Improving Neighbor Discovery by Operating at the Quantum Scale

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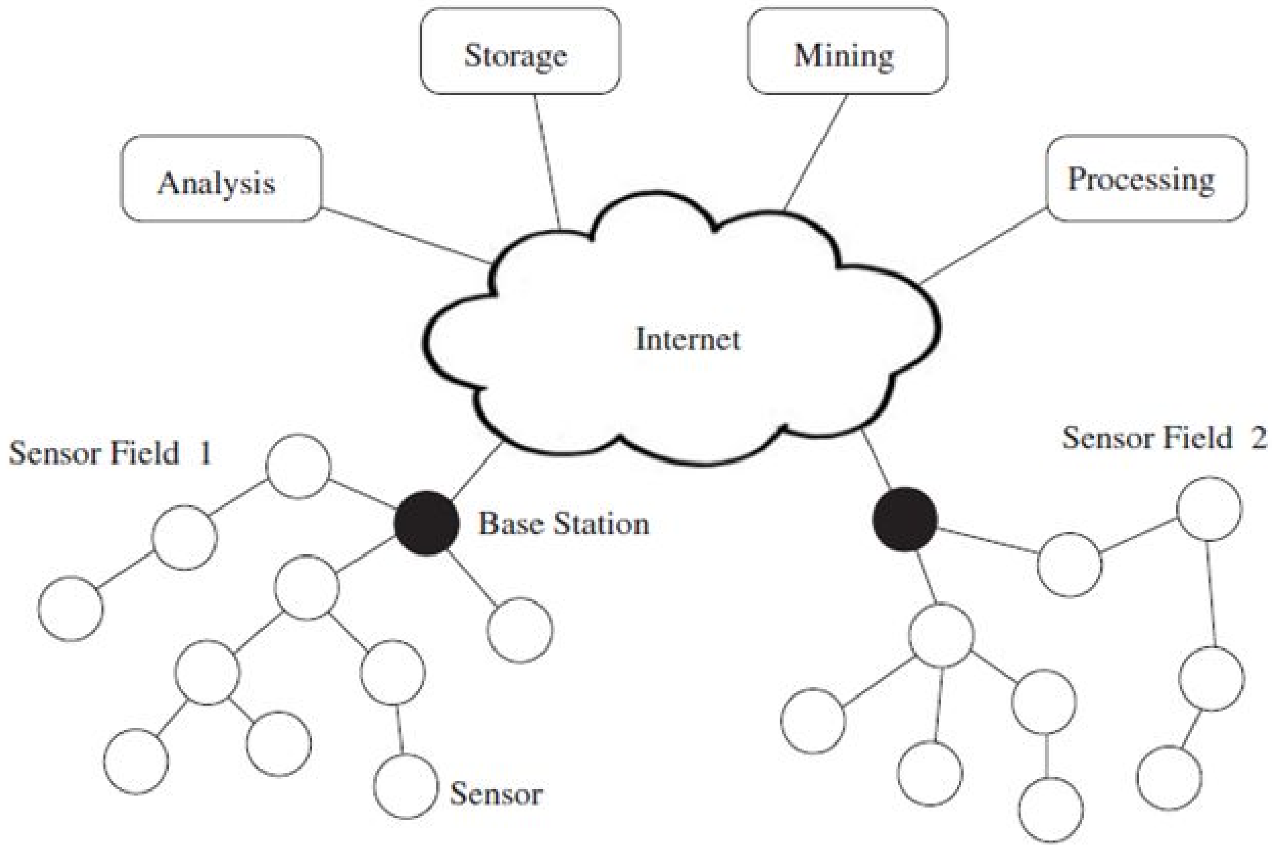
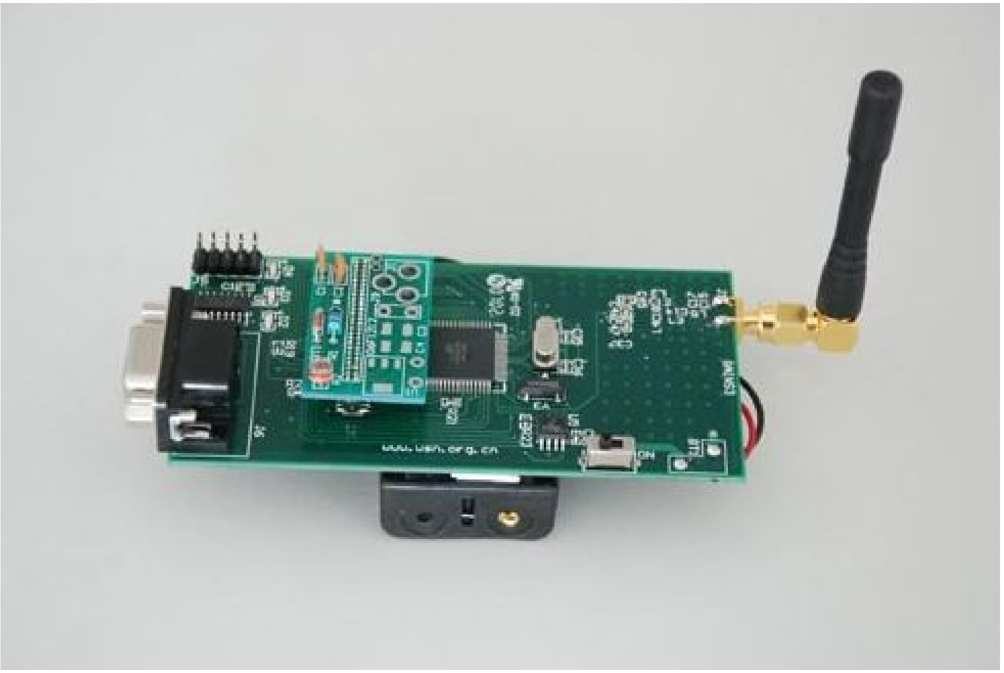
Wireless sensor networks



Power is important

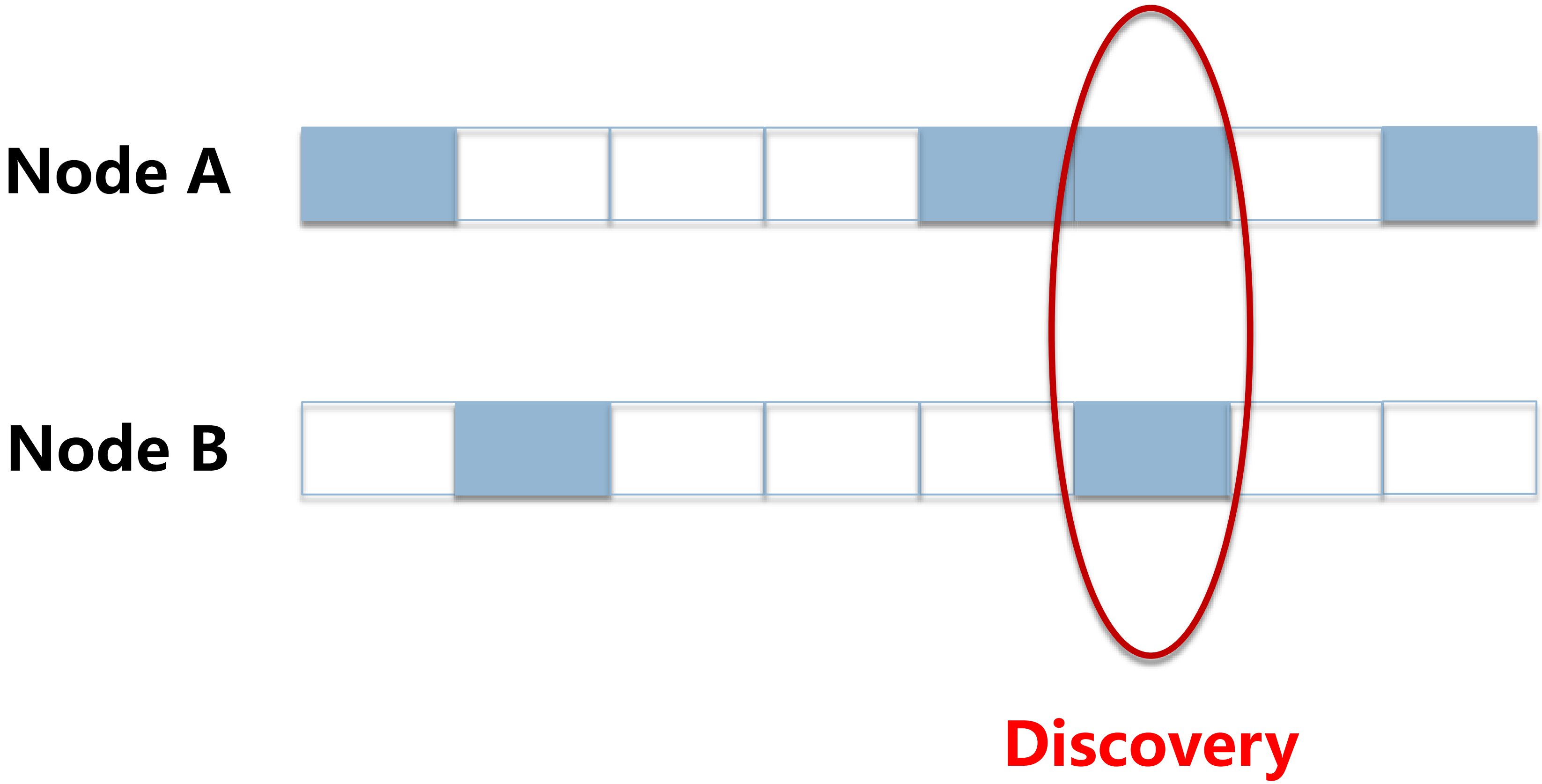


Duty-cycling adopted to save power

To support duty cycling

Need for **Neighbor discovery**

Neighbor discovery protocol



Neighbor discovery

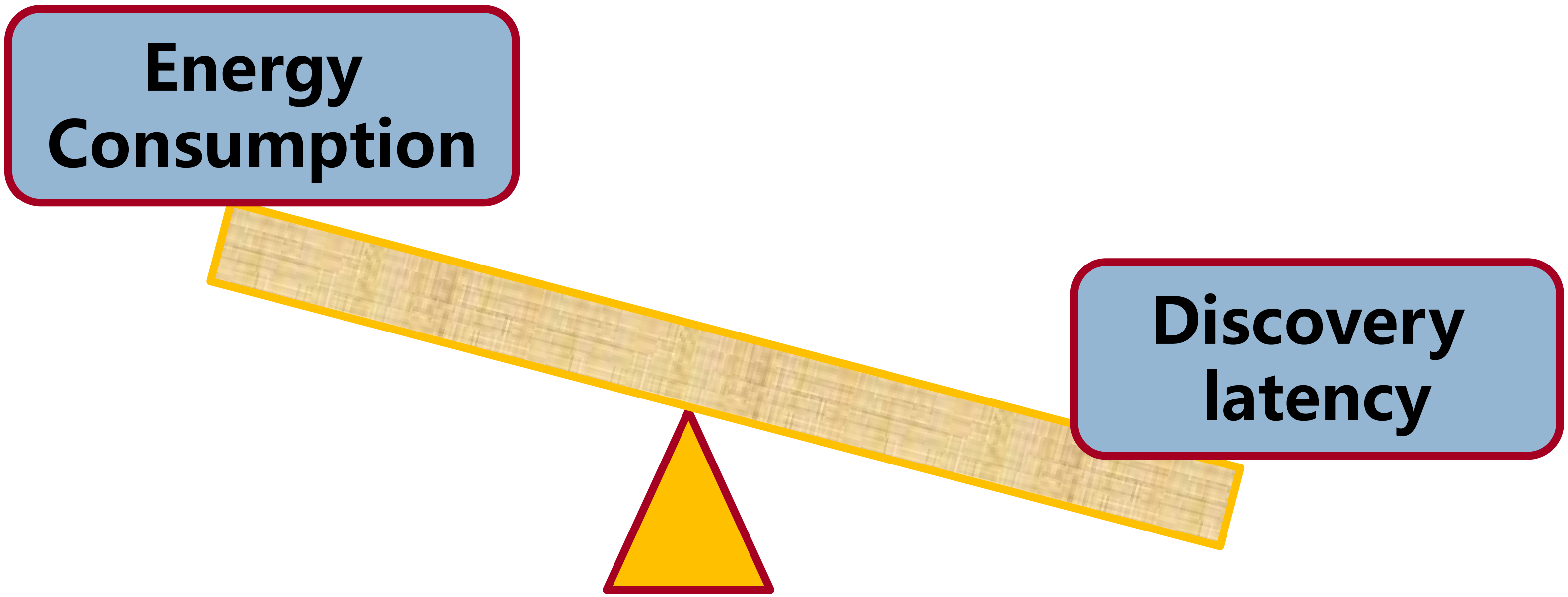
We always prefer…

Lower discovery latency
(fast discovery)

Less energy consumption
(efficient discovery)

Neighbor discovery

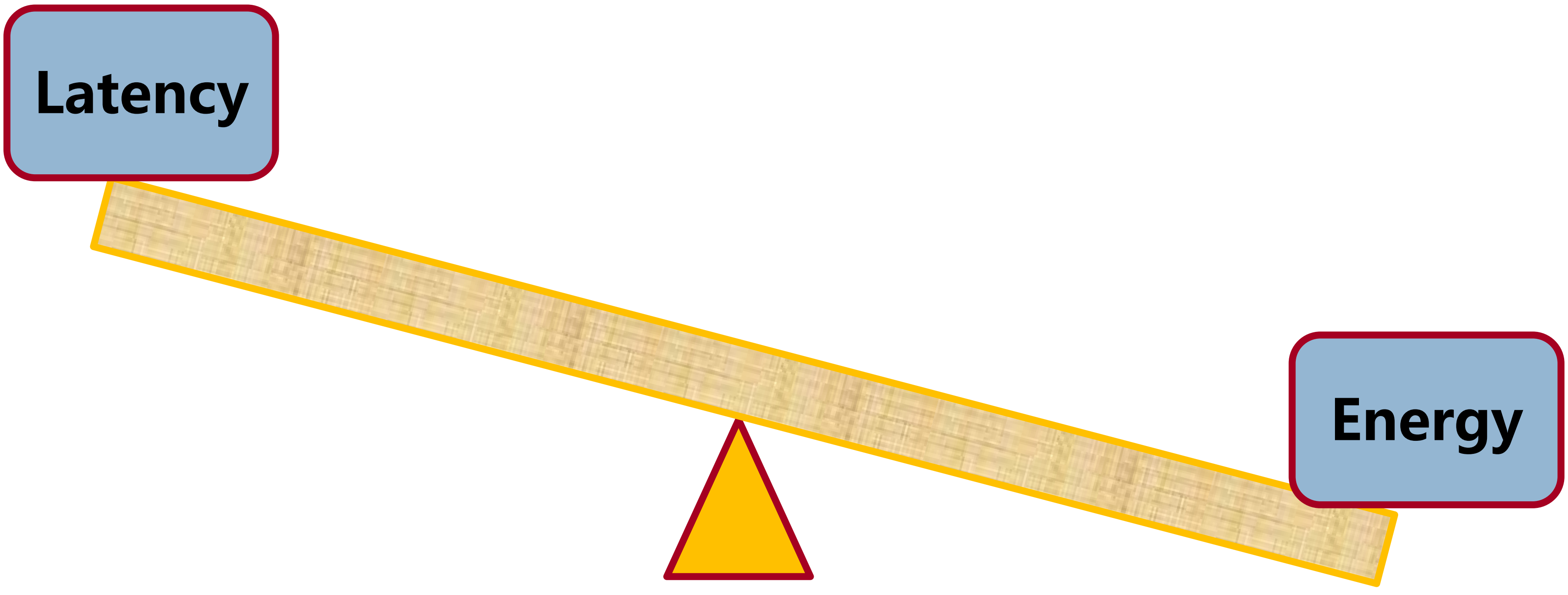
However …



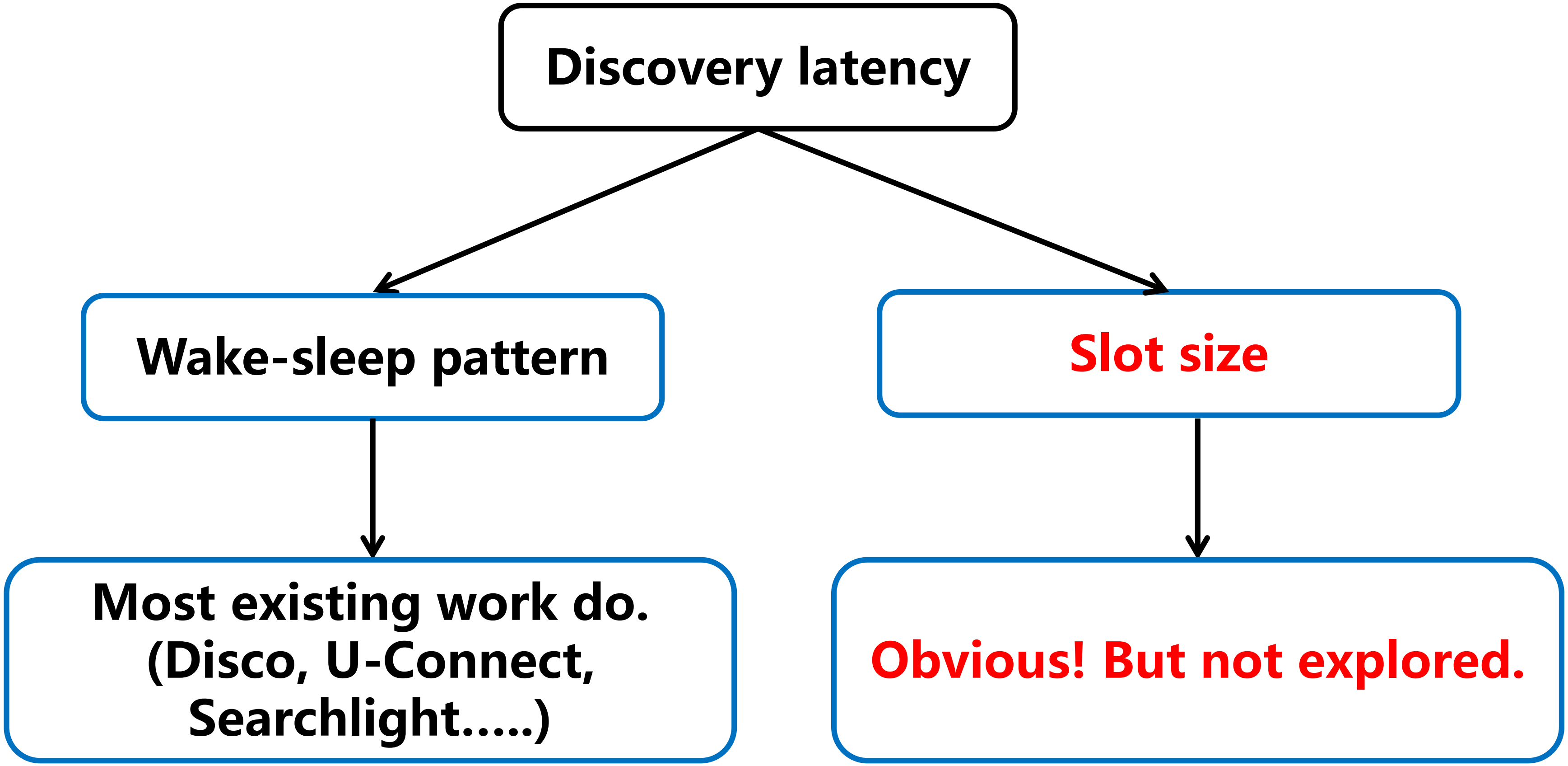
Tradeoff between latency and energy

Problem

Given a duty cycle, how to reduce latency?



Intuition


Discovery latency
Wake-sleep pattern
Slot size
Most existing work do.
(Disco, U-Connect,
Searchlight.....)
Obvious! But not explored.

Latency: Theory vs Practice

Existing work:

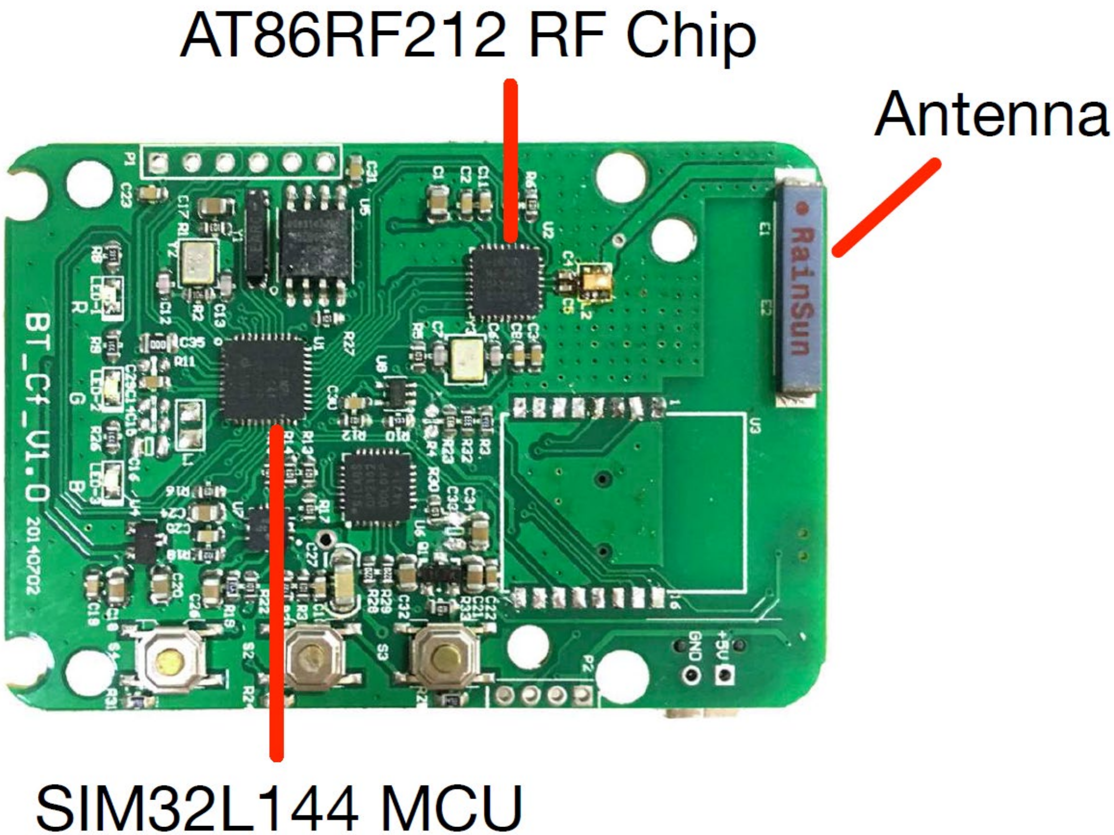
$$Latency = N\_slot$$

In practice:

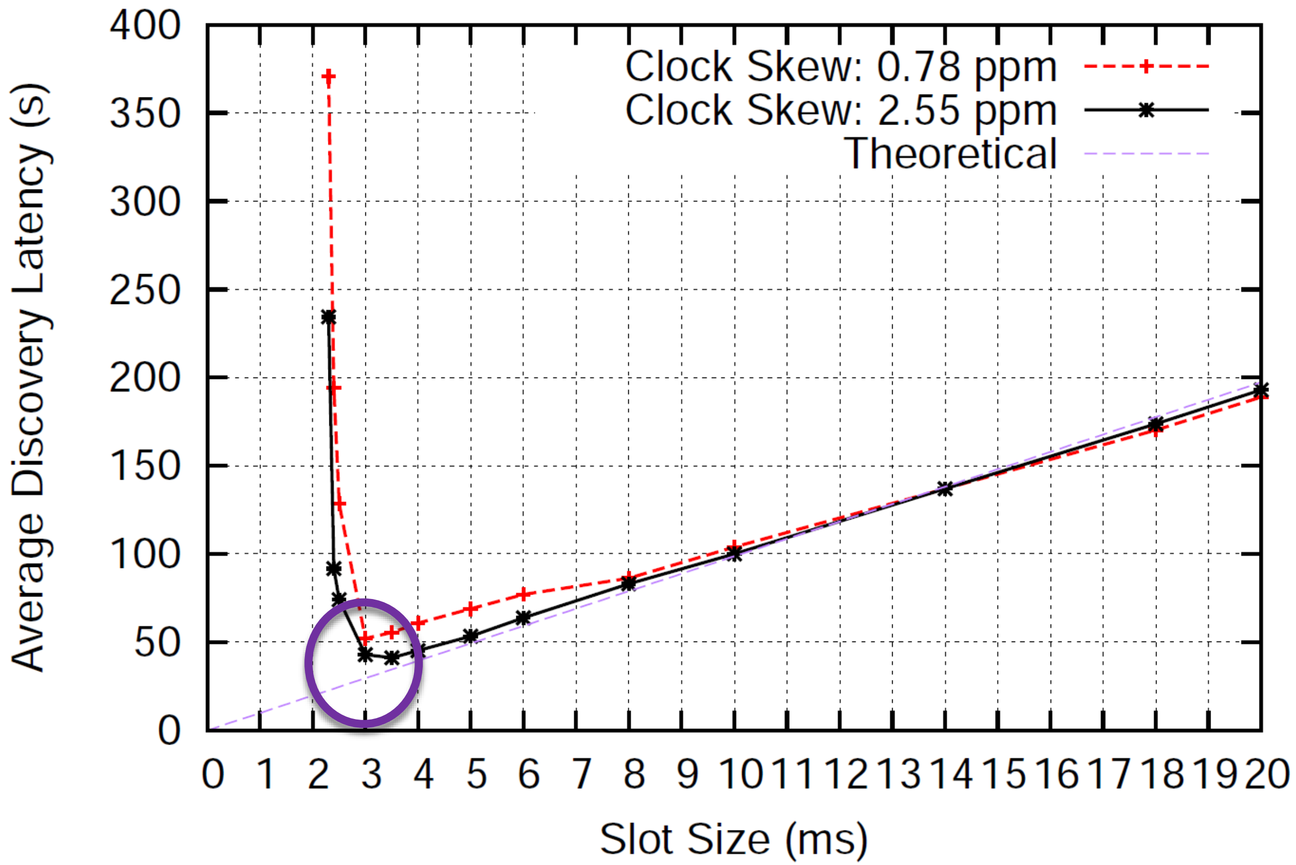
$$Latency = N\_slot \times S\_size$$

How far can we go in reducing latency simply by reducing the slot size?

Measurement study

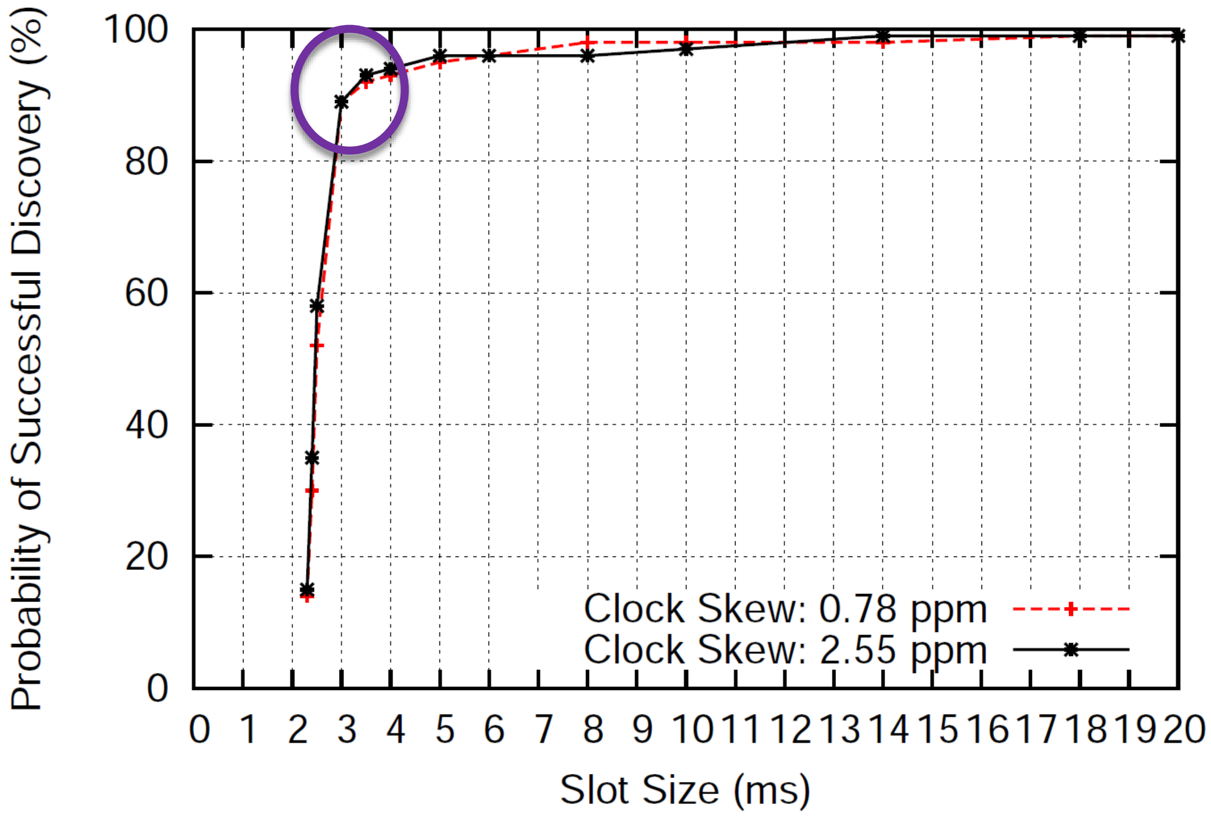


Measurement study



Quantum Scale

Measurement study

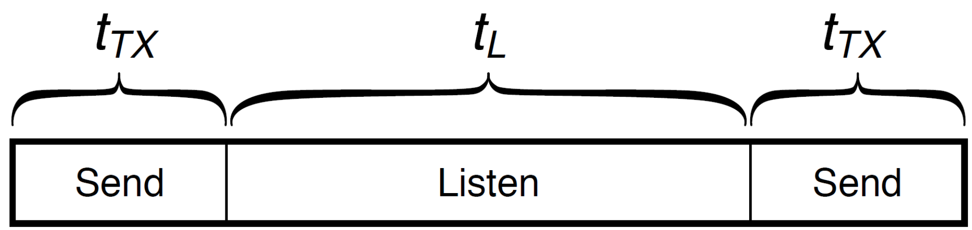


Within Quantum scale, active slots overlap **cannot** guarantee discovery in **one period**!

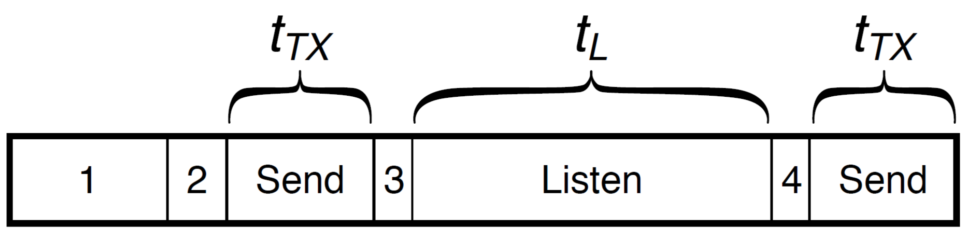
What happens at the Quantum scale?

- Active slot modeling

Theoretical:



Practical:



1. WARM_UP
2. TRX_OFF→PLL_ON
3. PLL_ON→RX_ON
4. RX_ON→PLL_ON

What happens at the Quantum scale?

- Active slot modeling

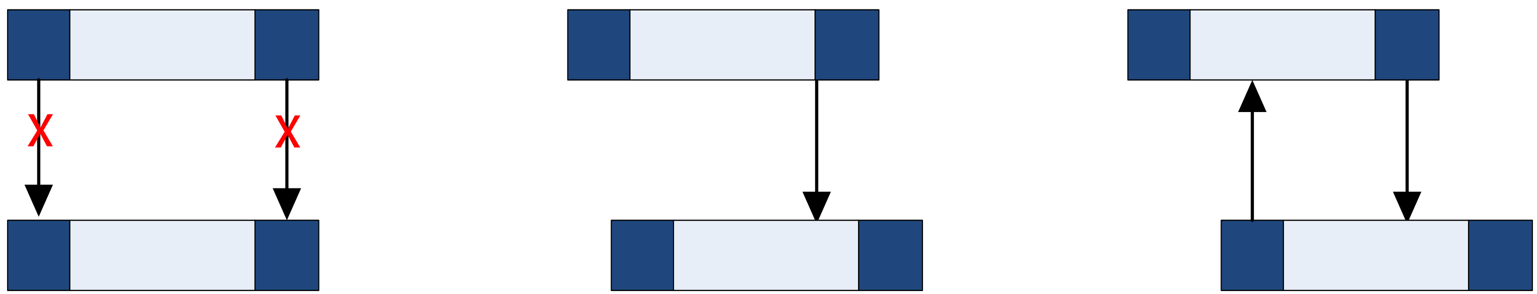
$$S = 2t_{TX} + t_D + \underbrace{t_{RX} + t_{PR}}_{t_L}$$

Pre slots

$$S = 2t_{TX} + t_L$$

What happens at the Quantum scale?

- Practical discovery cases



Discovery Failure | One-sided discovery | Mutual discovery

We treat one-sided and mutual discovery the **same** in practice

What happens at the Quantum scale?

- Latency with discovery failure

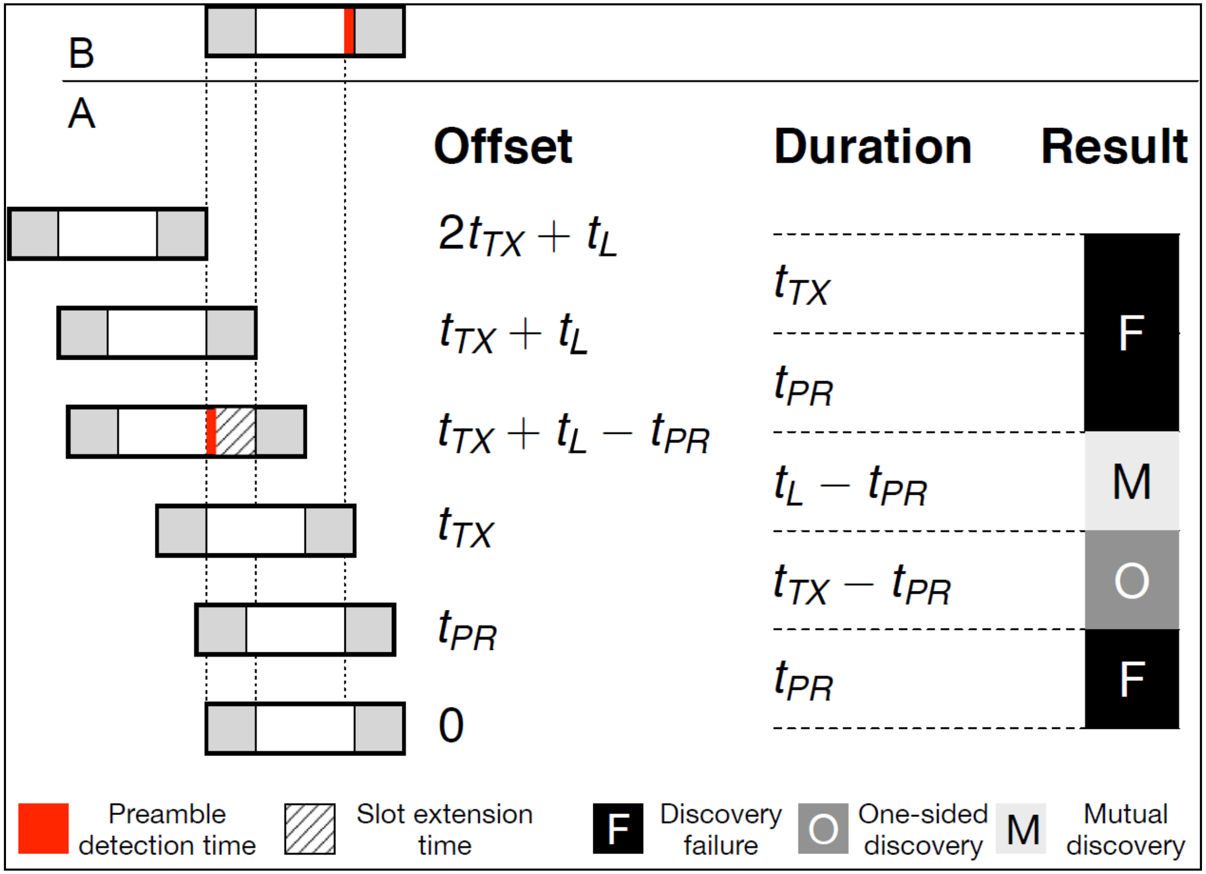
$$L_{theoretical} = N \times S$$

$$L_{actual} = N \times S + \Delta T$$

$$\bar{L}_{actual} = N \times S + P_{fail} \Delta T$$

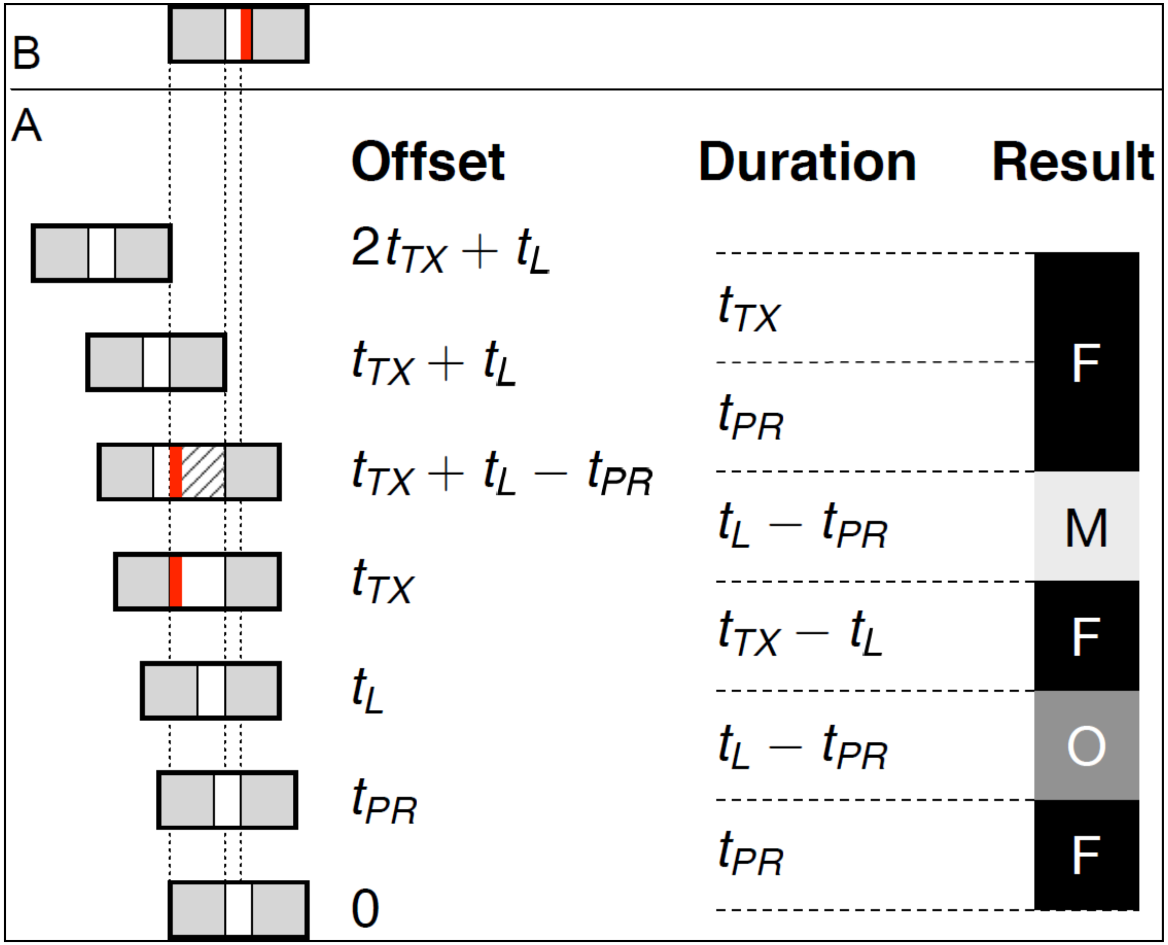
What happens at the Quantum scale?

- Quantifying P_{fail}



What happens at the Quantum scale?

- Quantifying P_{fail}



What happens at the Quantum scale?

- Quantifying P_{fail}

$$P_{\text{fail}} = \begin{cases} \dfrac{2t_{\text{TX}} - t_{\text{L}} + 2t_{\text{PR}}}{2t_{\text{TX}} + t_{\text{L}}}, & t_{\text{L}} \leq t_{\text{TX}} \\[2ex] \dfrac{t_{\text{TX}} + 2t_{\text{PR}}}{2t_{\text{TX}} + t_{\text{L}}}, & t_{\text{L}} > t_{\text{TX}} \end{cases}$$

P_{fail} increases when slot size decreases!

What we have learned?

- **Key findings**
  - **Collisions** between beacons have a non-negligible effect on latency when operating at Quantum scale.
  - **Synchronization** can cause ΔT to become very large when the relative clock skew between a pair of nodes is small

So how??

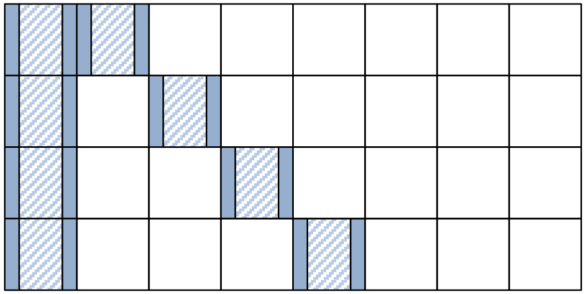
Mitigate beacon collisions → **Reduce Beacon density**

Reduce synchronization → **Introduce randomization**

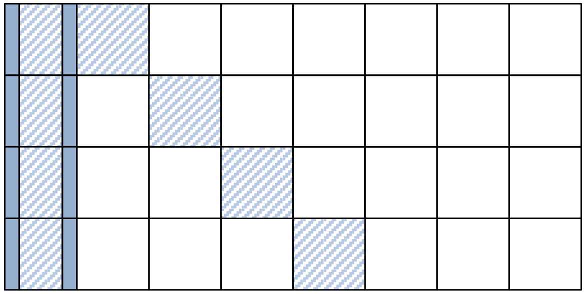
Our solutions

- Reducing beacon density (based on Searchlight)

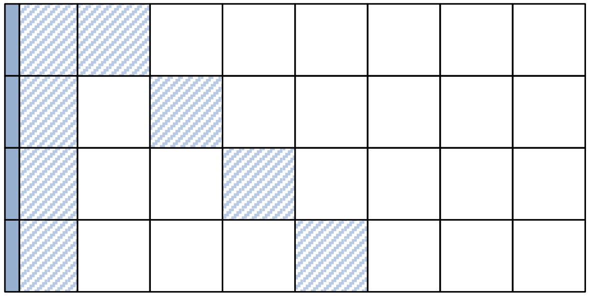
B-L-B



A(B-L-B)P(L)

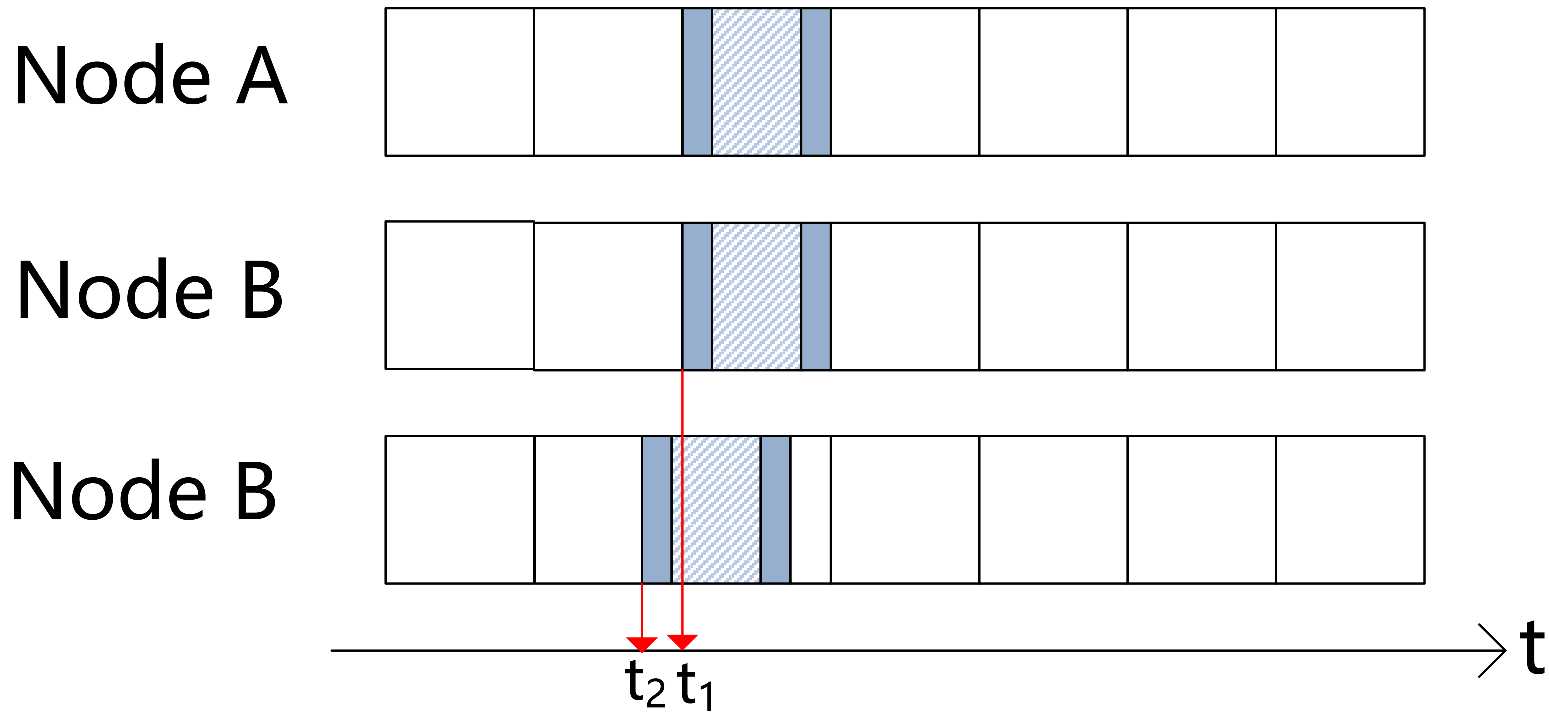


ABPL



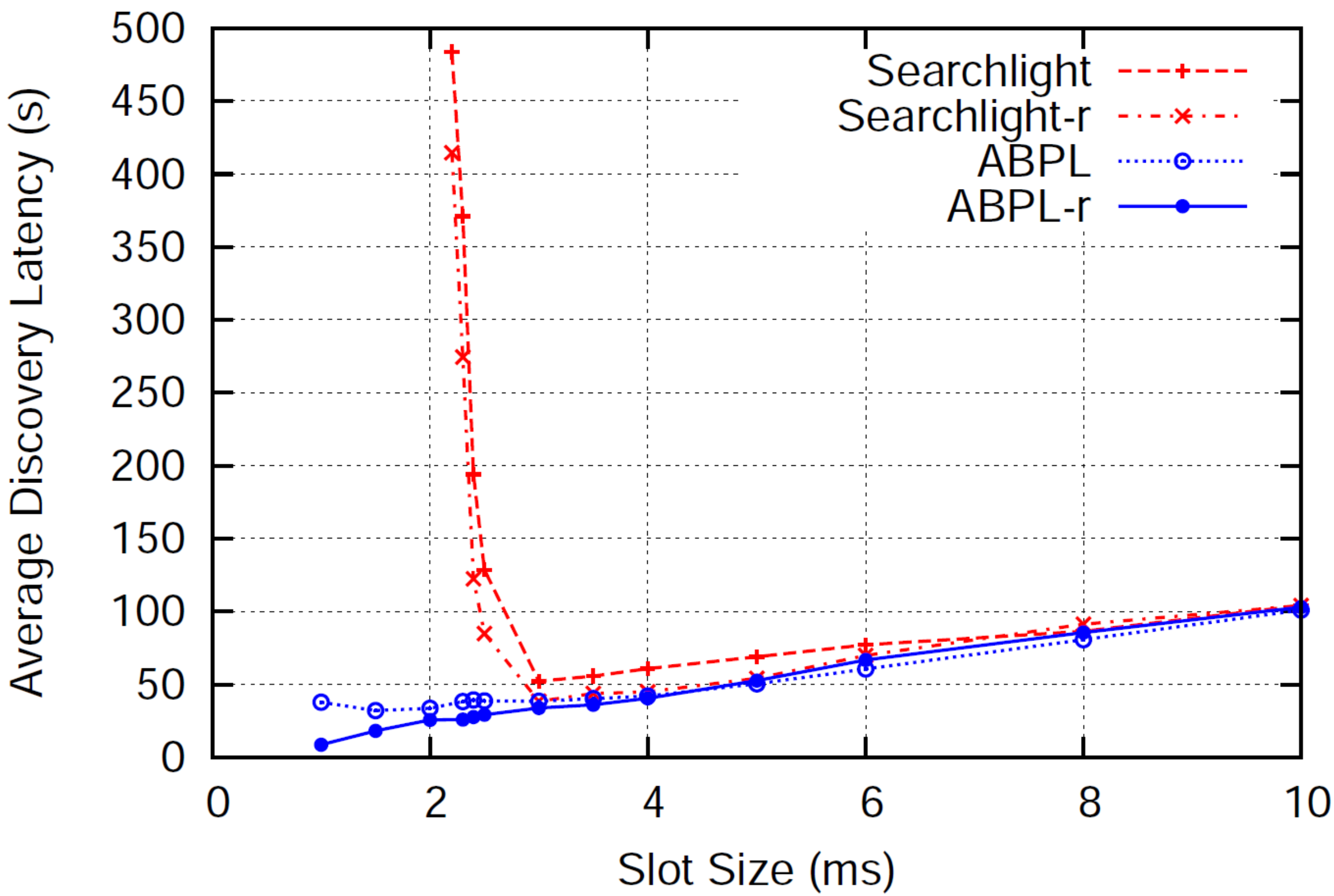
Our solutions

- Introducing randomization



Our solutions

- Effect of ABPL and Randomization



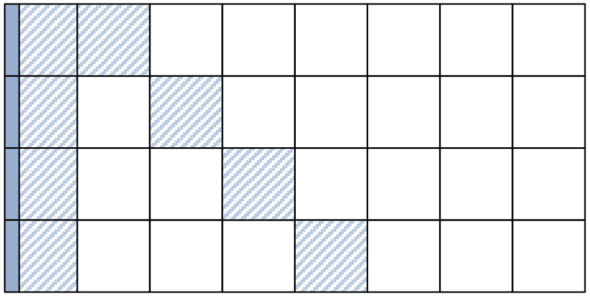
Finished?

Not yet!
we can do
even better!

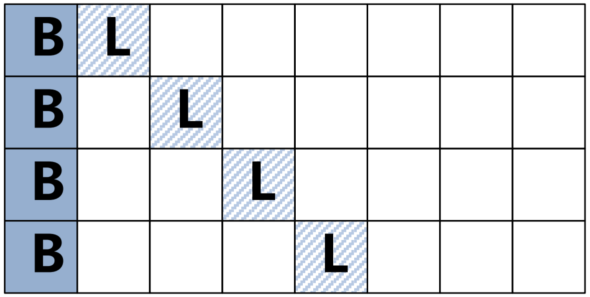
The limit of slot size

- Further reduce slot size

ABPL



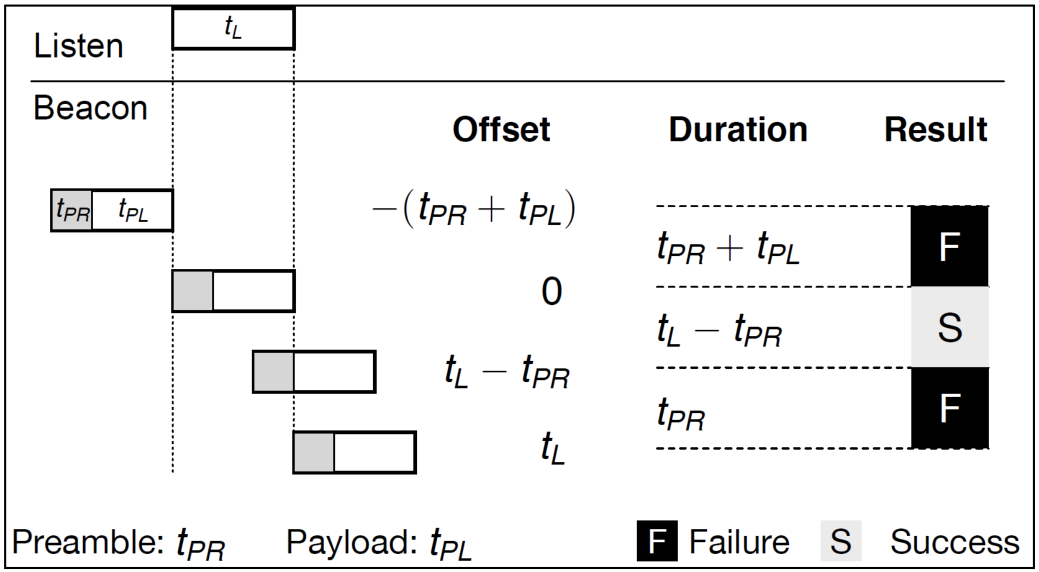
BL



Heterogeneous slots

Focused on listening

- **Probing considered harmful**



$$P_{fail} = \frac{t_{PR}}{t_L}$$

With a 1ms slot size and 0.2ms preamble, P_{fail} = **20%**

Combining all probe slots

- **Spotlight**

B	L						
B		L					
B			L				
B				L			

B	L	L	L	L			
B							
B							
B							

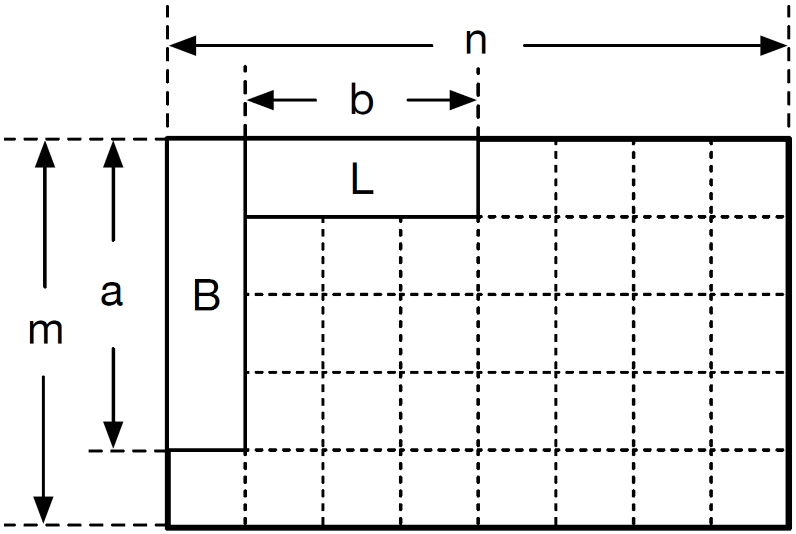
$$P_{fail} = \frac{t_{PR}}{t_L}$$

$$P_{fail} = \frac{t_{PR}}{n \bullet t_L}$$

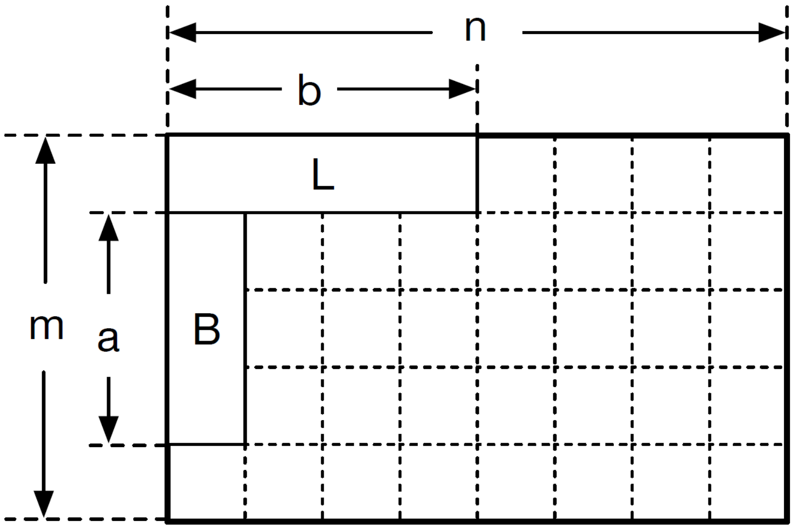
With 1% duty cycle,P_{fail} can be reduced from **20%** to **0.2%**

Spotlight

- BL diagrams with pattern matrices M(m,n,a,b)



Variant 1



Variant 2

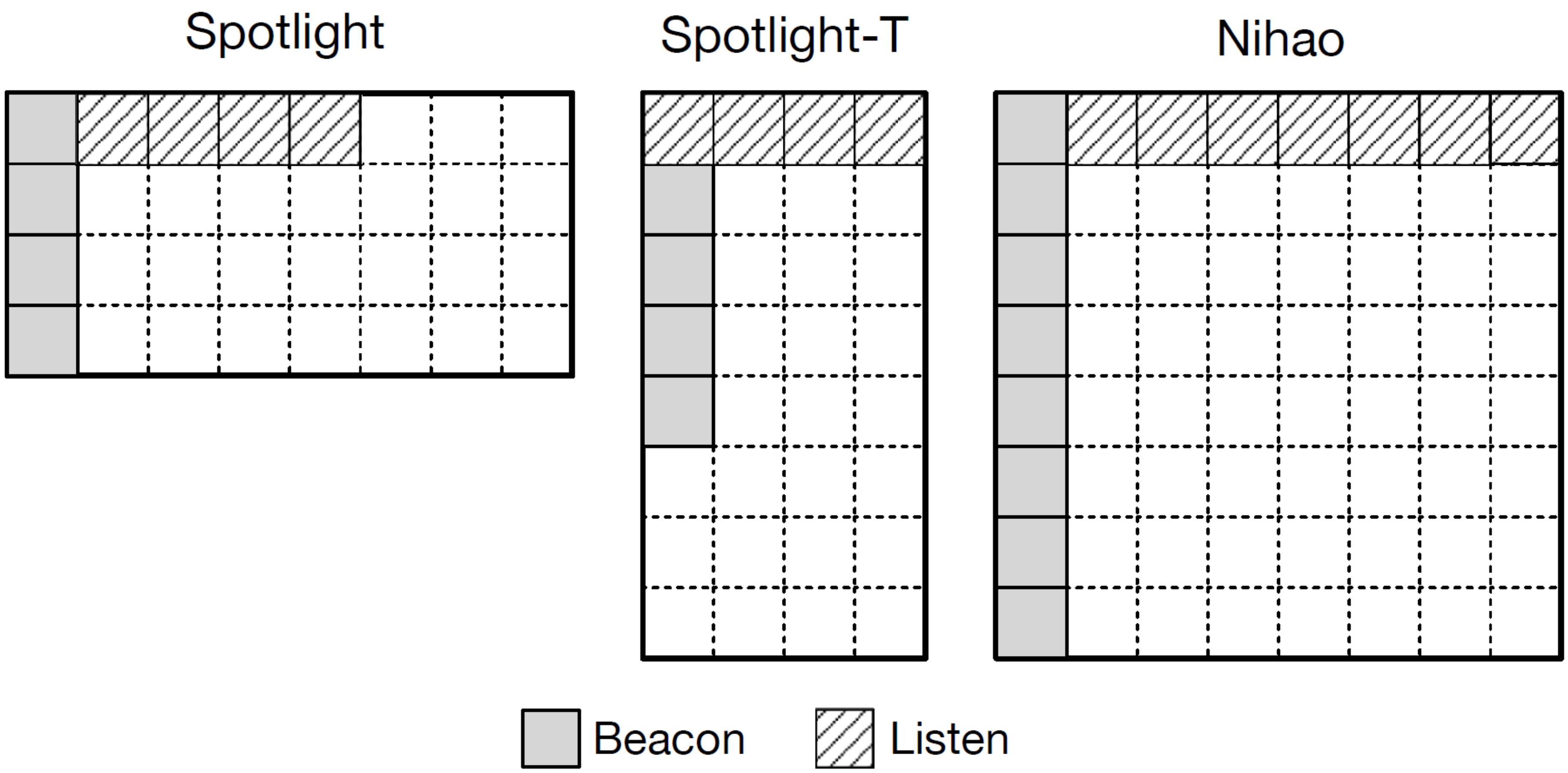
Spotlight with matrices M(m,2m,m,m)

Spotlight

- Achieve discovery guarantees
- Spotlight achieve the best worst-case latency
- Worst-case latency is *mn* slots
- Proof and details in paper!

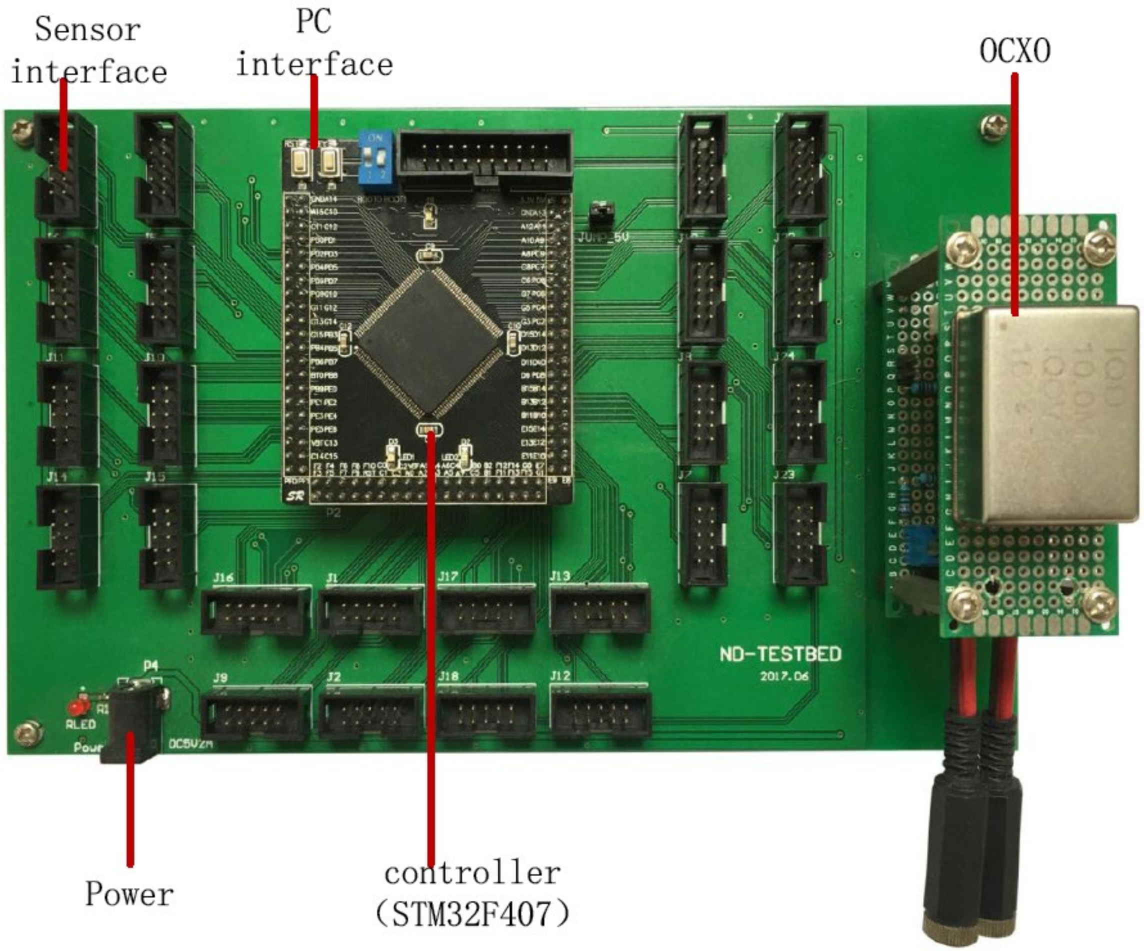
Spotlight

- Comparison with Nihao



Evaluation

- Testbed



Evaluation

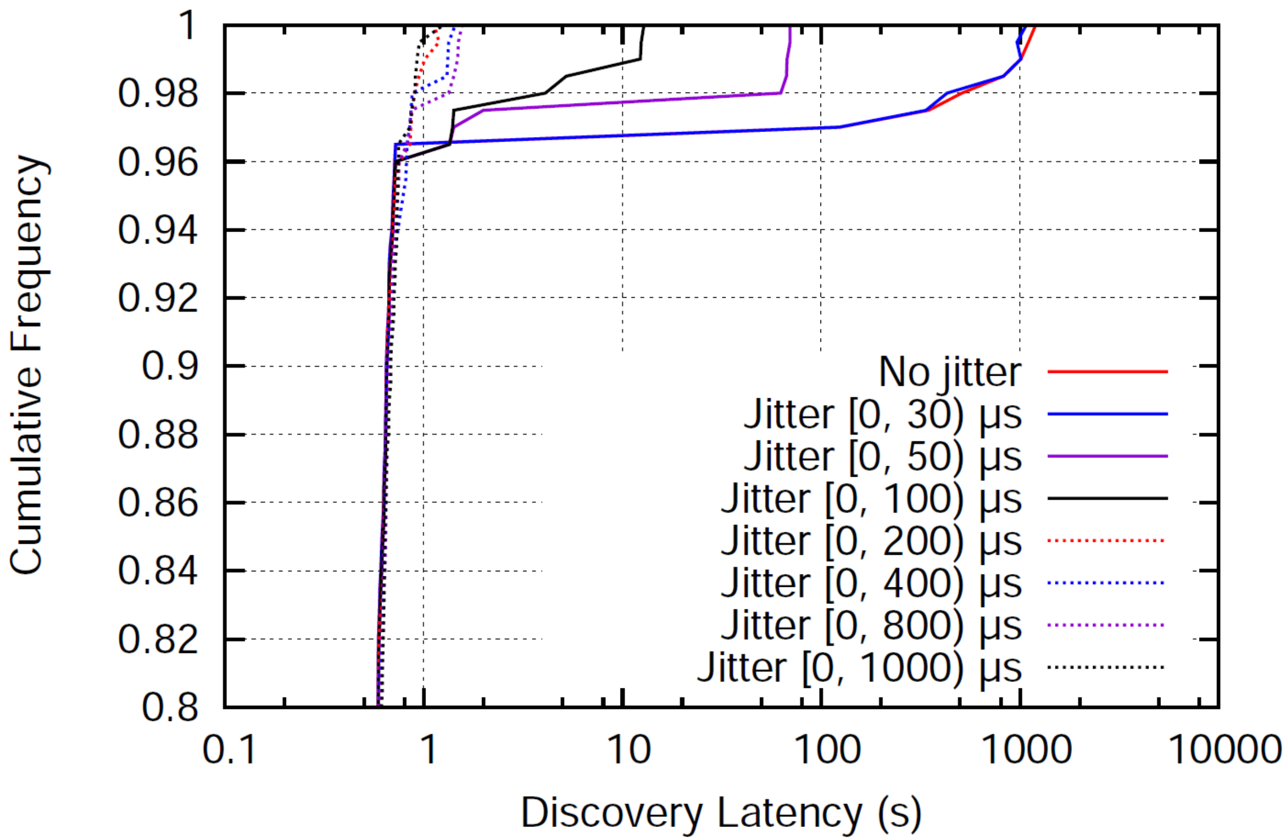
- **Experimental Setup**
  - Use 20 nodes
  - Duty cycle 1% and 5%

Parameters for evaluated algorithms

Algorithm	Duty Cycle	Period (slots)	Active slots
ABPL-r	1%	20,000	100BL+100L
B-Nihao	1%	$10,000(1+\alpha)^2$	1BL+199B+199L
Searchlight	1%	20,000	200BLB
Spotlight	1%	20,000	100B+100L
Spotlight-T	1%	20,000	100B+100L
ABPL-r	5%	800	20BL+20L
B-Nihao	5%	$400(1+\alpha)^2$	1BL+19B+19L
Searchlight	5%	800	40BLB
Spotlight	5%	800	20B+20L

Evaluation

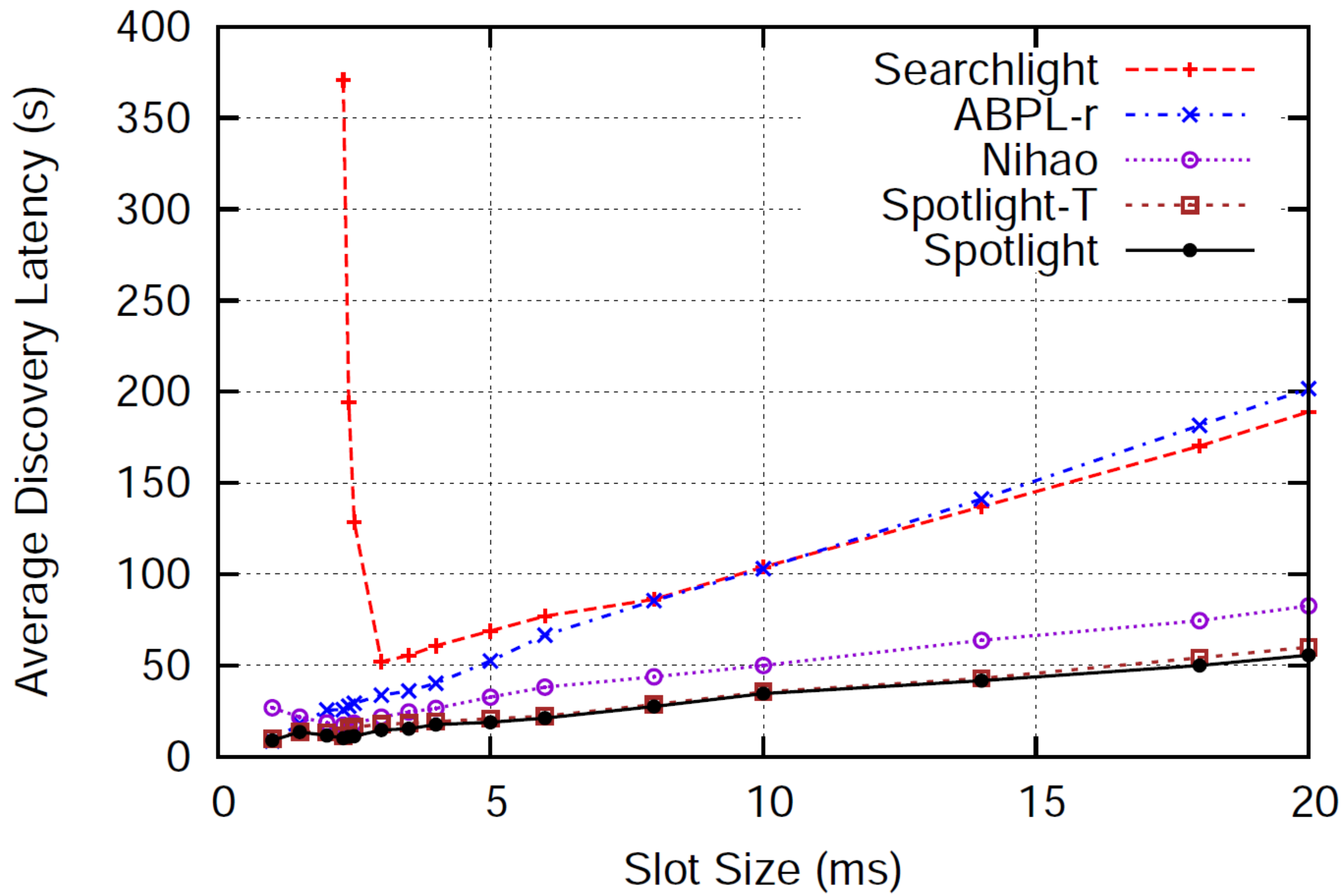
- Optimal amount of jitter



The jitter amount should be comparable to **preamble** length.

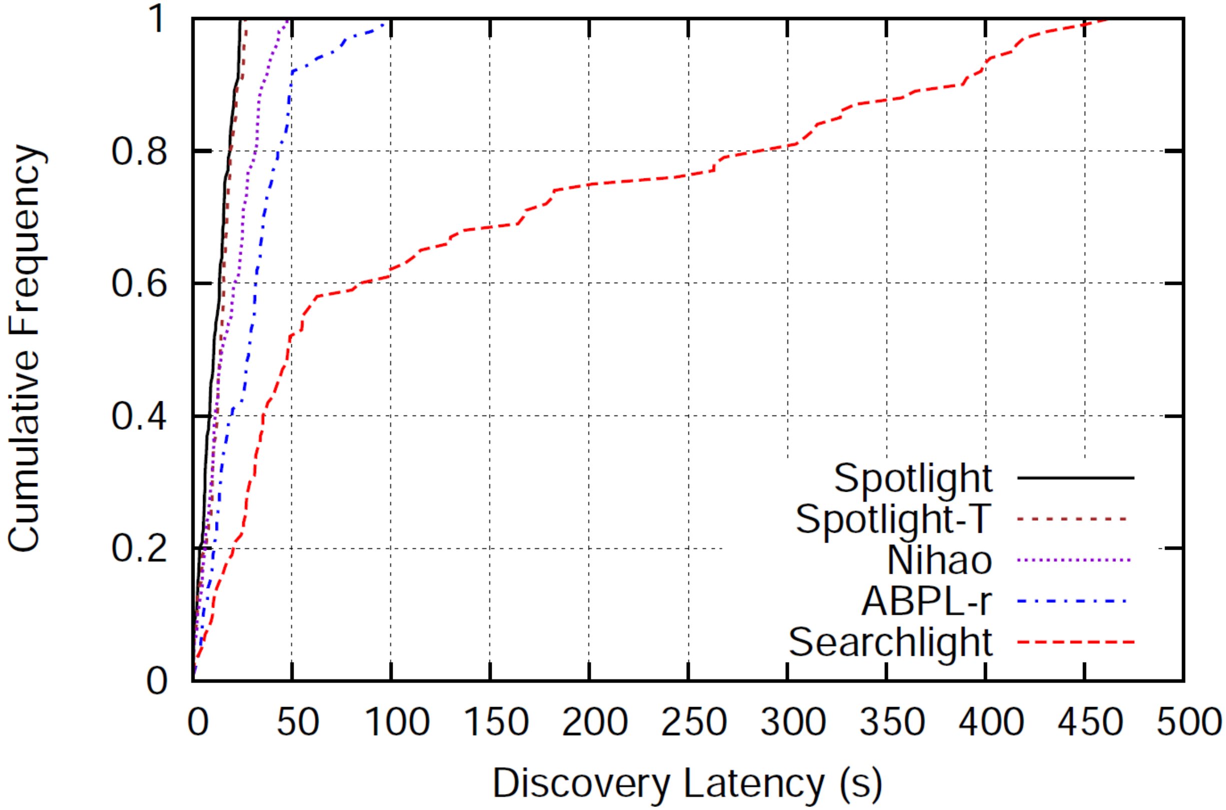
Evaluation

- **Comparison to the state-of-the-art**



Evaluation

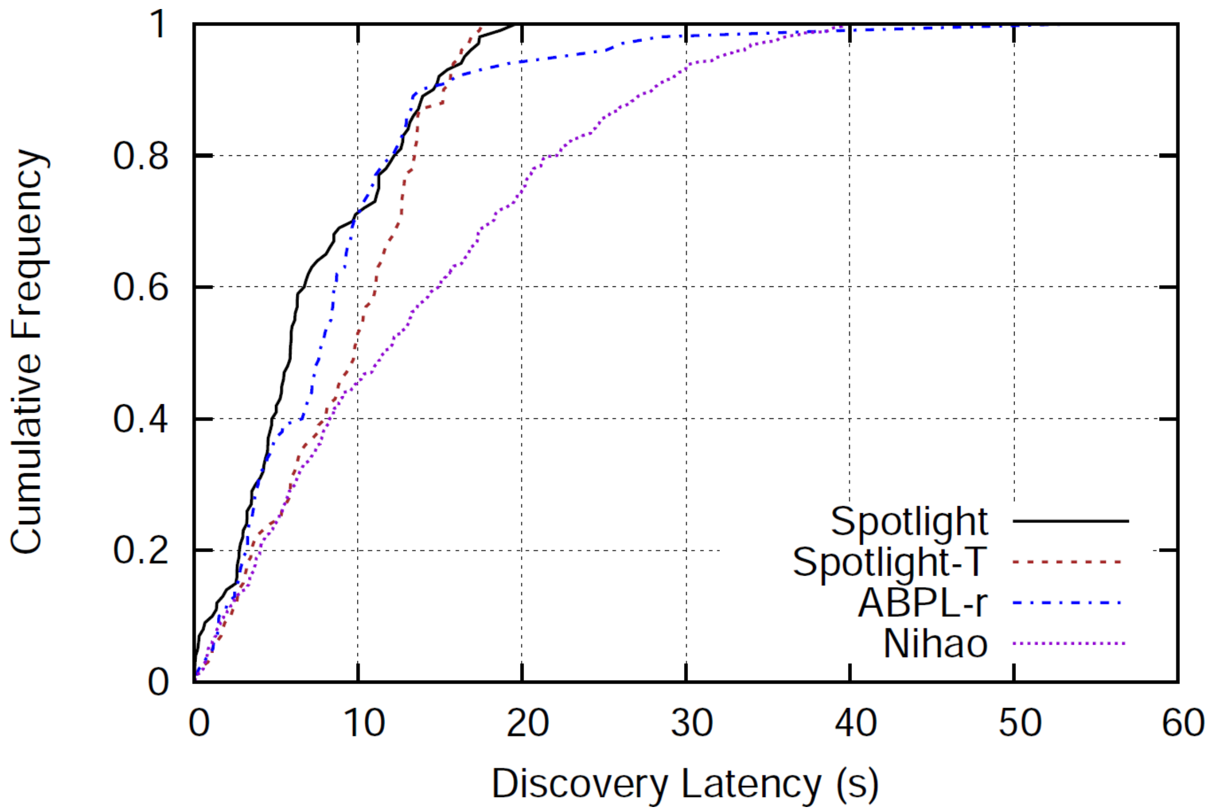
- **Comparison to the state-of-the-art**



CDF for 2.5ms slot size at 1% duty cycle.

Evaluation

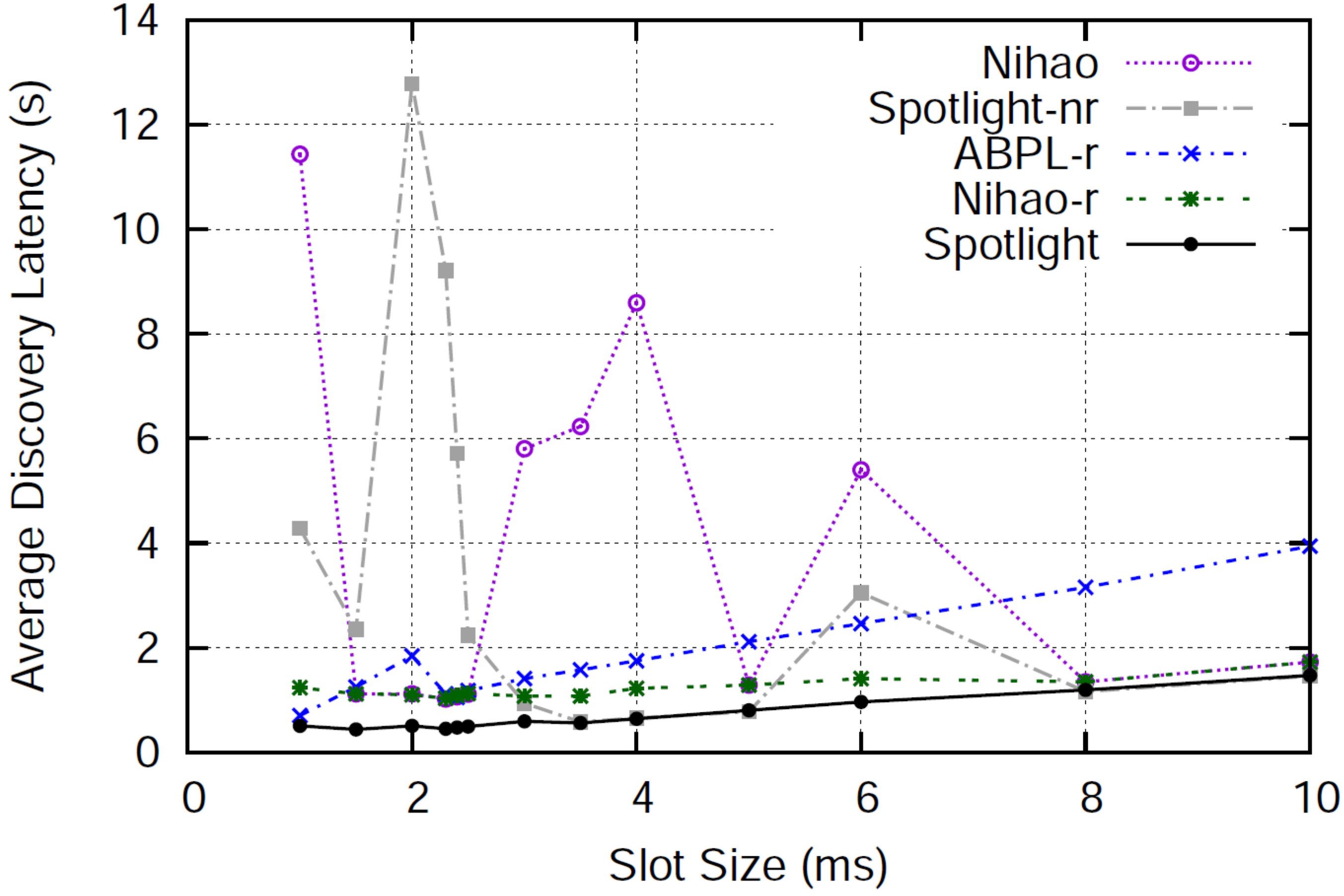
- Comparison to the state-of-the-art



CDF for 1ms slot size at 1% duty cycle.

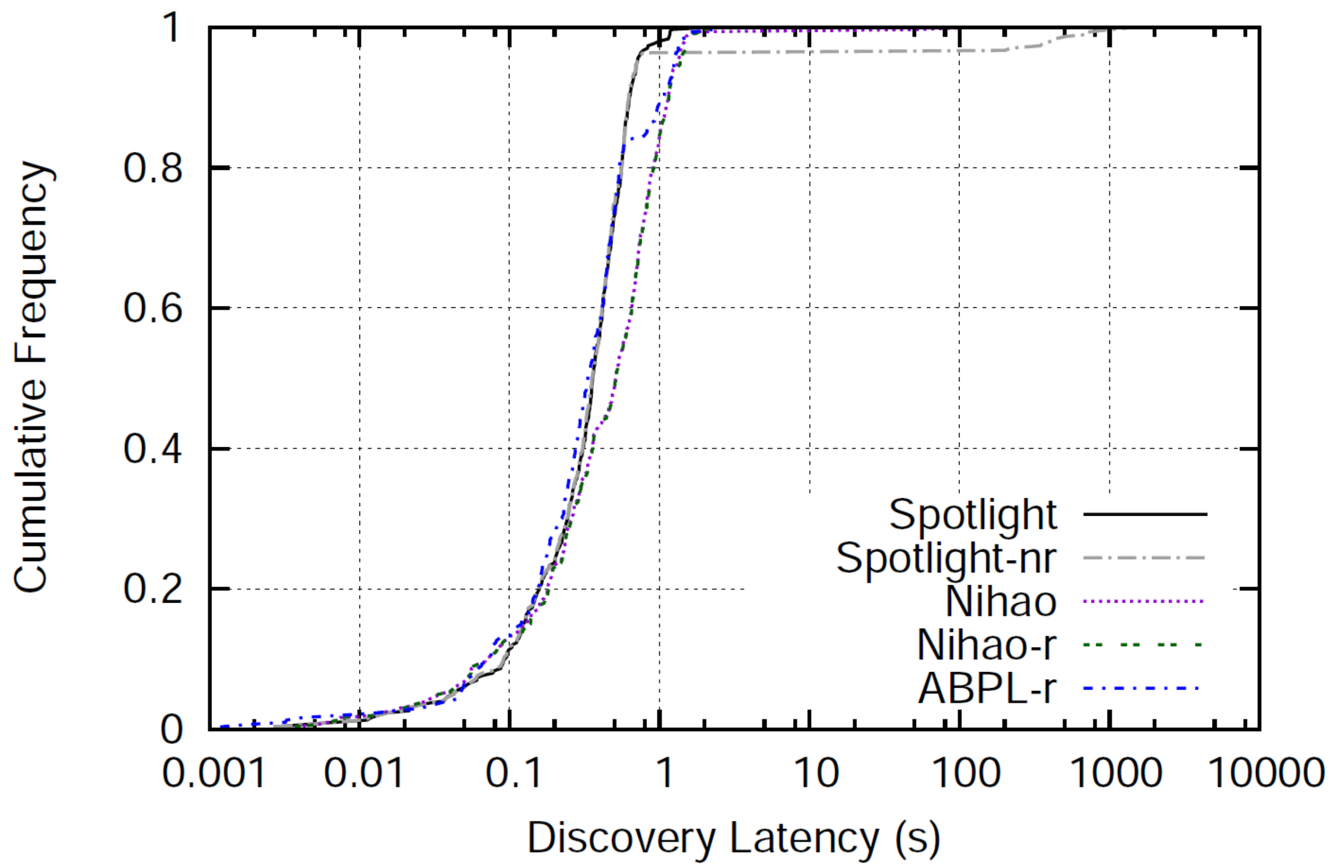
Evaluation

- Performance at higher duty cycle



Evaluation

- **Performance at higher duty cycle**



CDF for 1ms slot size at 5% duty cycle.

Summary

- Collisions between beacons and synchronization between nodes become more severe when operating at the Quantum scale.
- Reduce beacon density and introduce randomization to mitigate the collision and synchronization problem.
- We propose a new continuous-listening-based neighbor discovery algorithm called Spotlight.
- Evaluations with a practical sensor testbed show that Spotlight can achieve a 50% reduction in discovery latency over existing state-of-the-art protocols at the same energy consumption

Thank You!