Heartbeat-Based Synchronization Scheme for the Human Intranet: Modeling and Analysis

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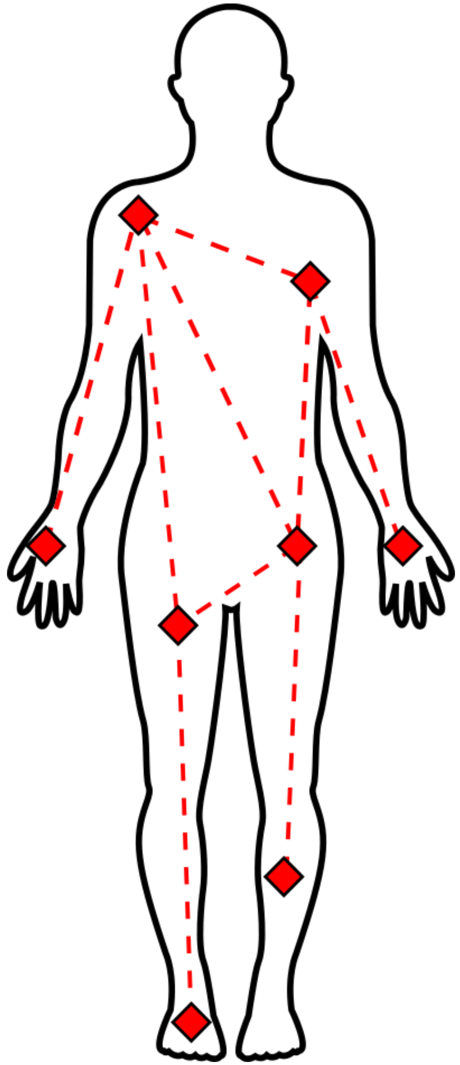
Introduction: The Human Intranet

- Human body-dedicated network
  - Medical (life support) & wellness applications
- Interface a wide variety of nodes
  - Actuators (Smart prosthetics, insulin pump…)
  - Sensors (Temperature, displacement…)

Signal	Sampling rate (Hz)	Data generation rate (bit/s)
ECG	120-250	1440-3000
Temperature	0.2-2	2.4-24
Oximetry	60	1440
Respiration rate	20	240
Heart rate	10	120
Biometric Z	10-20	120-240
Chemicals	10	120
Motion (/axis)	100-250	1200-3000
Neural recording (/channel)	10k - 30k	120k - 360k



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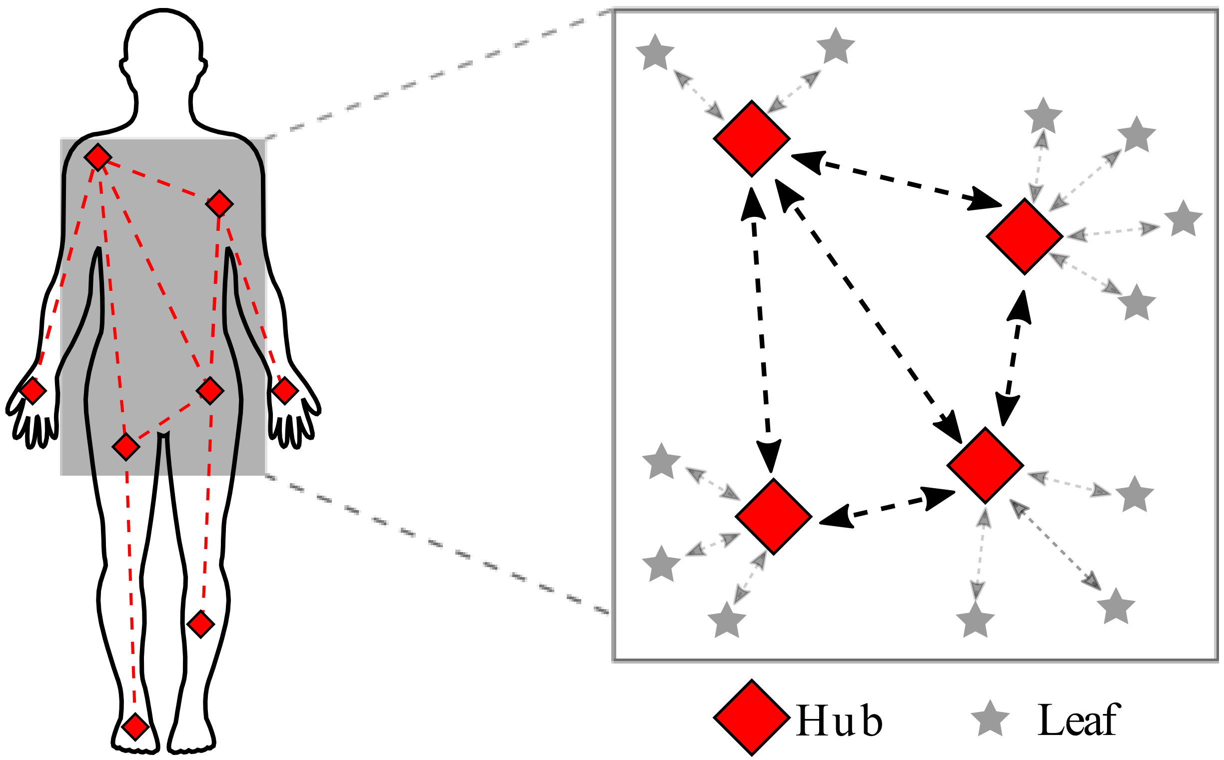
Introduction: The Human Intranet

- 2 types of nodes & communications
  - Hub to Hub Communication
    - Main traffic, bidirectional, meshed network
  - Leaf to Hub Communication
    - Local star topology around each hub
- Existing standards limited
  - 1- or 2-hop limited
  - Heavy synchronization overhead



- Efficient communication enabler for the Human Intranet ?

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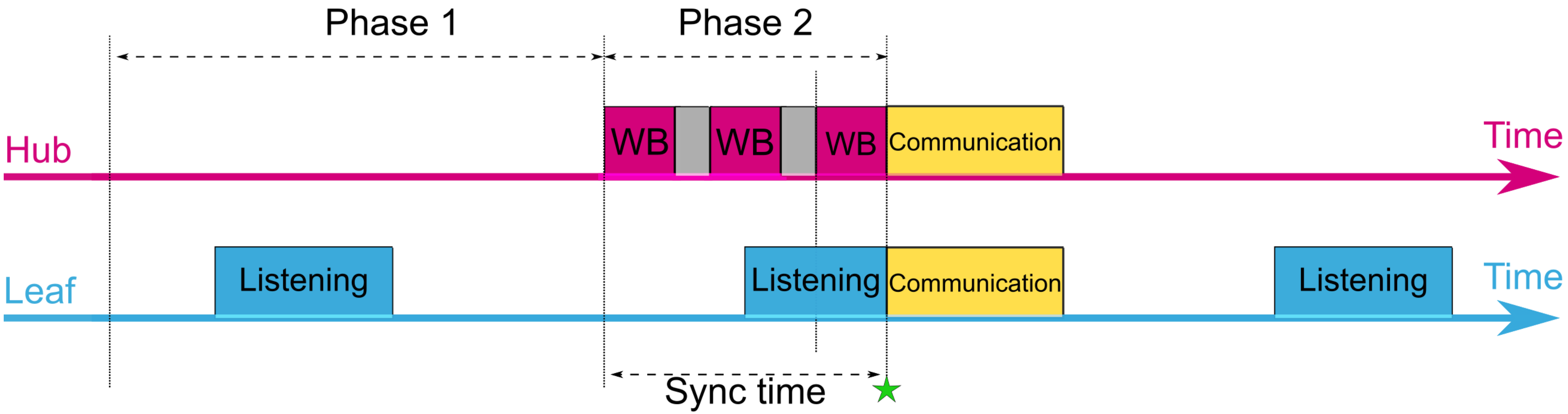
Synchronization and Duty-Cycled Receiver

- Synchronization efficiency is a key feature
  - Channel availability, power consumption& latency
- Common method: **Duty-Cycled Receiver**
  - No synchronization
  - Energy saving
  - Very efficient for long sleep periods
  - Asynchronous listening windows
  - Additional synchronization time required
  - Wake-up beacon generation mandatory



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Proposed solution: Heartbeat-Based Synchronization

- Heartbeat based: common clock for node's synchronization (Superframes)
  - Universal Human Clock, matching the human activity
  - Short time reference, reset on each heartbeat
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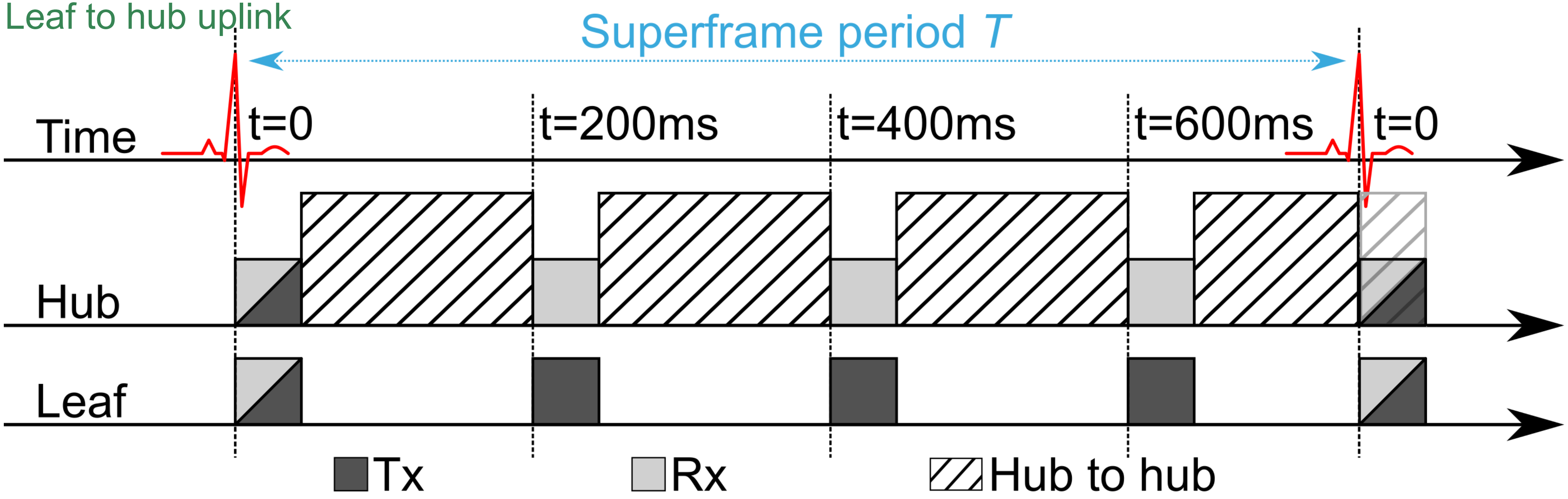
  - Hub to hub traffic punctured (sub-frames)
    - Leaf to hub uplink
  - Time-base accuracy
  - Heartbeat alignment over location
  - Overall efficiency



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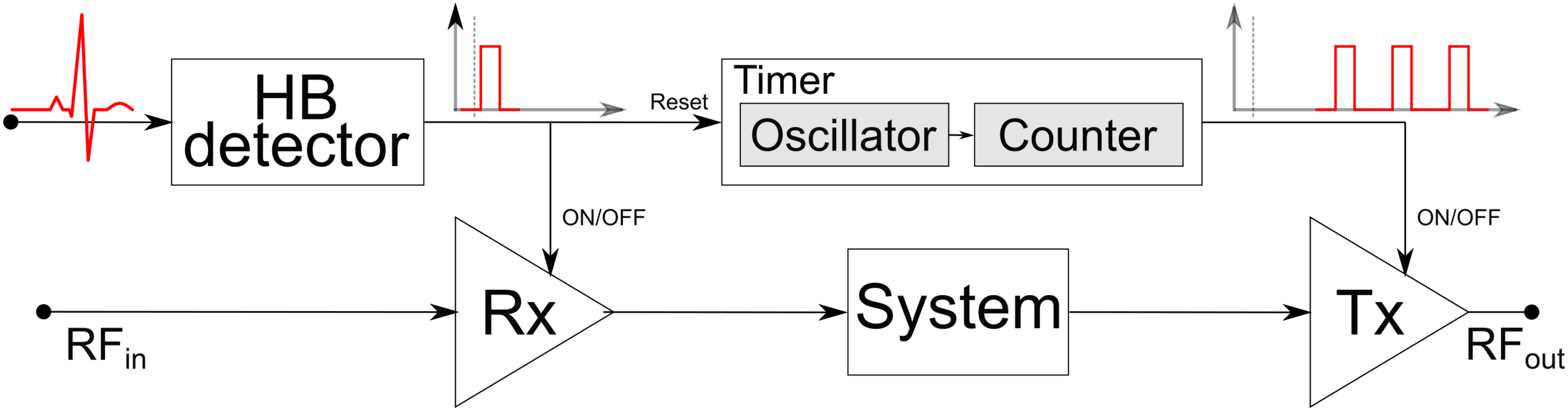
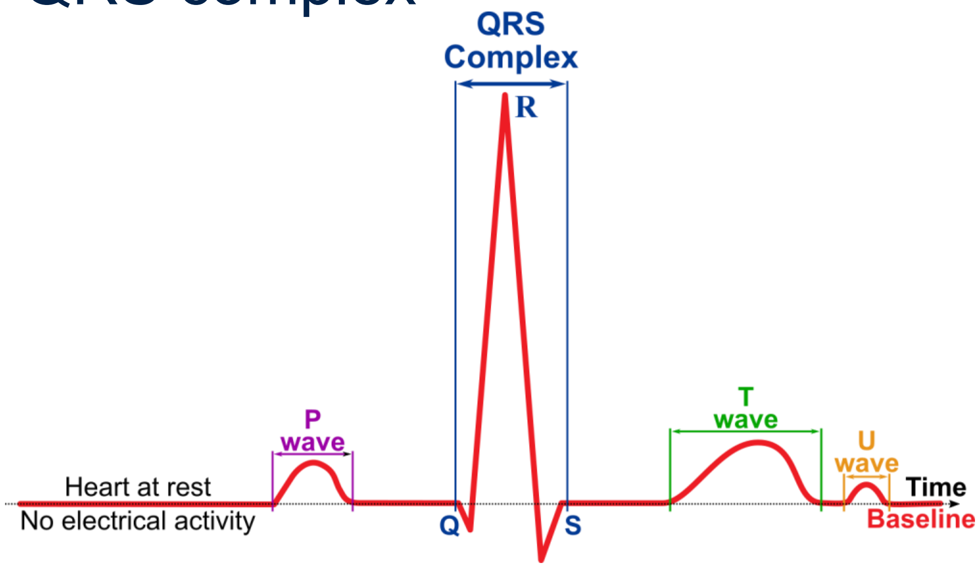
Synchronization functional block diagram

- Leaf architecture

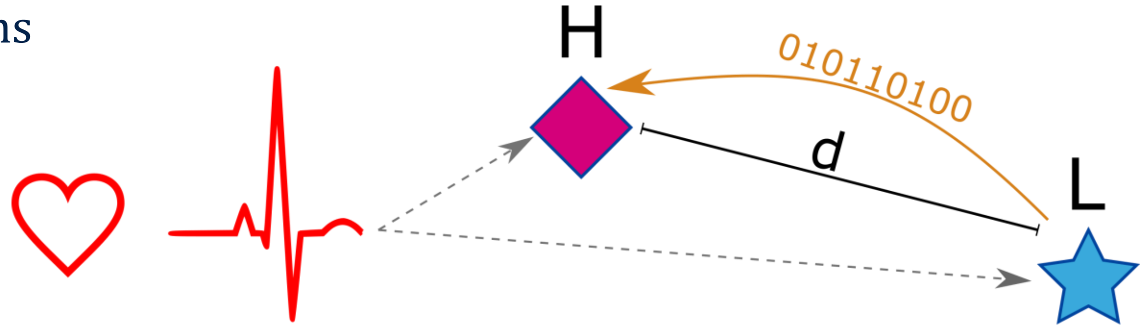


Heartbeat Detector Modeling

- Detects the highest magnitude peak “R” within the QRS complex



- Power consumption: $\boldsymbol{P_{HBd} = 100\, nW}$ [12]
- Propagation delay within the human body
  - Velocity: $v_{HB} > 250\, m/s$
  - Timing error: $\boldsymbol{\Delta t_{HB} < \frac{d}{250}}$
    - $d = 15\, cm \Rightarrow \Delta \mathrm{t_{HB}} = 0.6\ \mathrm{ms}$



[12] D. Da He et al., TBioCAS 2014.

Timer Modeling

- Timer global power consumption: $\boldsymbol{P_{timer} = 100\ nW}$ [17]
- **Oscillator offset frequency**
  - Static error
  - One-time calibration, tuning the counter auto-reload value
  - Timer error: $\boldsymbol{\Delta t_{counter} \leq \frac{1}{f_{osc}}}$
- **Oscillator frequency drift**
  - Slow frequency variations leading to timing error
  - Worst case: monotonous variation with time: $\boldsymbol{\Delta t_{drift}(t) = Drift_{osc} \cdot t}$
- **Oscillator accumulated random jitter (N cycles)**
  - Cycle-to-cycle variation, Gaussian normal distribution with 0 mean and σ variance
  - For N cycles (accumulation): $\sigma_N = \sqrt{N} \cdot \sigma$
    - A 4σ-window covers 99.993% of possible iterations :$\boldsymbol{\Delta t_{jitter} = 4 \cdot \sqrt{N} \cdot \sigma}$

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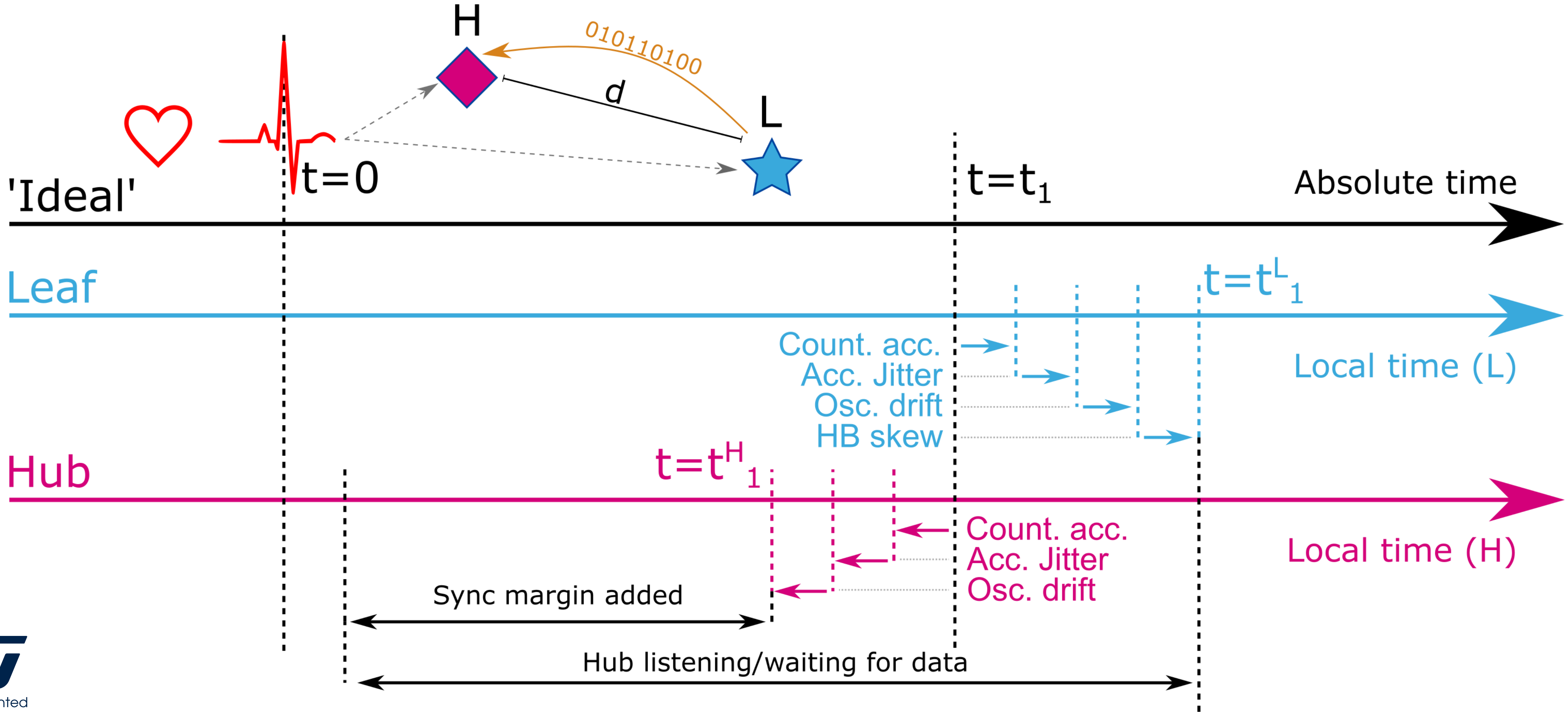
[17] S. Jeong *et al.*, JSSCC, 2015

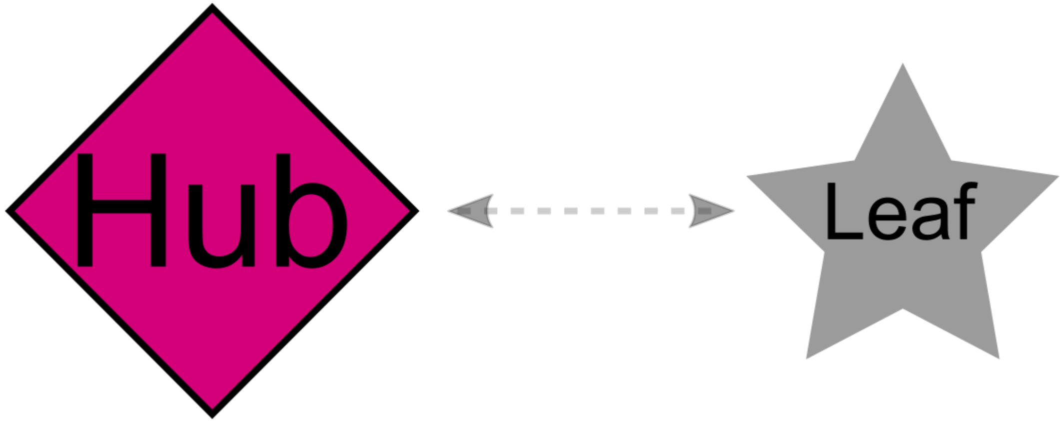
Synchronization Margin & guard interval

- $|Margin| = \Delta t_{HB} + 2 \cdot (\Delta t_{counter} + \Delta t_{drift} + \Delta t_{jitter})$



Metrics

- **Channel Availability (CA) for hub-to-hub communication**
  - $CA = \frac{Hub-to-hub}{Superframe}$ [%]
- **System Power Consumption (P)**
  - 1 leaf/hub pair: HBd, Timer, Tx, Rx
    - Synchronization margin included
- **Latency**
  - Data upload period (system setting)
  - No uncertainty nor additional synchronization time



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Hypothesis

- Equation-driven system analysis
- Comparison with a Duty-cycled Radio
- System specifications taken from state-of-the-art implementations

Description	Symbol	Value	Unit
Oscillator jitter variance	σ	1	µs
Oscillator drift	$Drift_{osc}$	500	ppm
Heartbeat detector power consumption [12]	P_{hbd}	100	nW
Timer power consumption [17]	P_{timer}	100	nW
Tx energy efficiency	E_{Tx}	100	nJ/b
Rx energy efficiency	E_{Rx}	100	nJ/b
Communication data rate	D_R	100	kb/s
Data generation rate (from leaf)	D_{gen}	1	kb/s
Wake-up beacon length	WB	16	b

[12] D. Da He et al., TBioCAS 2014.

[17] S. Jeong *et al.*, JSSCC, 2015

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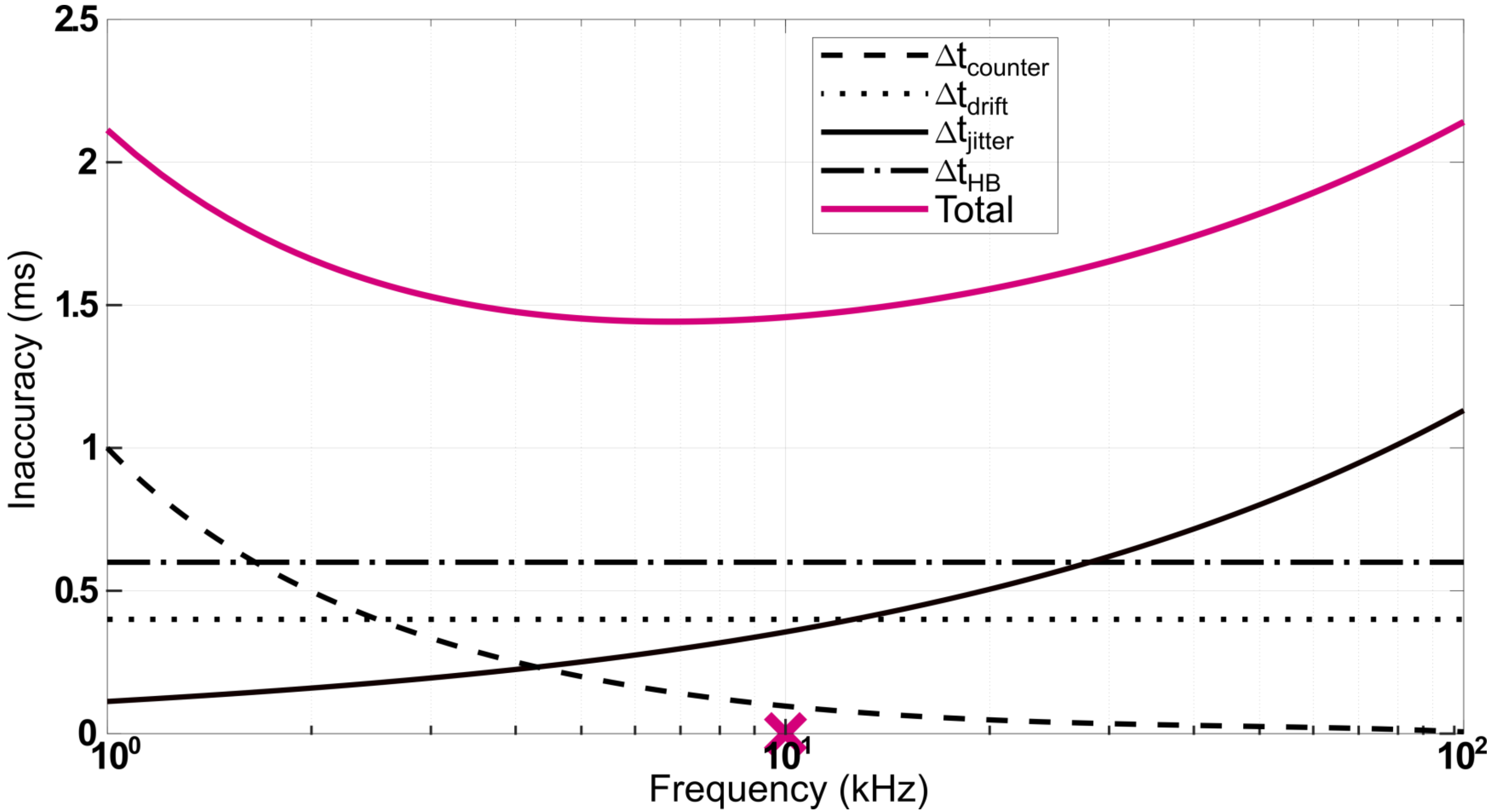
Optimal Oscillator Frequency

- Example for the given system
  - 800 ms superframe (heart rate of 75bpm)



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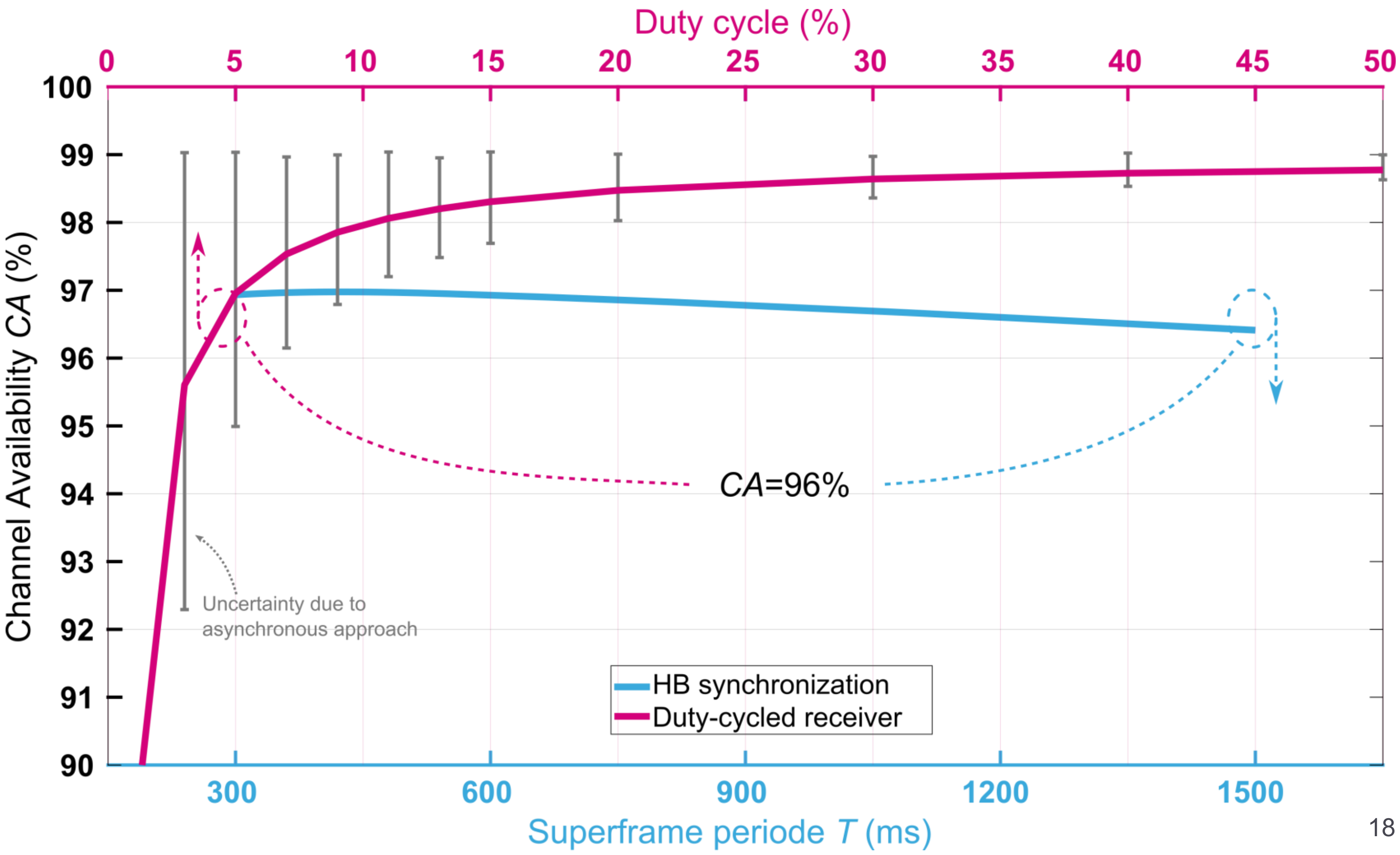
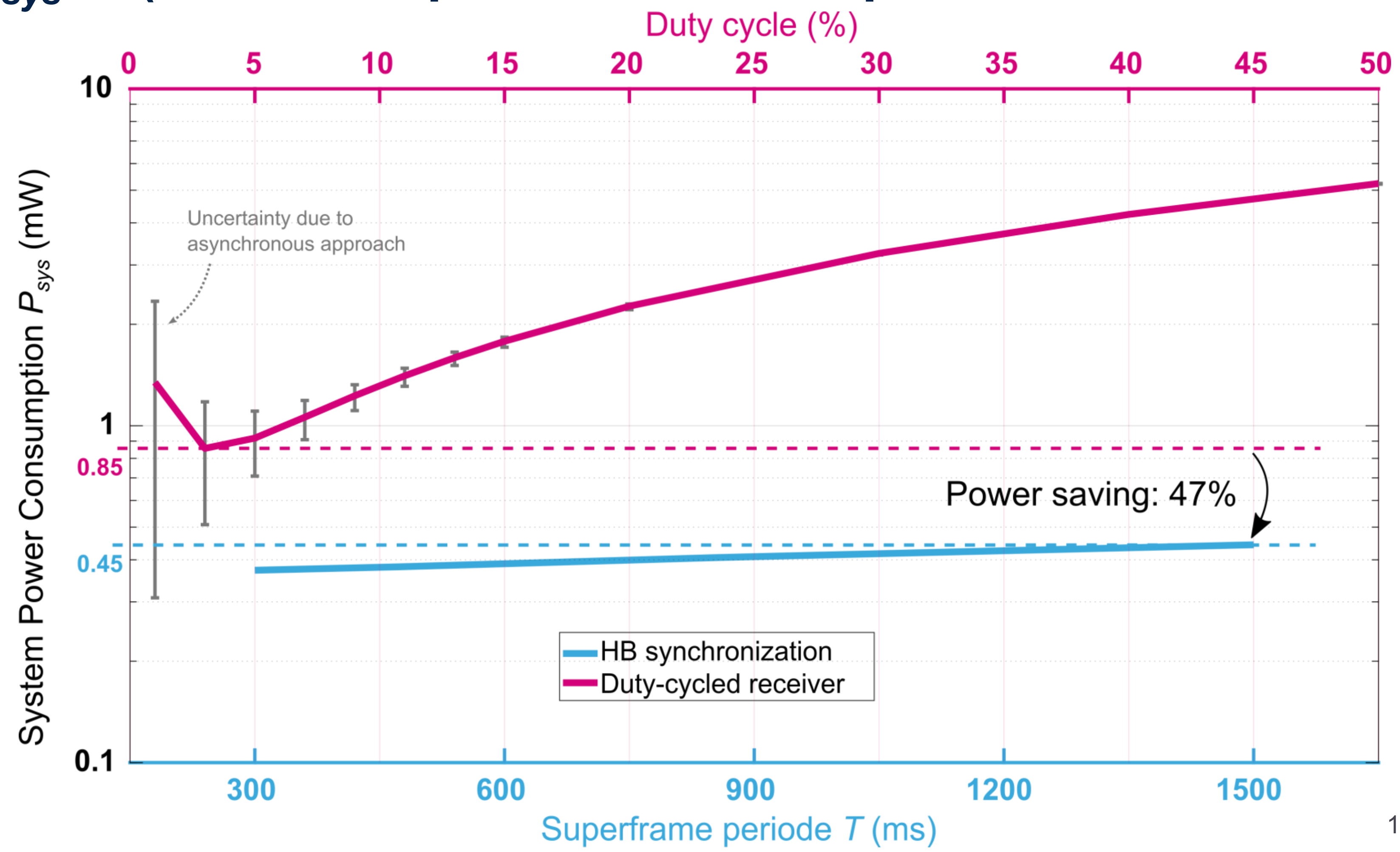
Results (1/n)

- **Channel availability – *CA* – (1 leaf-hub pair for 200 ms upload period)**
  HB-sync
  - CA > 96%
  - Deterministic
- Duty-cycled Rx
  - High CA for duty cycle > 4%
  - Uncertainty
    - Higher probability to miss the WB as the duty cycle is small
  - CA drops significantly for low duty cycles



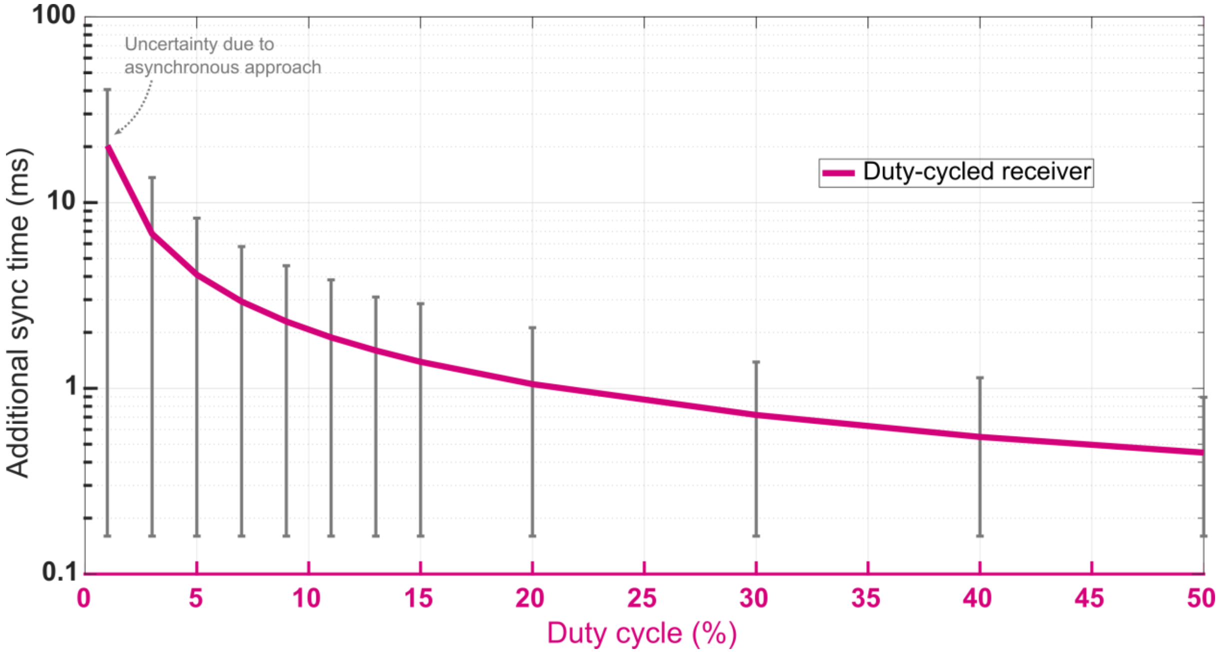
Results (2/3)

- **Power consumption – P_{sys} – (1 leaf-hub pair for 200 ms upload period)**
  - HB-sync
    - P_{sys} deterministic
  - Duty-cycled Rx
    - Uncertainty
  - Power saving > 47%



Results (3/3)

- **Heartbeat** synchronization **does NOT** suffer additional latency
  - Margin taken on purpose
- **Duty-cycled Radio suffers** additional synchronization latency
  - By nature
  - Probabilistic: Could be problematic for critical application



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Conclusion

- We proposed a novel heartbeat-based synchronization for the Human Intranet
- Follows a framed structure and is divided in subframes

Advantages:

- Optimizes
  - Channel availability
  - Power consumption: 47% more energy efficient than a Duty-cycled radio*
- Offers a tight control on latency
- Compatible with Body Coupled Communication

Drawback

- Additional electrodes for heartbeat detection

Future work

- Need for dedicated MAC protocol (under investigation)
  - Superframe duration variation
  - Last transmission interruption
- Possibility to interface multiple heartbeat detection technology

*upload every 200 ms with the same hardware

Thank you

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