO - SO = 1$			$MO - SO = 2$		
	$SO = 1$	$SO = 2$	$SO = 3$	$SO = 1$	$SO = 2$	$SO = 3$
D_S [ms]	1.92	3.84	7.68	1.92	3.84	7.68
max. packet size [byte]	18	66	116	18	66	116
D_{MF} (length of MSF) [ms]	61.44	122.88	245.76	122.88	245.76	491.52
number of GTS (per second)						
without CAP-reduction	14 (224)	14 (112)	14 (56)	28 (224)	28 (112)	28 (56)
with CAP-reduction	22 (352)	22 (176)	22 (88)	52 (416)	52 (208)	52 (104)

Execution Time