On Optimal Neighbor Discovery

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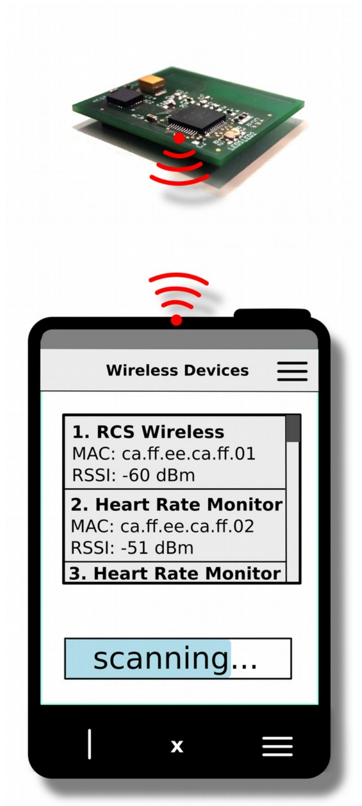
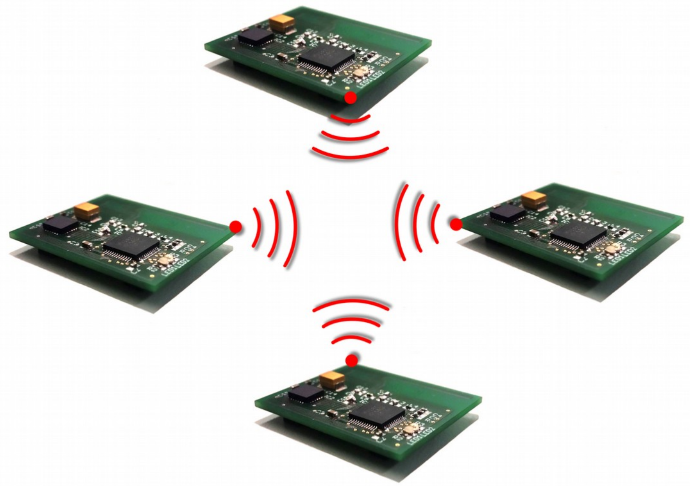
CH 918/5-1 - “Slotless Neighbor Discovery“

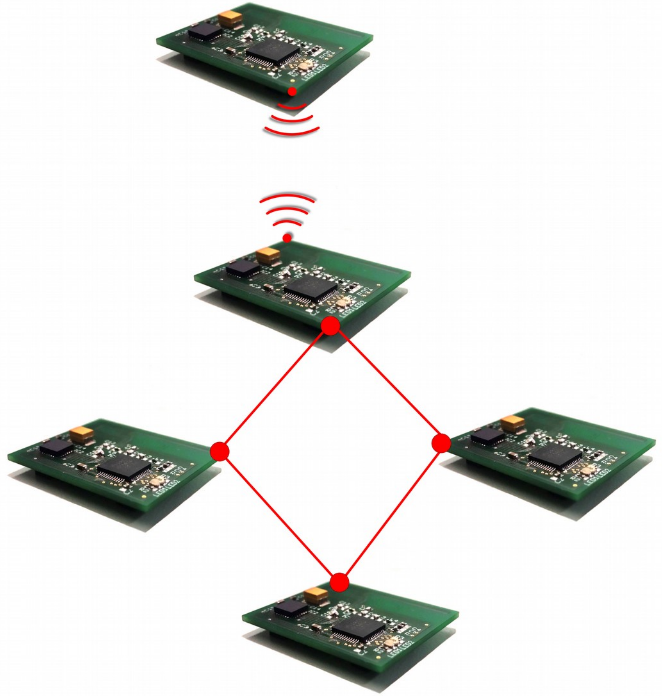
Neighbor Discovery in MANETs



Pairwise



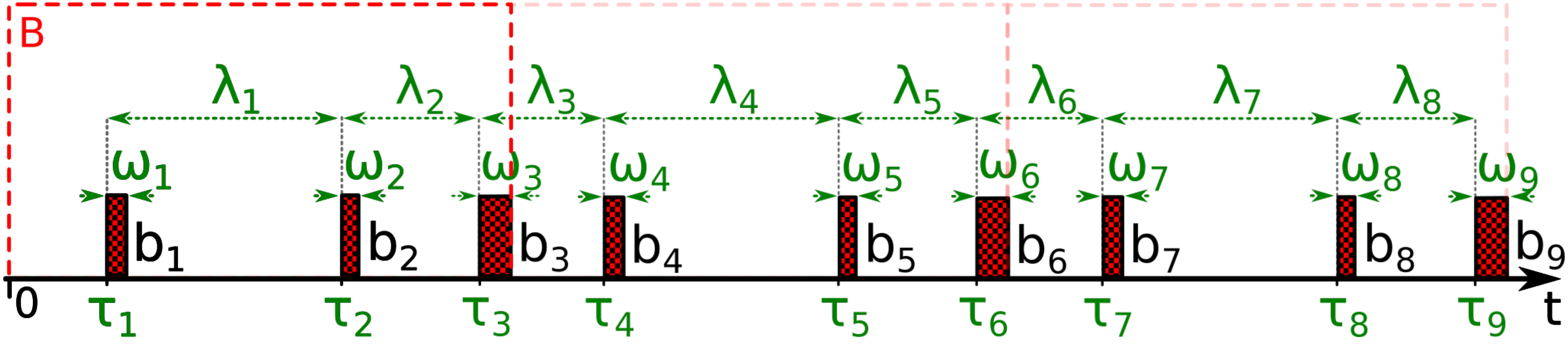
Groupwise



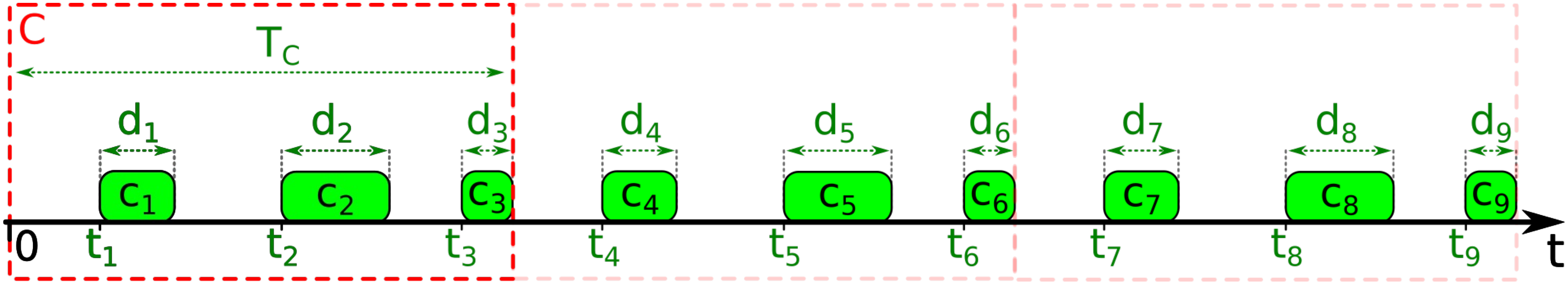
Pairwise in Groups

Realizing Neighbor Discovery

Transmission Sequence B

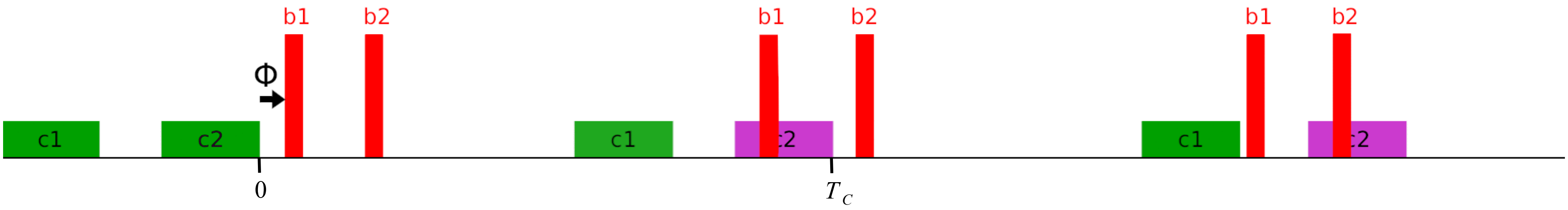


Reception Sequence C



Deterministic ND

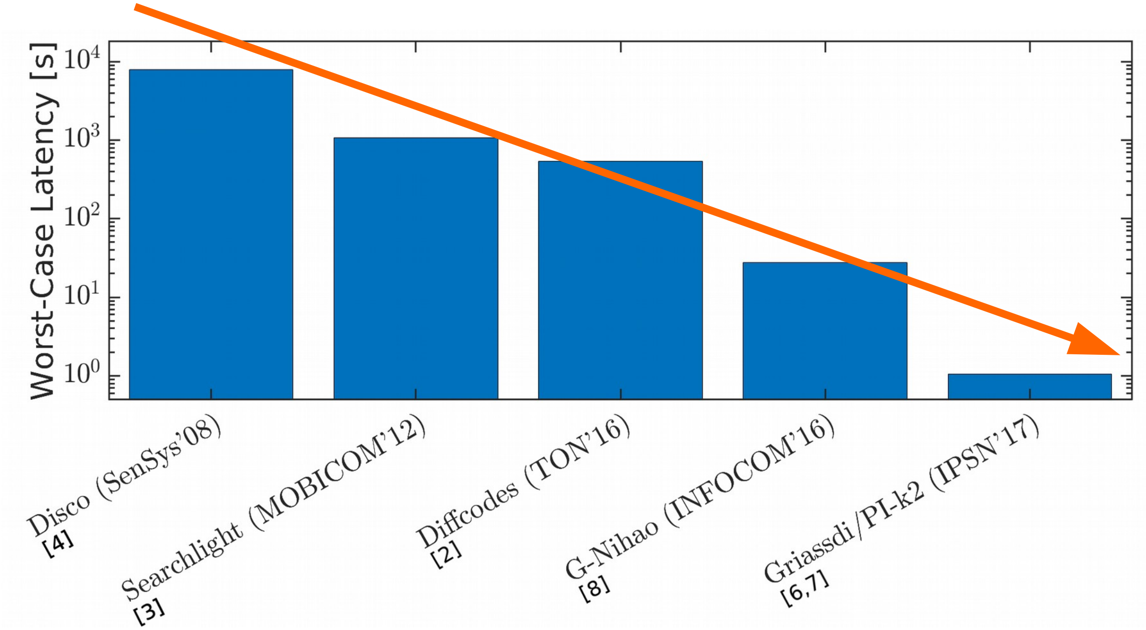
The first beacon in range of a sender falls into an instance of the reception window sequence with a random offset ϕ



The discovery latency becomes bounded, if a beacon overlaps with a reception window for every value of ϕ

What is the “lowest“ worst-case latency?

Goal of ND: Guarantee discovery within the lowest time and with the lowest duty-cycle (and hence energy budget)



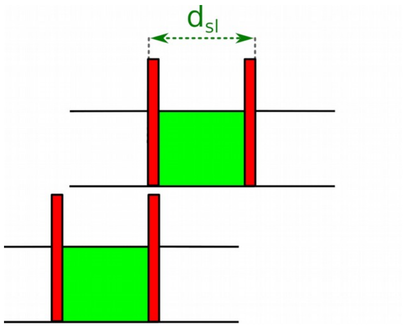
Key-Assumptions for this comparison: Duty-Cycle: 10%; Failure-Rate: 0.19%; Griassdi/PI-kM with some custom modifcations

1) Given a certain duty-cycle, what is the lowest possible worst-case latency?

2) Comparisons depend on multiple parameters and are hence subjective in the absence of bounds

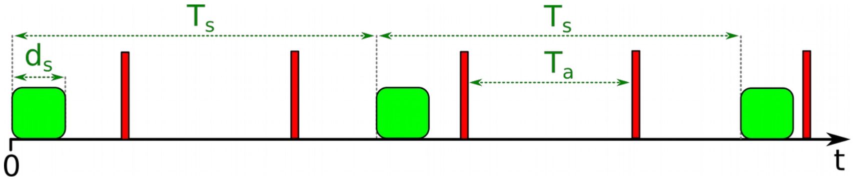
Slotted vs Slotless Neighbor Discovery

Slotted



- As soon as a pair of active slots from two devices partially overlaps, mutual discovery is guaranteed
- Schedule of active and passive slots needs to guarantee overlapping pairs of slots on two devices.
- Bound in terms of a worst-case number of slots is known [1], but not what the minimum slot length is

Slotless, Periodic Interval-Based

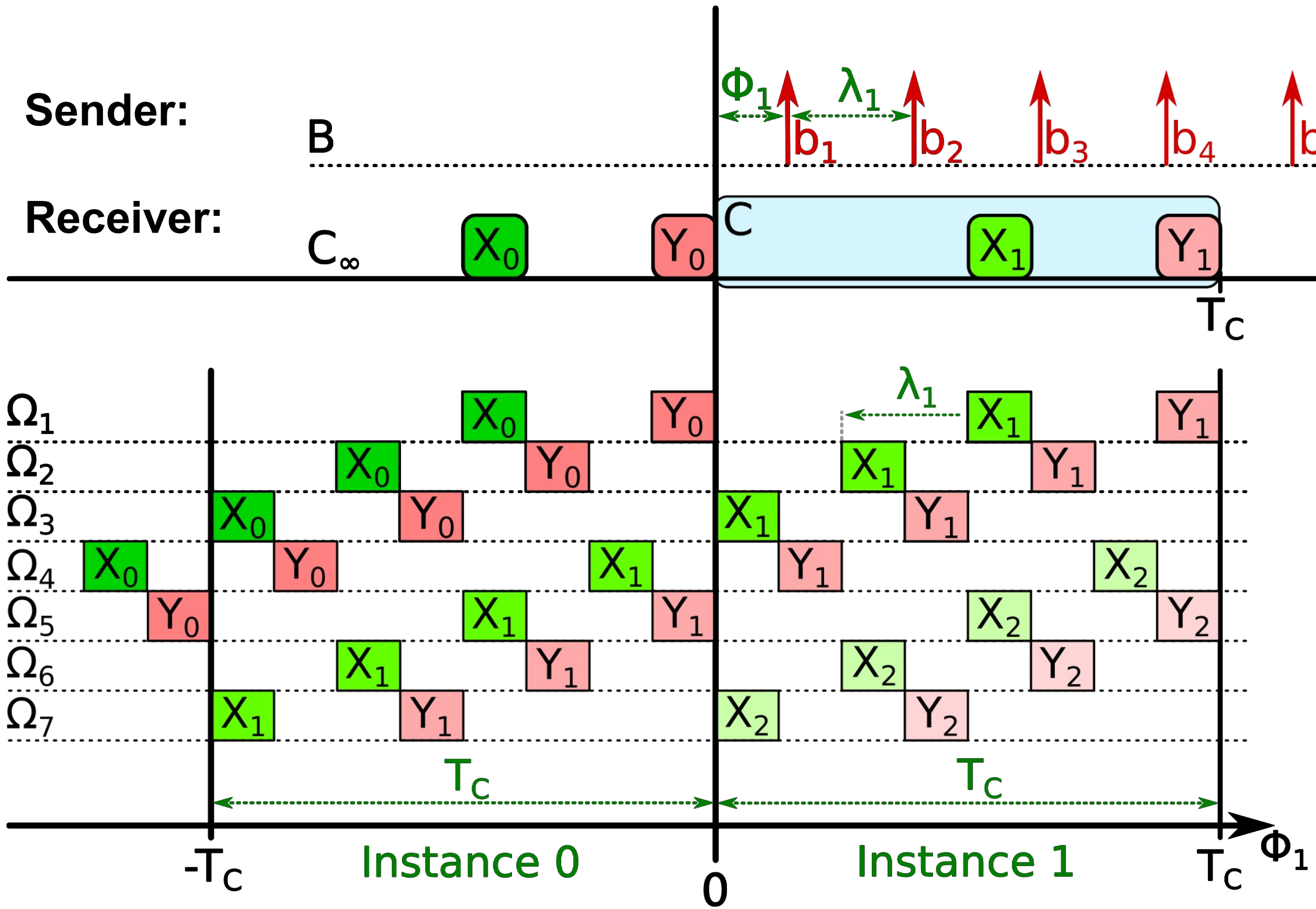


e.g., Bluetooth Low Energy, ANT/ANT+

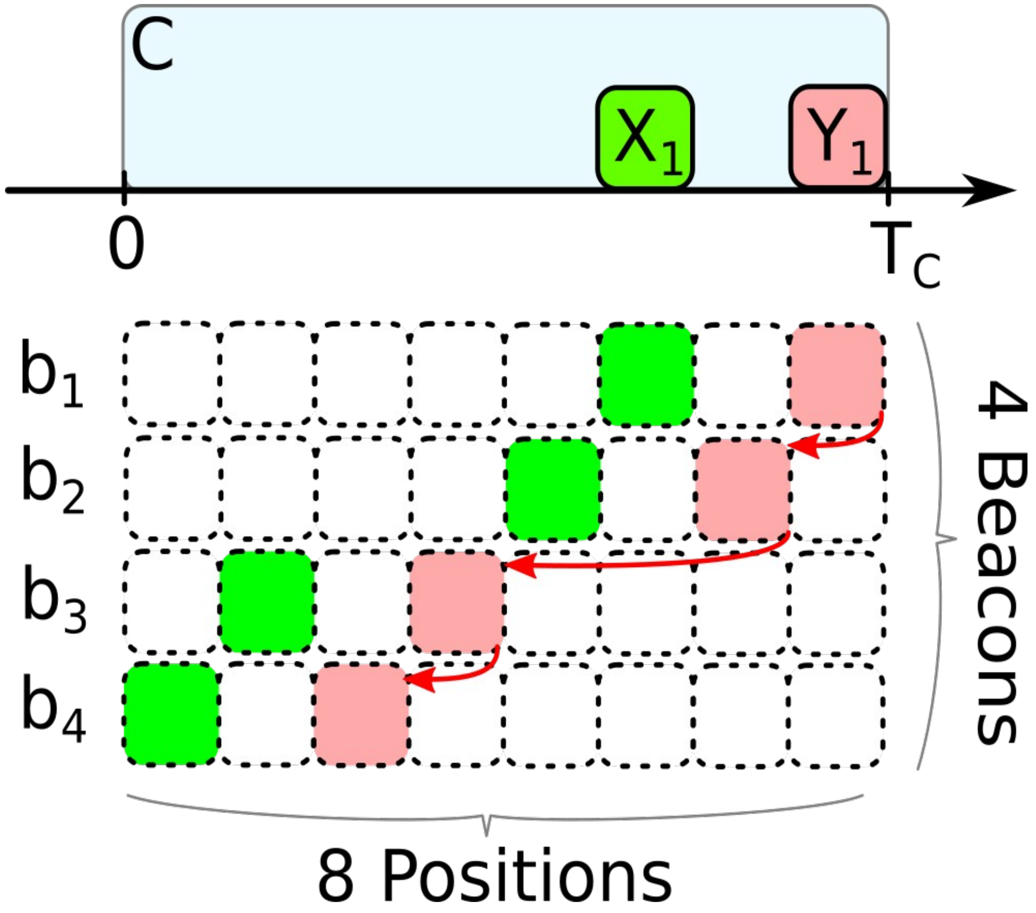
- Beacons and reception windows are scheduled with peridoic intervals
- Performance depends on the interval- and reception window lengths
- Performance not clear due to lack of optimal parametrizations

[1] Rong Zheng, Jennifer C. Hou, and Lui Sha. Optimal Block Design for Asynchronous Wake-Up Schedules and Its Applications in Multihop Wireless Networks. IEEE Transactions on Mobile Computing (TMC) 5, 9 (2006), 1228–1241.

Coverage Maps



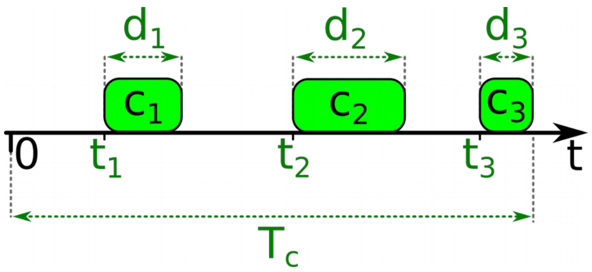
Determinism



Generalization: Minimum Number of Beacons

Minimum number of beacons for deterministic ND:

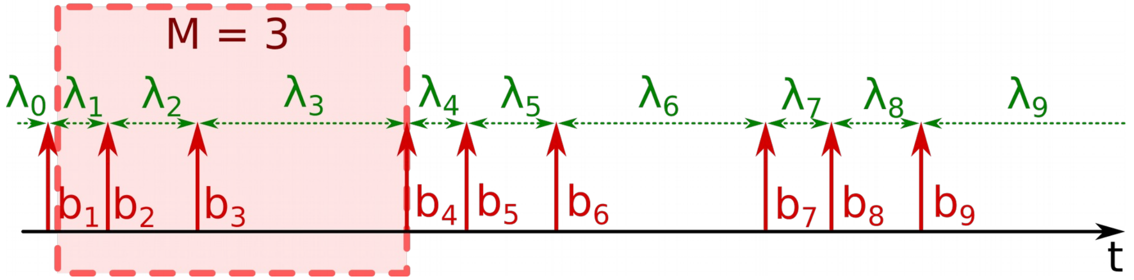
$$M = \left\lceil \frac{\sum_i d_i}{T_c} \right\rceil$$



- Fewer than M beacons → Sequence is not deterministic
- More than M beacons → Sequence covers some offsets redundantly

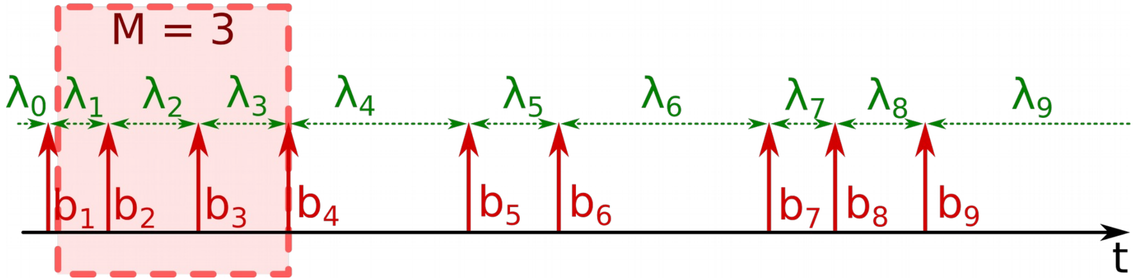
→ In an optimal sequence, exactly M beacons lead to deterministic neighbor discovery!

How to space M consecutive beacons?

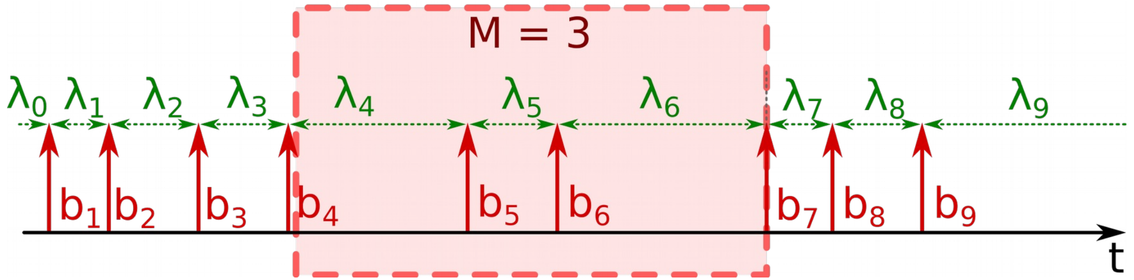


$I_A = \lambda_1 + \lambda_2 + \lambda_3$

...reduce λ_3:



$I_B = \lambda_1 + \lambda_2 + \lambda_3 < I_A$



$I_C = \lambda_4 + \lambda_5 + \lambda_6 > I_A$

How to space M consecutive beacons?

- With $\bar{\lambda}$ being the average time distance between two neighboring beacons, the optimal distance of every M consecutive beacons is $M \cdot \bar{\lambda}$
- $\bar{\lambda}$ is defined by the duty-cycle β (and hence energy budget) for transmission

→ **Fundamental bound for unidirectional ND:**

Given a beacon transmission duration ω, a reception between a receiver with duty-cycle γ and a sender with duty-cycle β cannot be guaranteed within fewer than

$$L = M \cdot \bar{\lambda} = \left\lceil \frac{1}{\gamma} \right\rceil \frac{\omega}{\beta}$$

time-units.

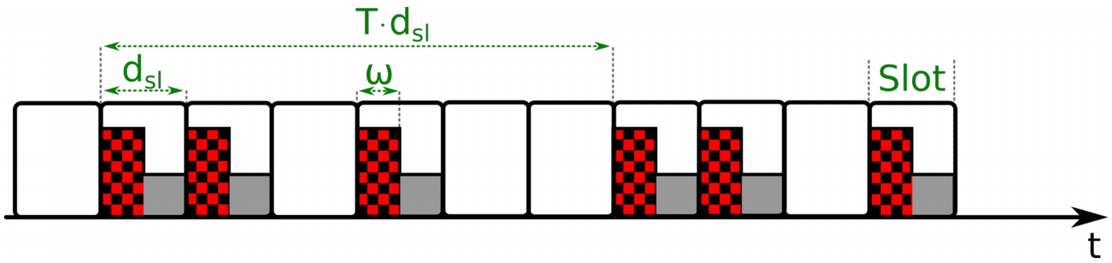
Bounds for Different Scenarios

Scenario	Description	Status
Unidirectional	**One** device **sends** beacons, the other one **listens**	✓
Symmetric Two-Way	Both devices discover each other with **identical** duty-cycles	✓
Asymmetric Two Way, Known Duty-Cycles	Both devices discover each other with **different**, **known duty-cycles**	✓
Asymmetric Two Way, Unknown Duty-Cycles	Both devices discover each other with **different**, **unknown duty-cycles**	✗
Mutually Exclusive One-Way	Both devices carry out transmission and reception, but **only one can discover is opposite**	✓
Channel-Utilization-Constrained Bidirectional	Both devices discover each other, but the collision rate and hence the **channel utilization is limited**	✓
Multiple Devices	**N different devices** discover each other (with identical/different duty-cycles) simultaneously with **limited failure-rate**	✗

Optimality in the Latency/Duty-Cycle Metric

Slotted Protocols

- A worst-case number of slots is known from [1]
- Worst-case latency L is proportional to the slot length d_{sl}
- When setting the slot length to one beacon transmission duration, the bound for slotted protocols coincides with the theoretical bound for symmetric ND
- However, $d_{sl} = \omega$ is not feasible in practice



Slot schedule according to:

[1] Rong Zheng, Jennifer C. Hou, and Lui Sha. Optimal Block Design for Asynchronous Wake-Up Schedules and Its Applications in Multihop Wireless Networks. IEEE Transactions on Mobile Computing (TMC) 5, 9 (2006), 1228–1241.

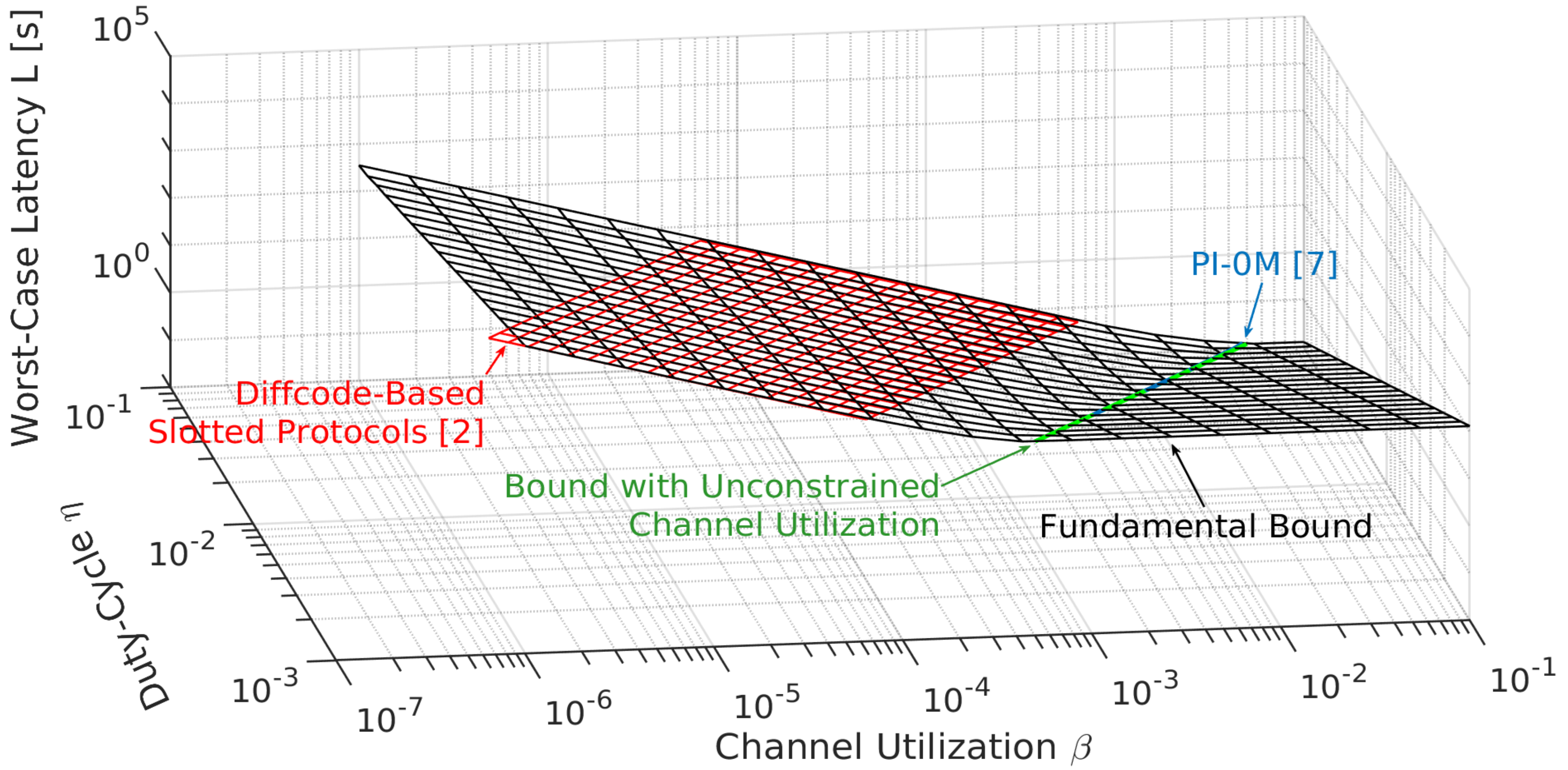
Slotted Protocols cannot achieve optimal latency/duty-cycle relations

PI-Based Protocols

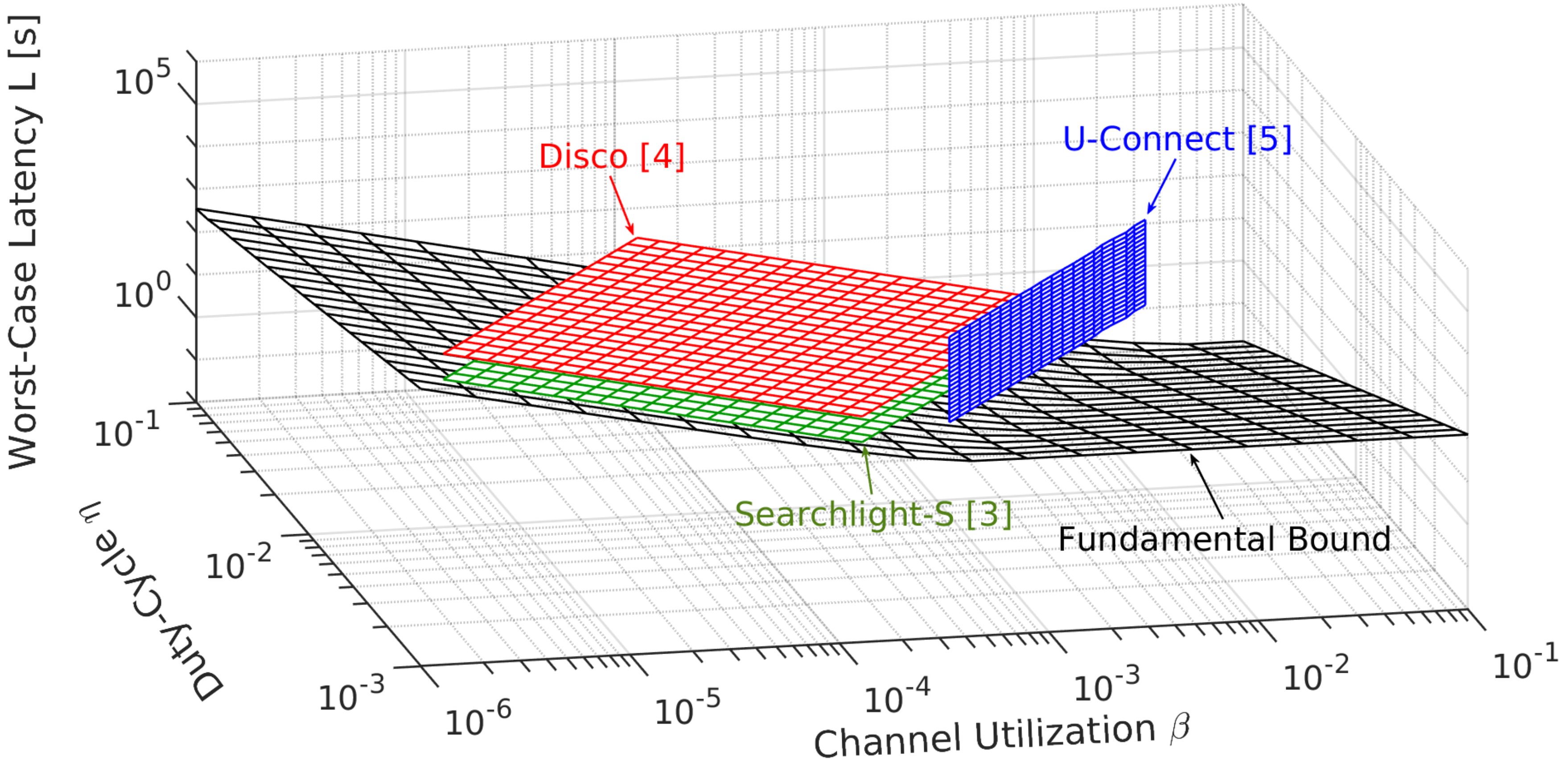
When configured according to the PI-0M parametrization scheme [7], the latencies achieved using PI-based protocols coincide with the bound for symmetric ND

PI-based protocols can achieve optimal latency/duty-cycle relations

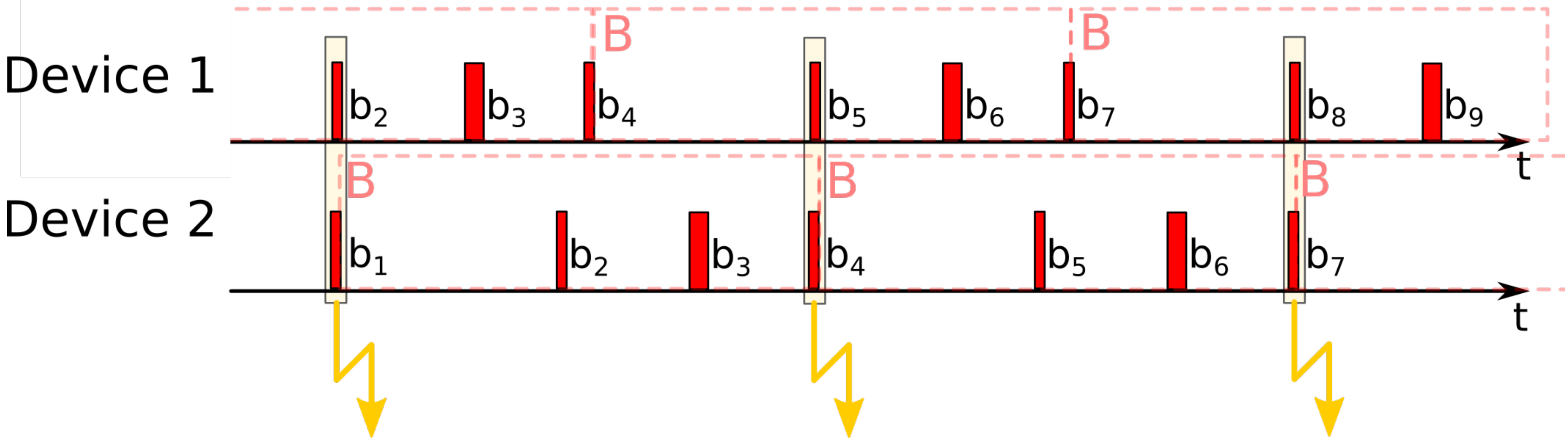
Optimality in the Latency/Duty-Cycle/Channel Utilization Metric



Optimality in the Latency/Duty-Cycle/Channel Utilization Metric (2)

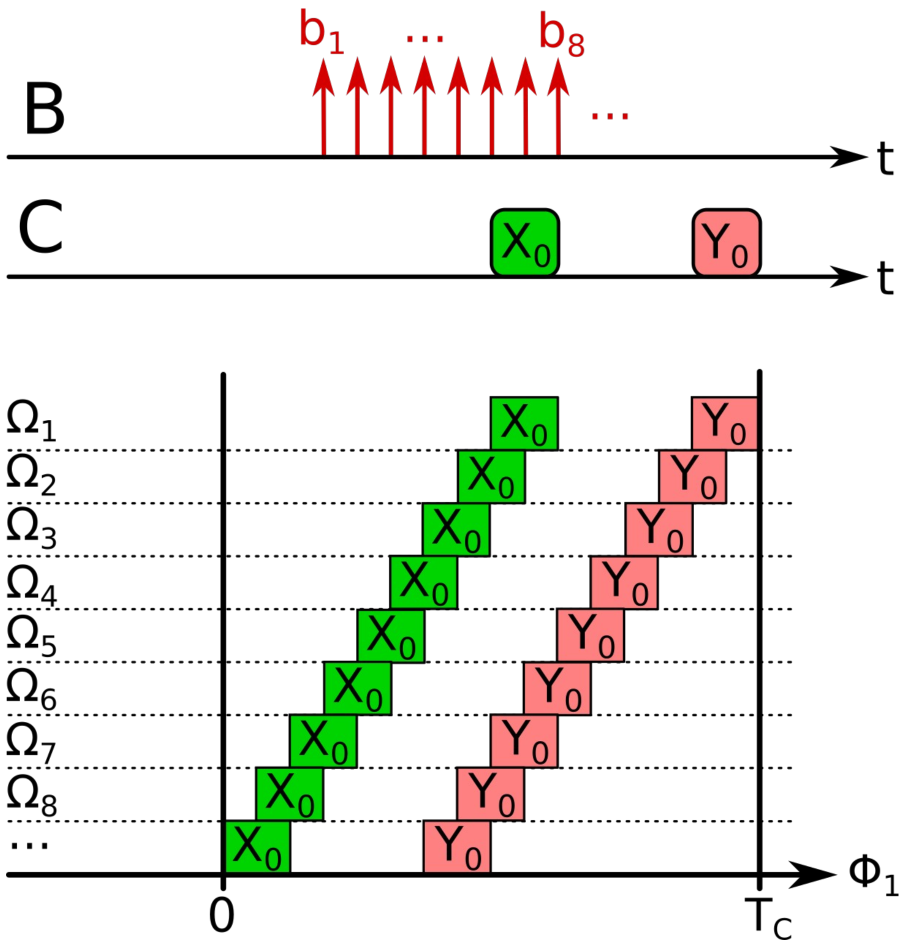


Multiple Devices



Refined notion of bounds:
What is the best discovery latency that can be guaranteed for N devices with a given rate of failed discoveries?

Multiple Devices (2)



To be answered:

- How many times should each offset be covered?
- What is the optimal channel utilization?
- How can beacon collisions be decorrelated from each other?

Conclusion

- Performance Limits of pairwise ND have been derived
- Some existing protocols perform optimally, whereas others do not
- There is no potential to increase the worst-case discovery latencies in pairwise ND
- However, for the case of multiple devices discovering each other simultaneously, no bounds are known. Hence, the optimality of known protocols remains unknown in such scenarios.

Literature:

- **[1] Diffcodes:** Rong Zheng, Jennifer C. Hou, and Lui Sha. Optimal Block Design for Asynchronous Wake-Up Schedules and Its Applications in Multihop Wireless Networks. IEEE Transactions on Mobile Computing (TMC) 5, 9 (2006), 1228–1241.
  [2] Diffcodes: Tong Meng, Fan Wu, Guihai Chen: Code-Based Neighbor Discovery Protocols in Mobile Wireless Networks. IEEE/ACM Trans. Netw. 24(2): 806-819 (2016)
- **[3] Searchlight:** Mehedi Bakht, Matt Trower, and Robin Hillary Kravets. Searchlight: Won't You Be My Neighbor?. In Annual International Conference on Mobile Computing and Networking (MOBICOM), 2012
- **[4] Disco:** Prabal Dutta and David E. Culler. Practical Asynchronous Neighbor Discovery and Rendezvous for Mobile Sensing Applications. ACM Conference on Embedded Network Sensor Systems (SenSys), 2018
- **[5] U-Connect:** Arvind Kandhalu, Karthik Lakshmanan, and Ragunathan Rajkumar. U-Connect: A Low-Latency Energy-Efficient Asynchronous Neighbor Discovery Protocol. International Conference on Information Processing in Sensor Networks (IPSN), 2010.
- **[6] Griassdi:** Philipp H. Kindt, Daniel Yunge, Gerhard Reinerth, and Samarjit Chakraborty. Griassdi: Mutually Assisted Slotless Neighbor Discovery. ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN), 2013
- **[7] PI-k2/PI-0M:** Philipp H. Kindt, Marco Saur, and Samarjit Chakraborty. 2016. Slotless Protocols for Fast and Energy-Efficient Neighbor Discovery. CoRR abs/1605.05614, 2016
- **[8] Nihao:** Ying Qiu, ShiNing Li, Xiangsen Xu, Zhigang Li: Talk more listen less: Energy-efficient neighbor discovery in wireless sensor networks. INFOCOM 2016

Questions

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Thanks for your attention!