Enabling Bit-by-Bit Backscatter Communication in Severe Energy Harvesting Environments

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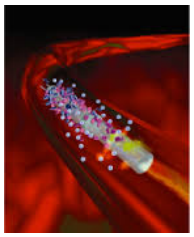
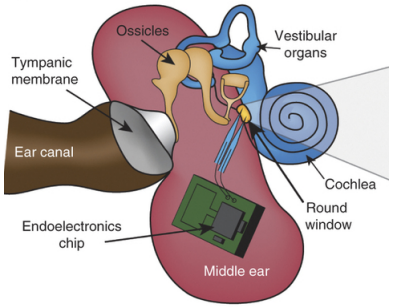
Network Stacks on Energy Harvesting Sensors

Micro-powered sensors



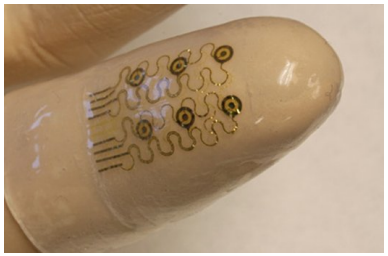
Glucose sensor in bloodstream

Vital signs bandaid



In-ear molecular sensor

Google contact lens



Epidermal electronics

Network Stacks on Energy Harvesting Sensors

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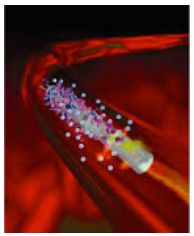

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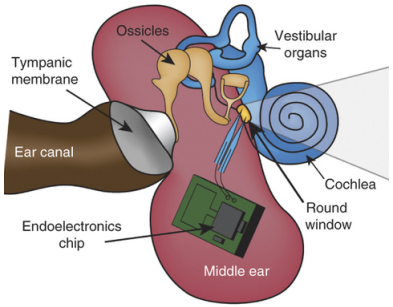

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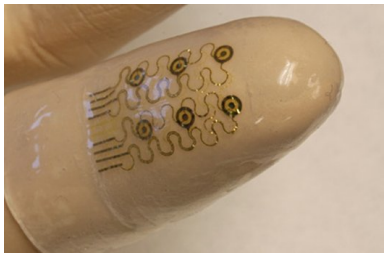
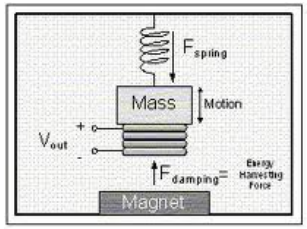


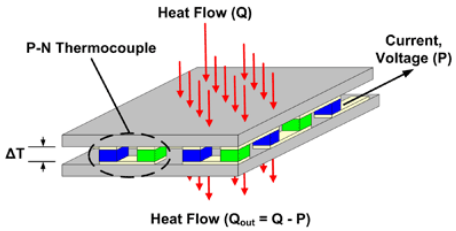
Epidermal electronics

Energy Harvester

Micro-solar cells

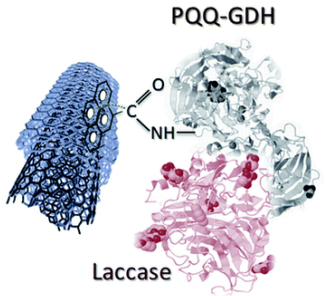


Vibration



Thermal gradient

Wireless signal



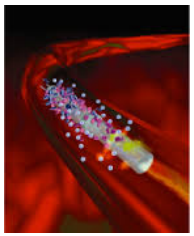
Biofuel cells

Network Stacks on Energy Harvesting Sensors

Network stack

PHY | Link | MAC | Transport | APP

Micro-powered sensors



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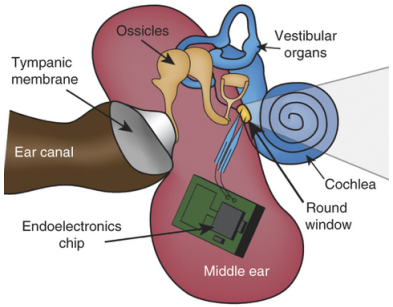

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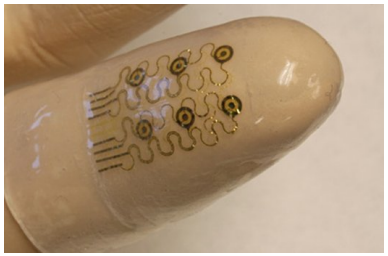

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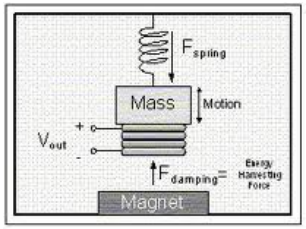
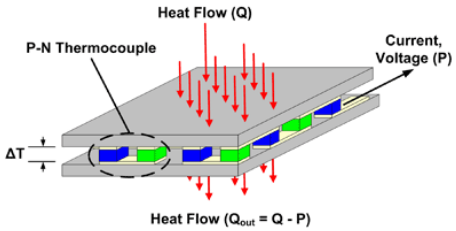


Vibration



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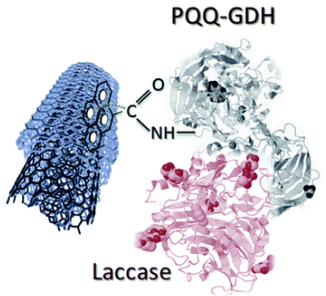
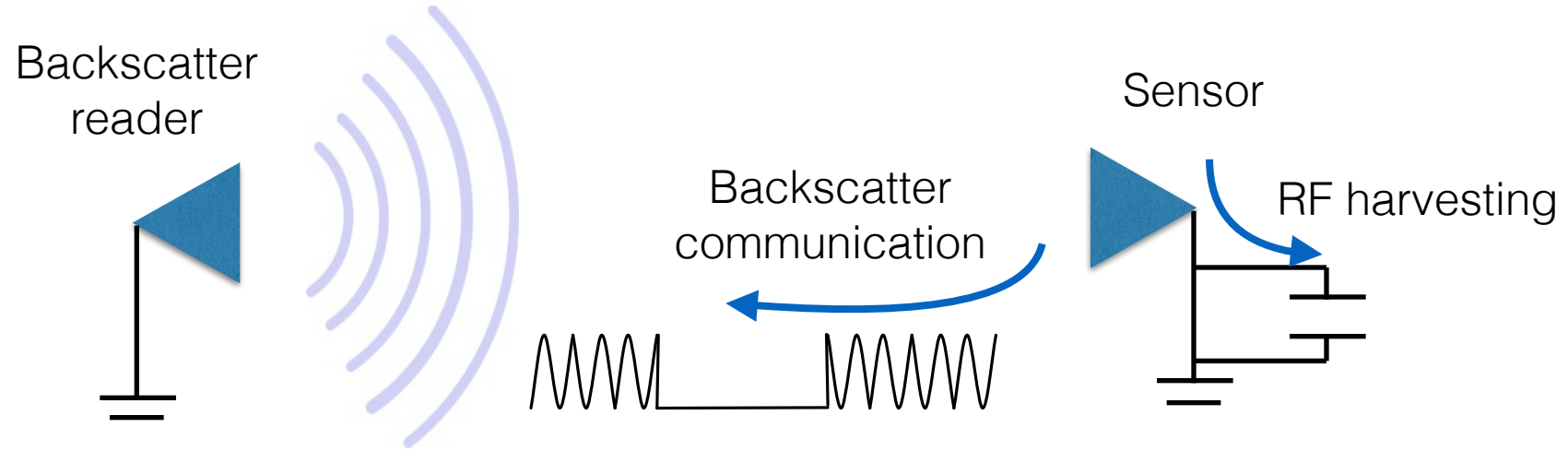


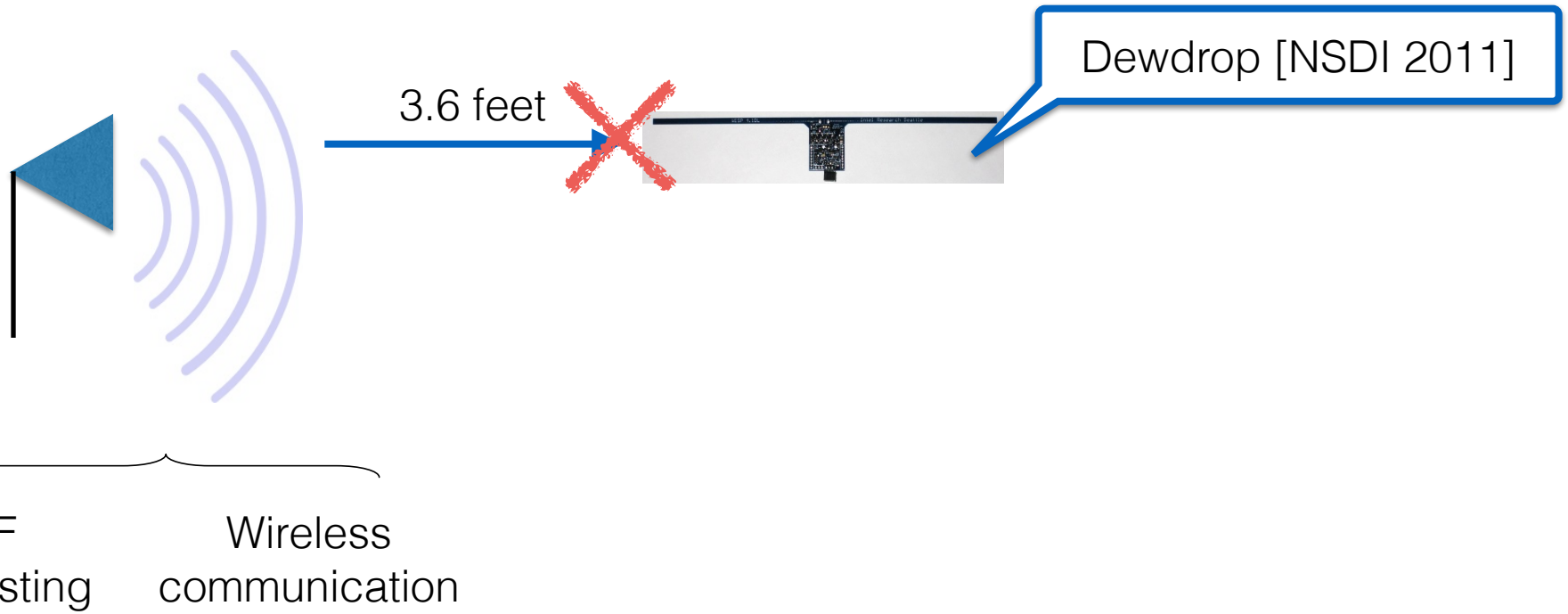
Biofuel cells

RF Harvesting and Backscatter Communication

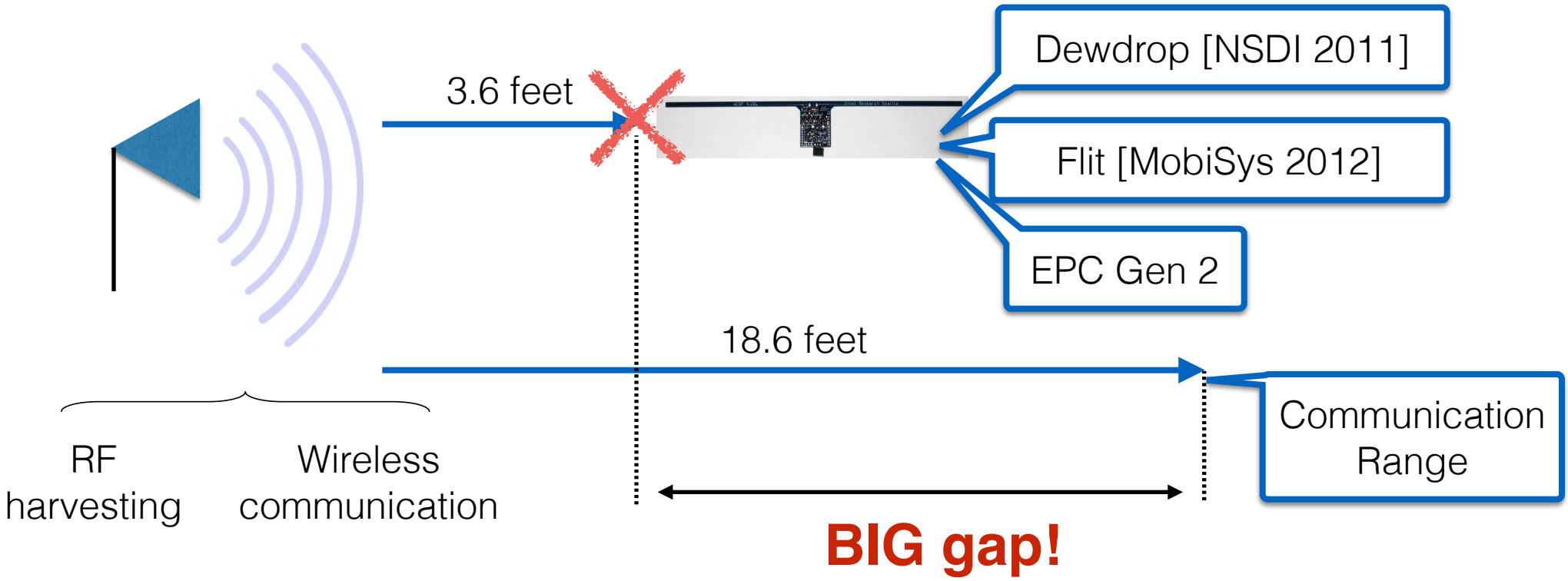


Backscatter radios enable RF energy harvesting as well as ultra low power wireless communication.

Big Gap between Operational and Comm Range



Big Gap between Operational and Comm Range



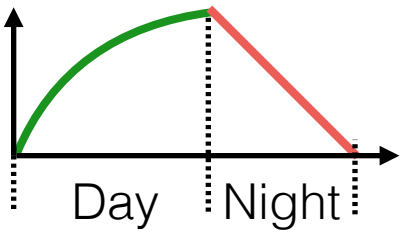
Why a big gap between the operational range and the comm range?

Energy Harvesting Systems

Macro energy harvesting

Huge energy buffer

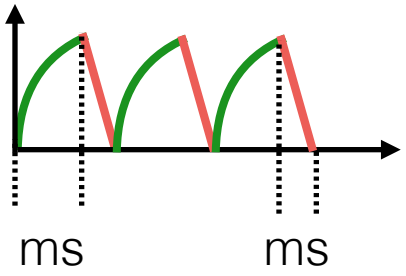
Long time scale



Micro energy harvesting

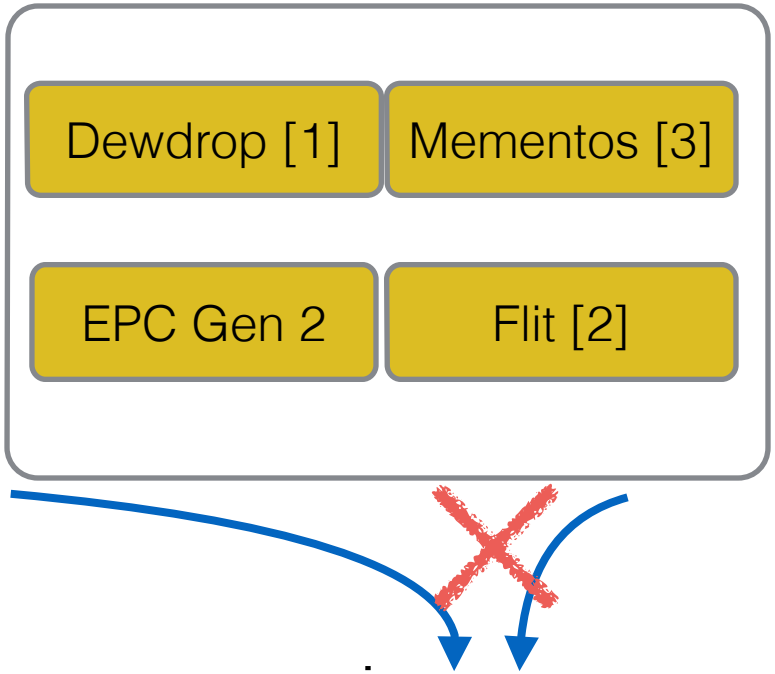
Tiny energy buffer

~ms time scale

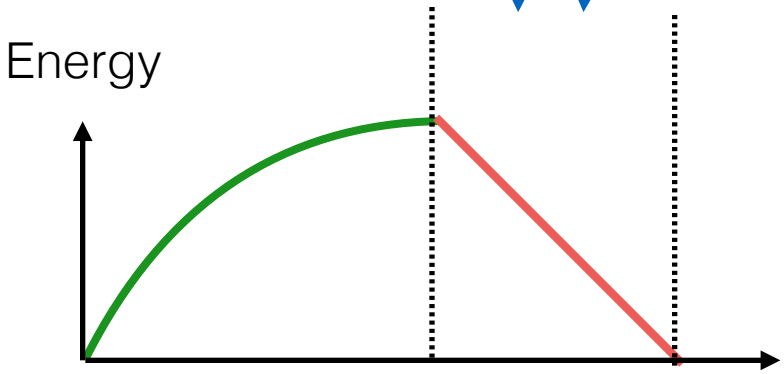


Tiny amount of energy accumulated for a single discharge cycle.

Why is operational range limited?

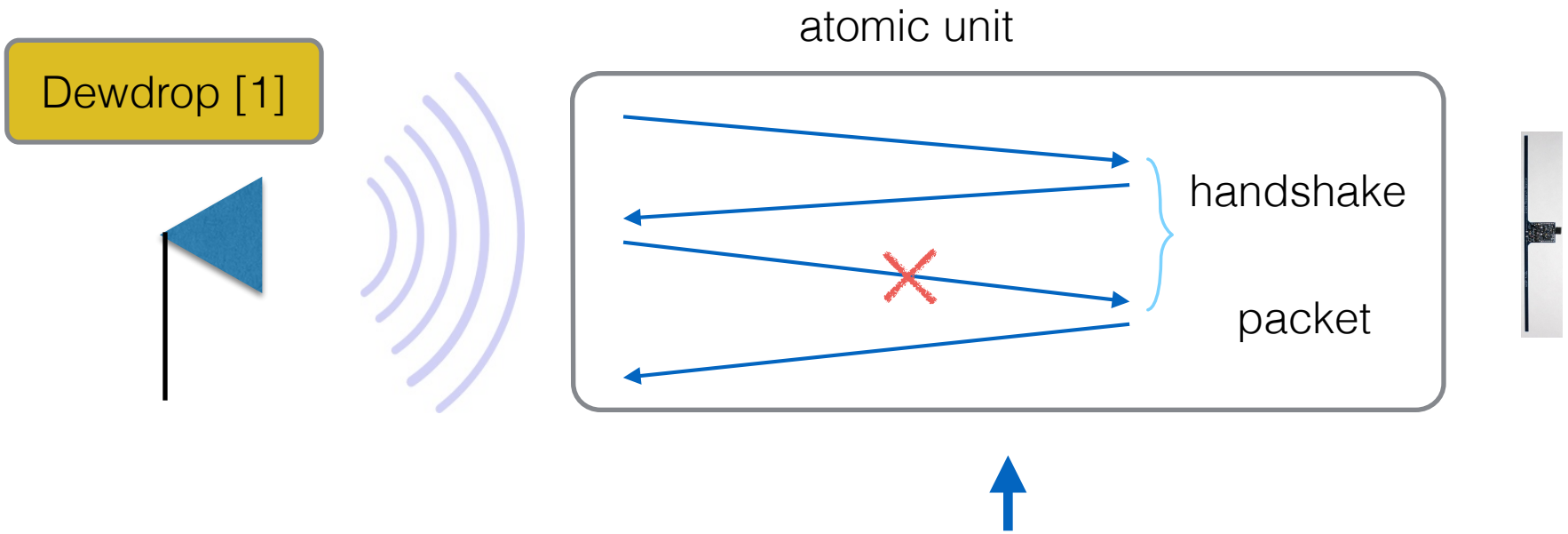


Key - task executed needs to complete within a single discharge cycle.



[1] Dewdrop. NSDI 2011. [2] Flit. MobiSys 2012. [3] Mementos. ASPLOS 2011.

Why is operational range limited?



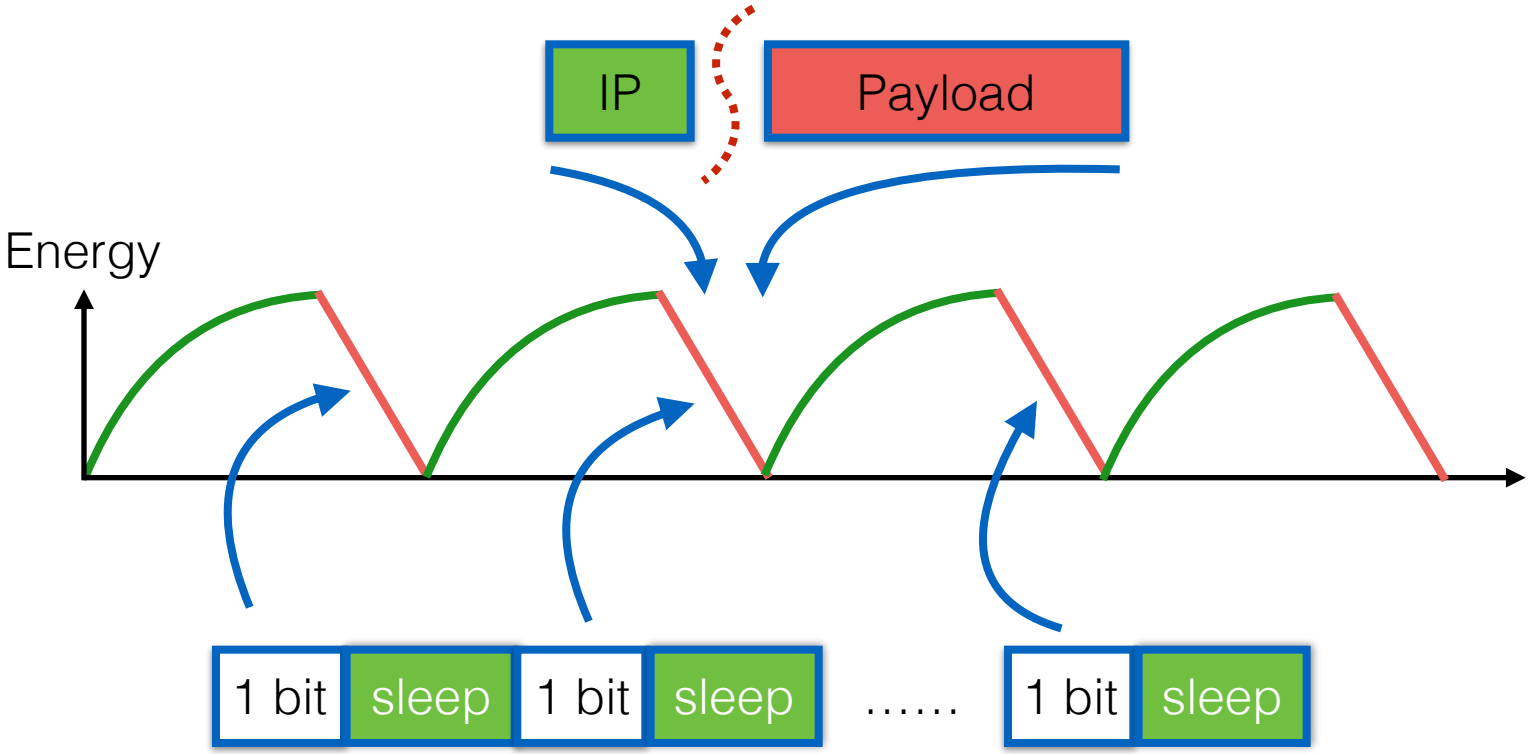
Atomic units cannot fit into a single discharge cycle.

Insight - drive the atomic unit down to the smallest unit!

[1] Dewdrop. NSDI 2011

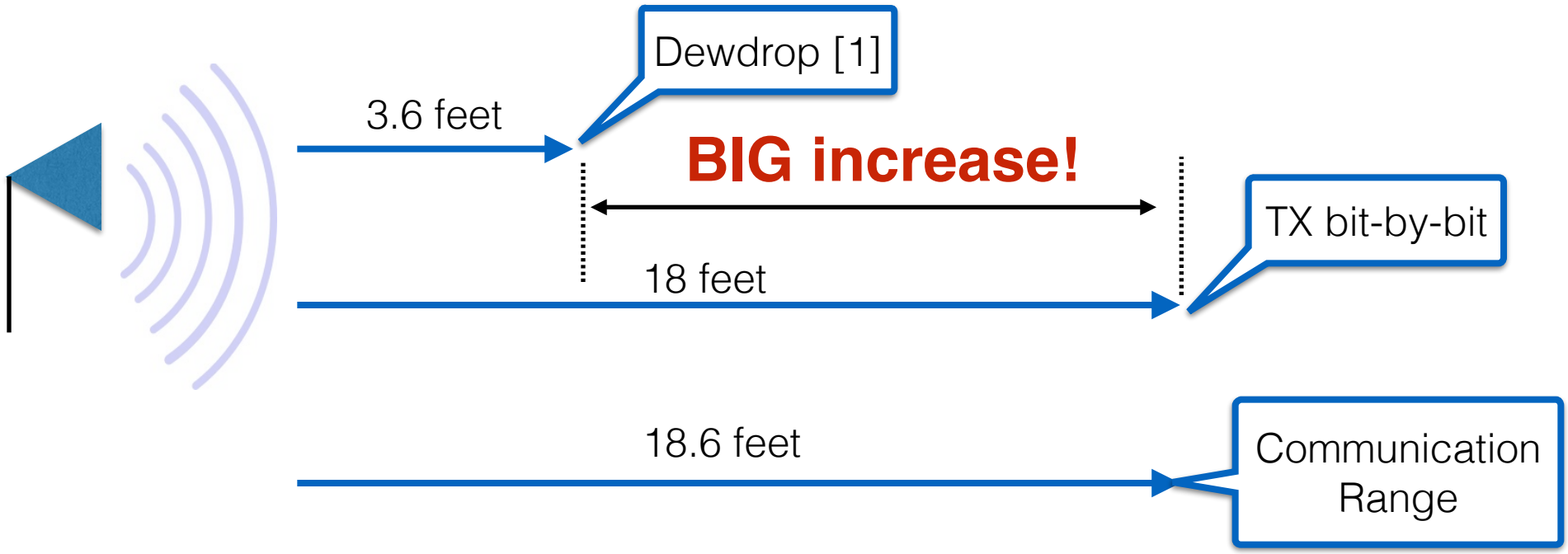
Transmit the Smallest Atomic Unit

Packet - atomic unit of a network stack



1 bit - atomic unit of a network stack

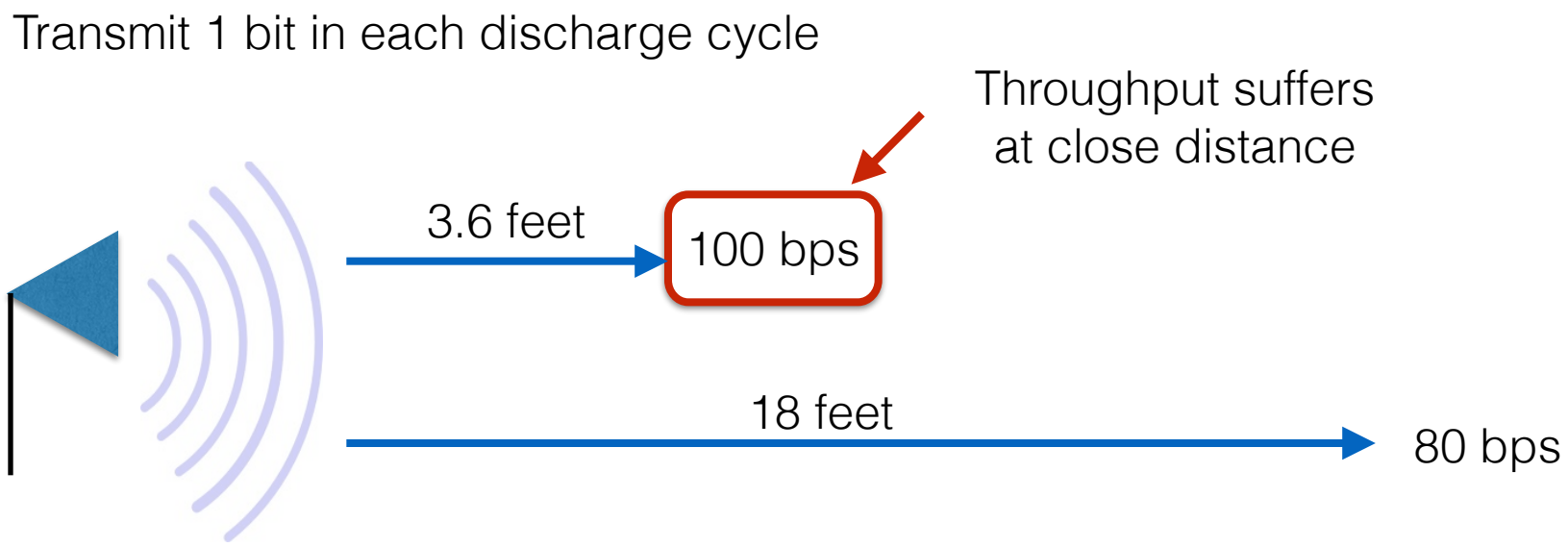
Operational Range Benefit of Bit-by-bit Transmission



Transmitting 1 bit each time pushes the operational range to the extreme.

[1] Dewdrop. NSDI 2011

Throughput suffers for bit-by-bit transfer



How to achieve maximum communication throughput while still maintain the capability of operating at the maximum range?

Auto tuning μframe controller

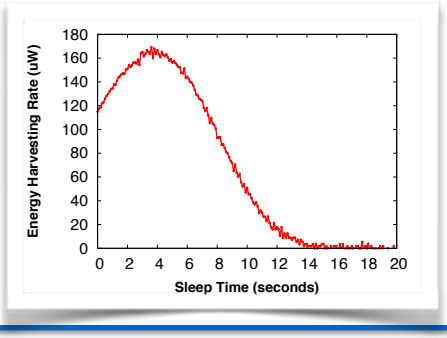
Goal - maximize communication throughput while maintain the capability to operate at the maximum range.

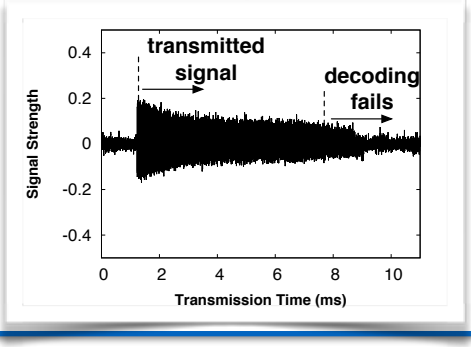
Decision - Decide which parameters to tune for maximizing communication throughput as well as operational range.

sleep interval

μframe size

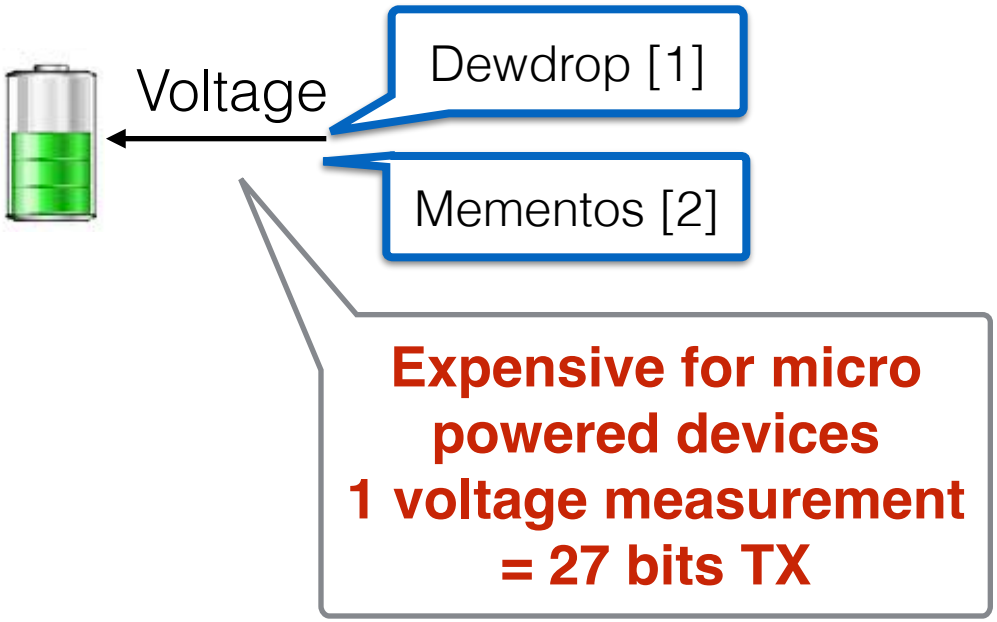
Tuning - How to tune each parameter for throughput and operational range optimization?





Which parameters to tune for optimal throughput?

What parameters to tune cheaply?



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Which parameters to tune for optimal throughput?

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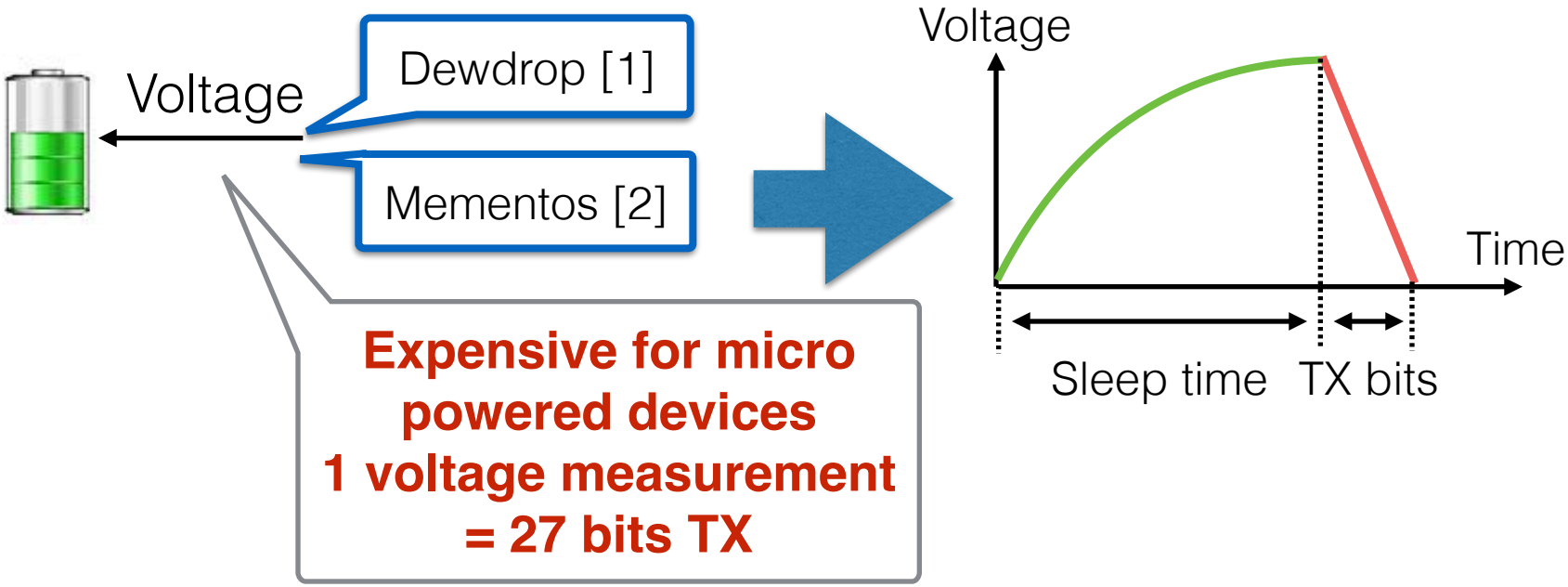
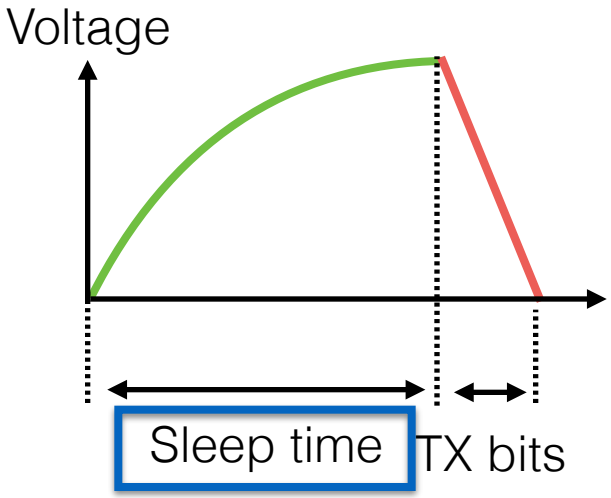


Measuring bits and time is cheaper than measuring voltage

[1] Dewdrop. NSDI 2011. [2] Mementos. ASPLOS 2011.

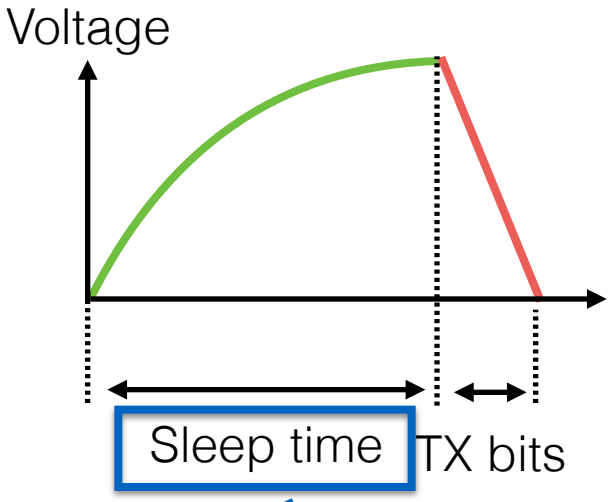
How to choose the sleep time?



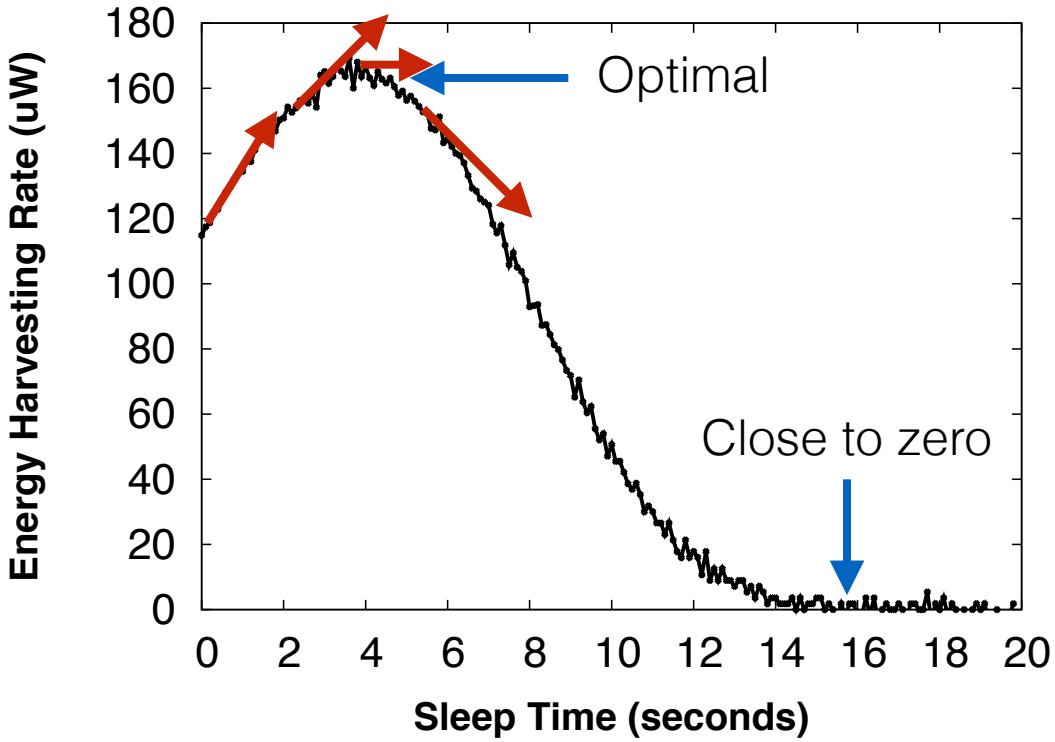
Long sleep time = more energy buffered

?

How to choose the sleep time?

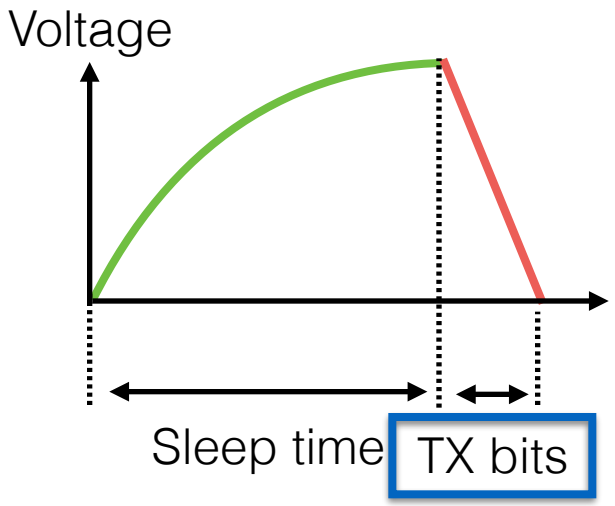


Gradient search



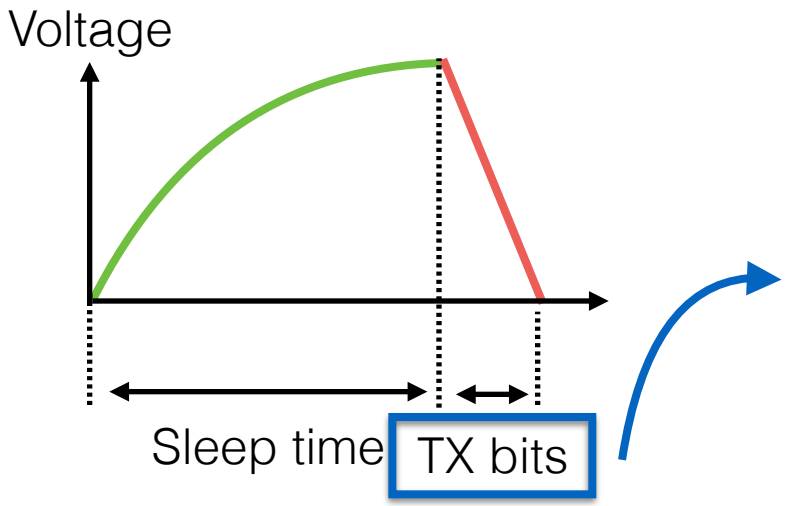
$$H = C \times V_{max}^2 \times \tau^{-1}\left(1 - e^{-t_s/\tau}\right)e^{-t_s/\tau}$$

How to choose the number of bits in a μframe?

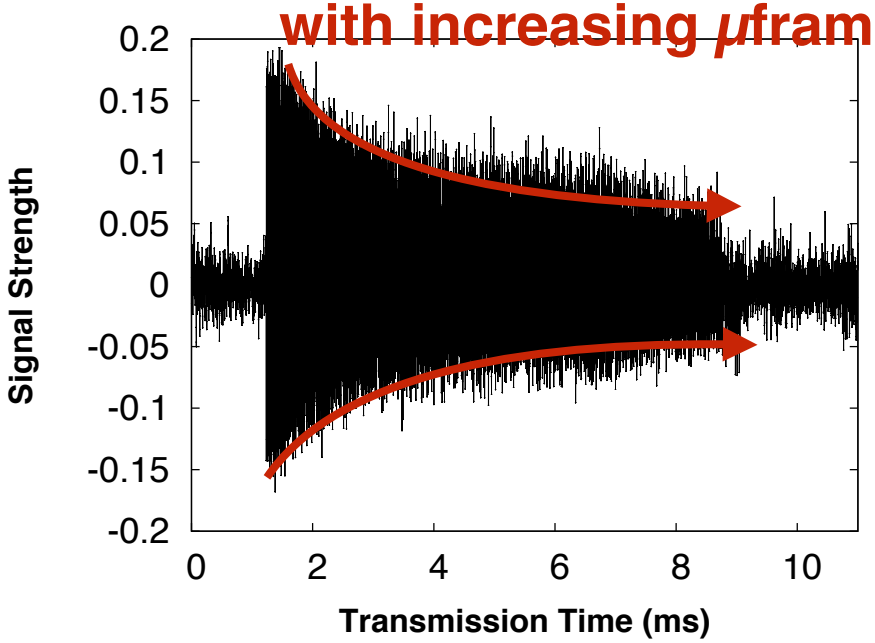


Deplete charged energy and transmit as much as possible?

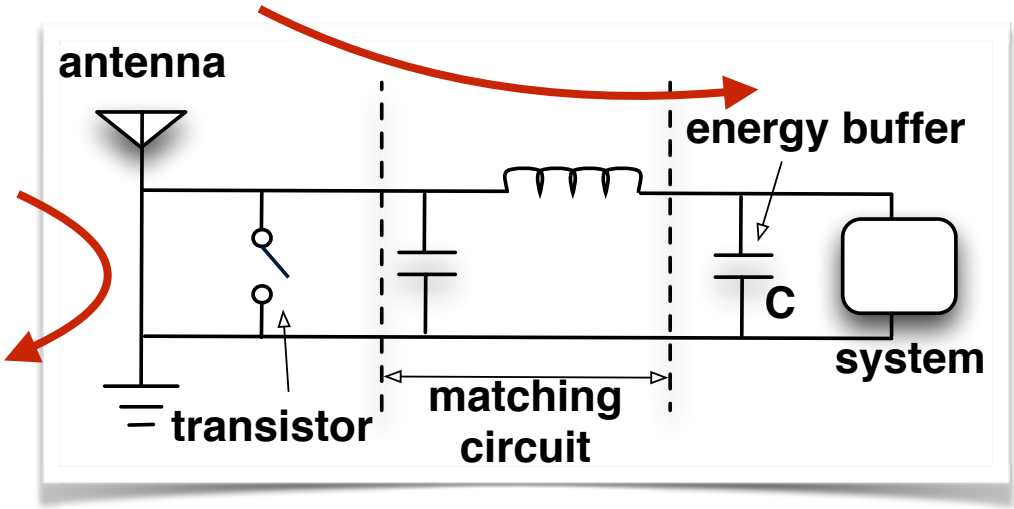
How to choose the number of bits in a μframe?



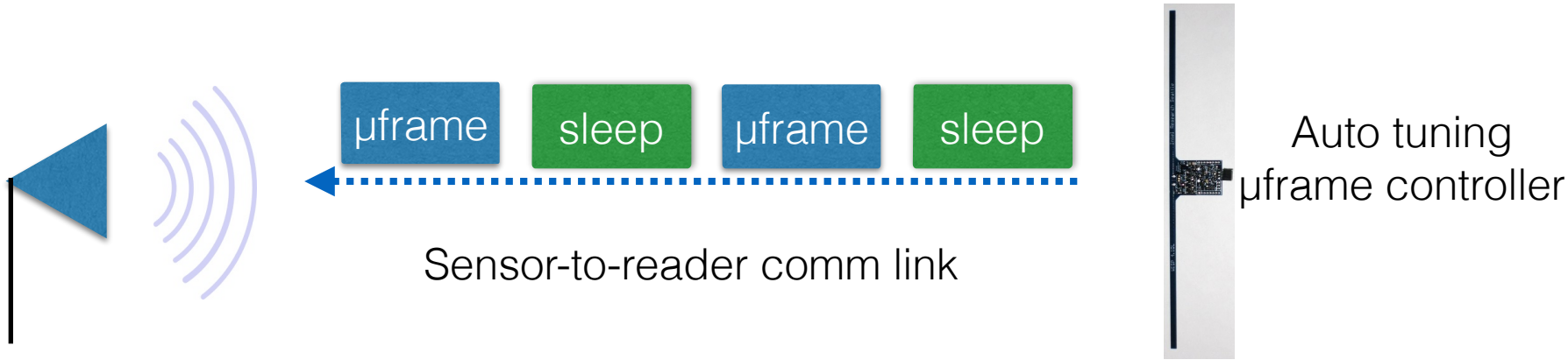
Surprising SNR degradation with increasing *μ*frame length



Less RF power is reflected when the local energy becomes low.



Tuning μframes for the sensor-to-reader and reader-to-sensor links



Tuning μframes for the sensor-to-reader and reader-to-sensor links

μframe | sleep | μframe | sleep

Sensor-to-reader comm link

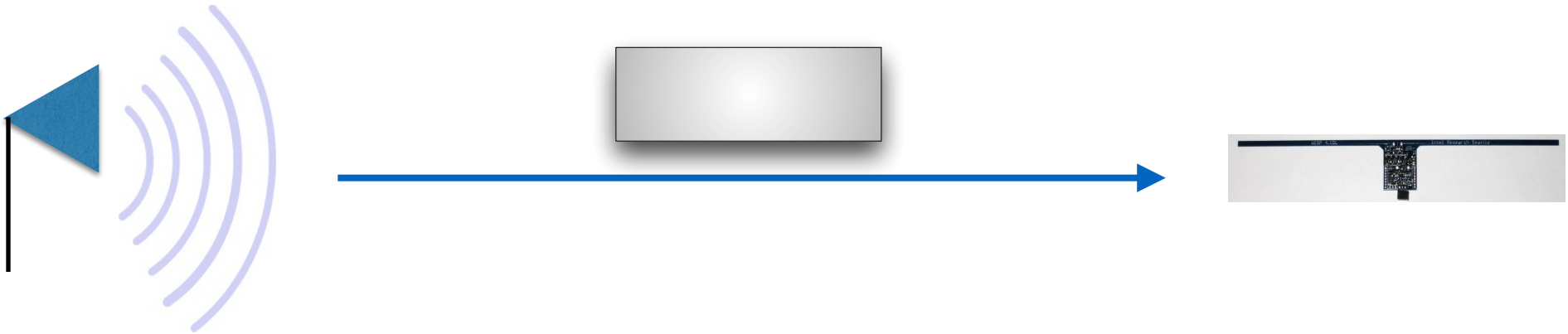
Auto tuning μframe controller

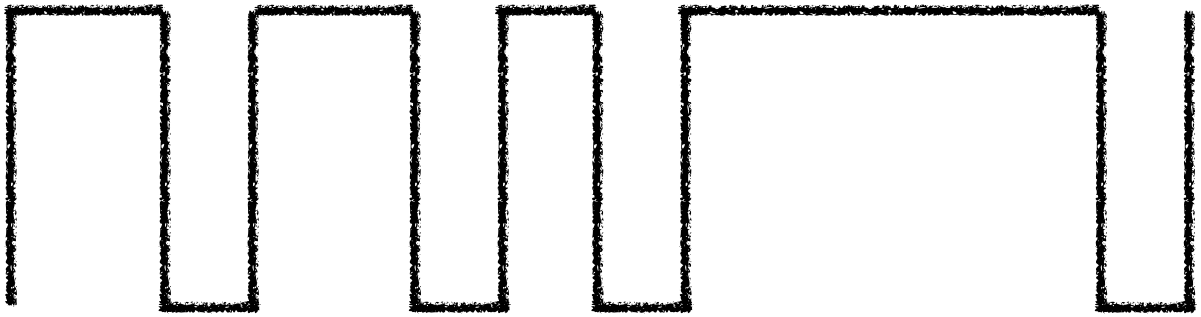
?

Reader-to-sensor comm link

Available energy on the sensor?

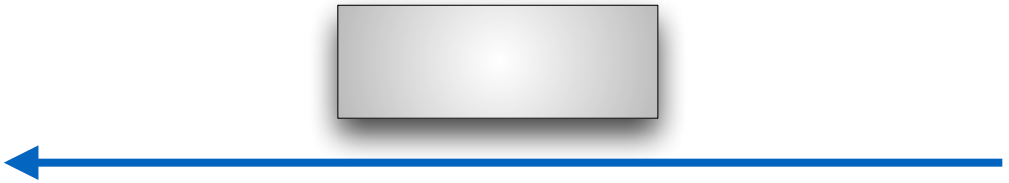
Remote interrupt - interrupt reader-to-sensor stream

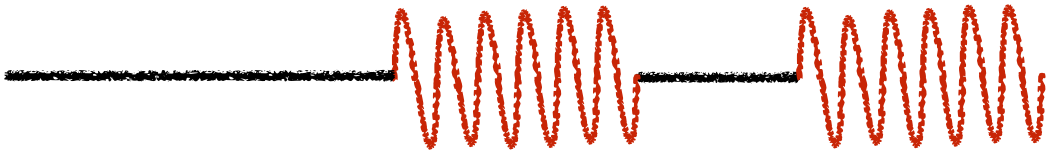




Backscatter reader's signal

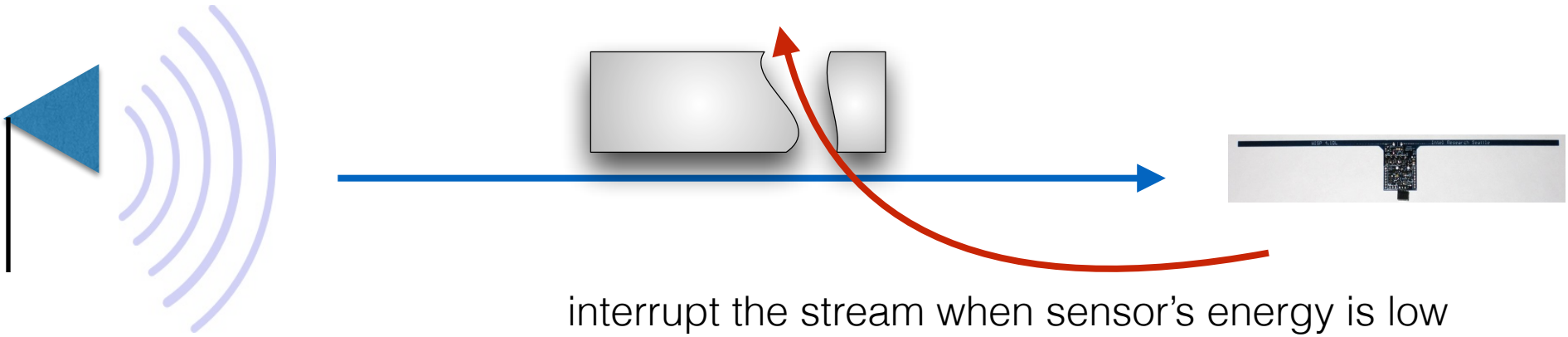
Remote interrupt - interrupt reader-to-sensor stream



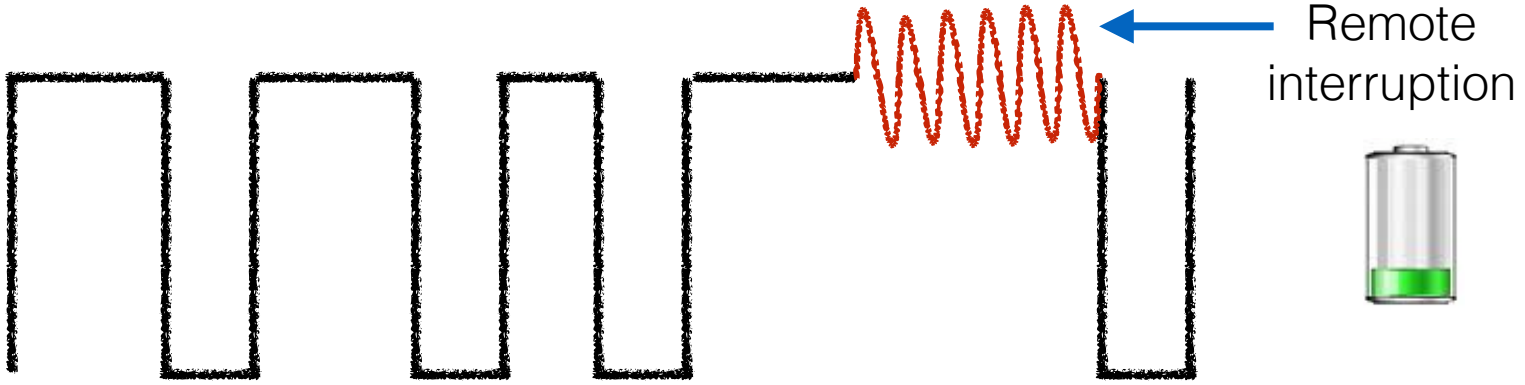


Backscattered sensor signal

In-band Remote interrupt



interrupt the stream when sensor's energy is low



Independent communication:

1. The backscatter reader turns on and off the carrier wave.
2. The sensor detunes and tunes the carrier wave.

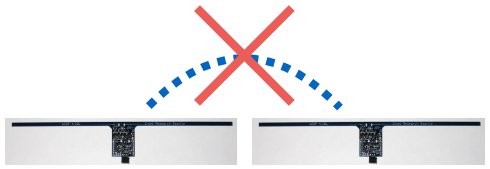
How to interleave μframes across sensors?

MAC for interleaving μframes

Why should we interleave?

Channel efficiency

Challenges



How to interleave?

token bucket

Auto tuning μframe controller

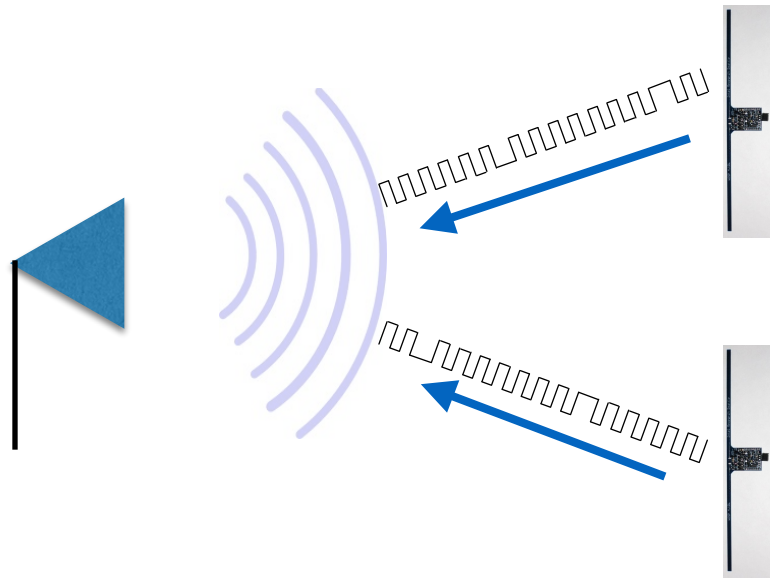
Selecting the sleep time

Selecting the num of TX bits

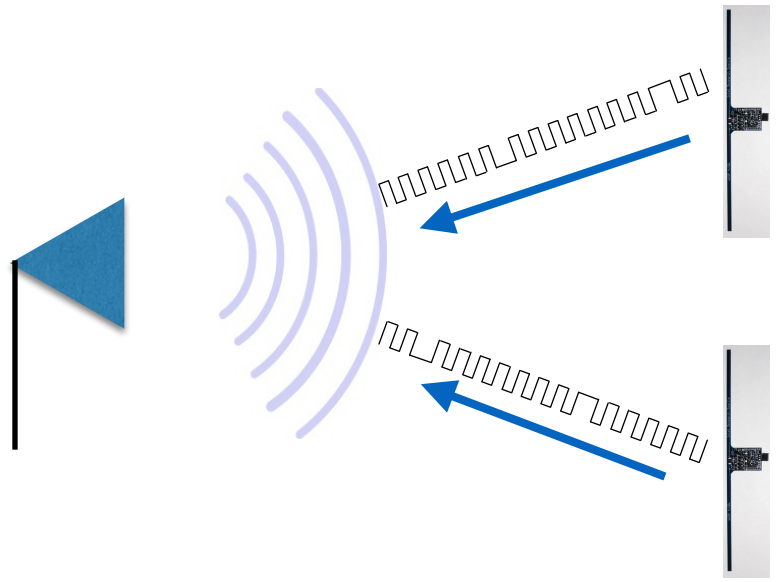
Auto tuning for the reader-to-sensor comm link

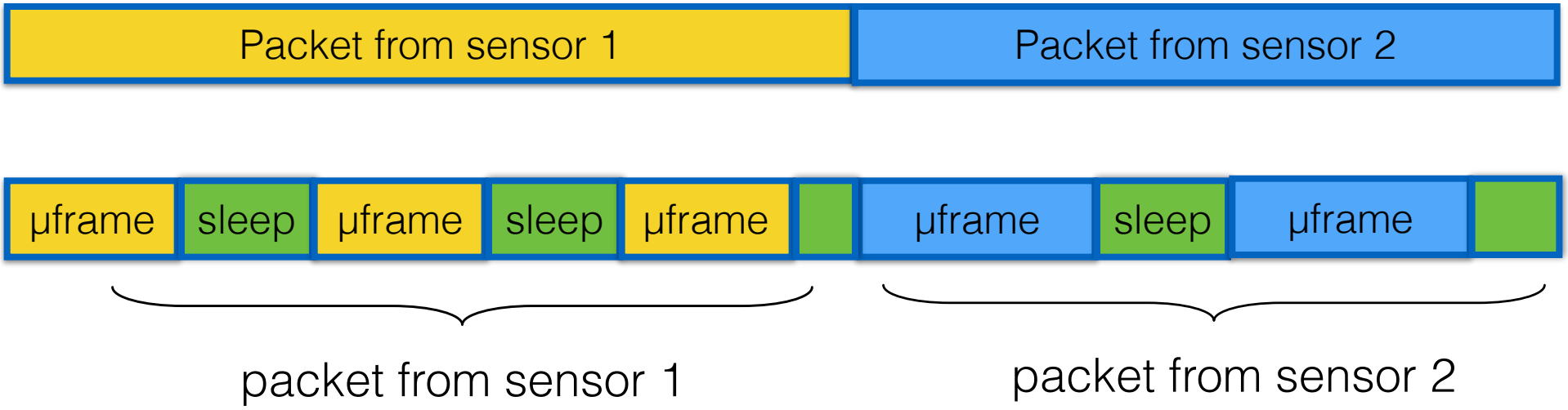
Implementation - trim the overhead of each μframe

Interleaving sensors on the packet level

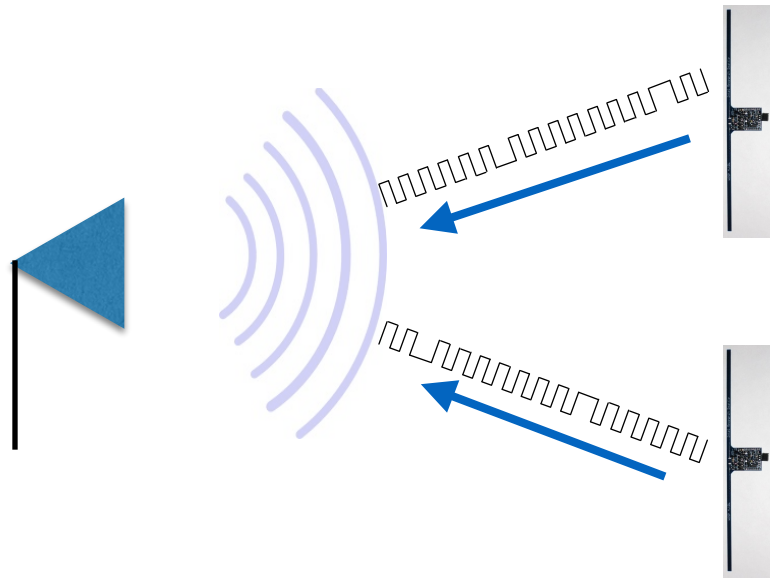


Interleaving sensors on the packet level





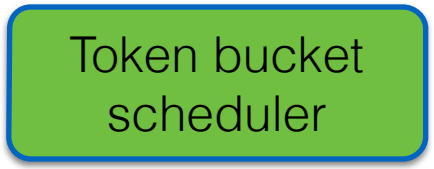
Interleaving sensors on the μframe level

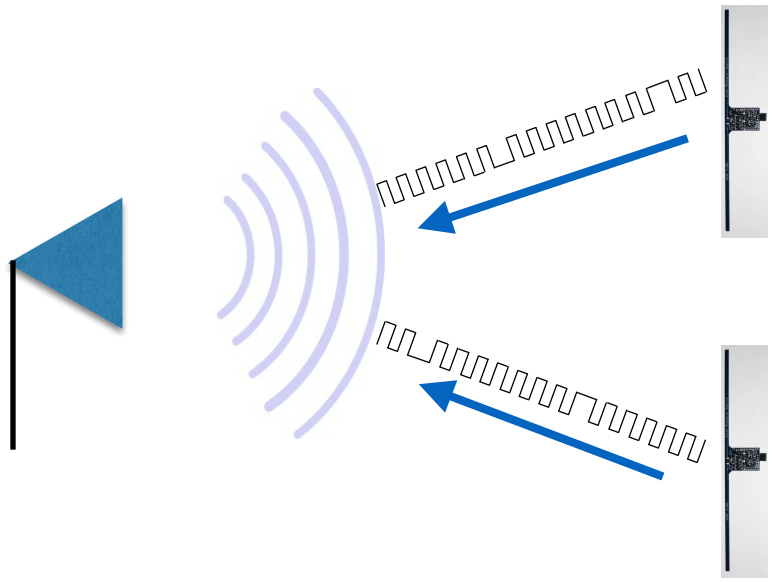


interleaving at μframes level

Token bucket based scheduling algorithm

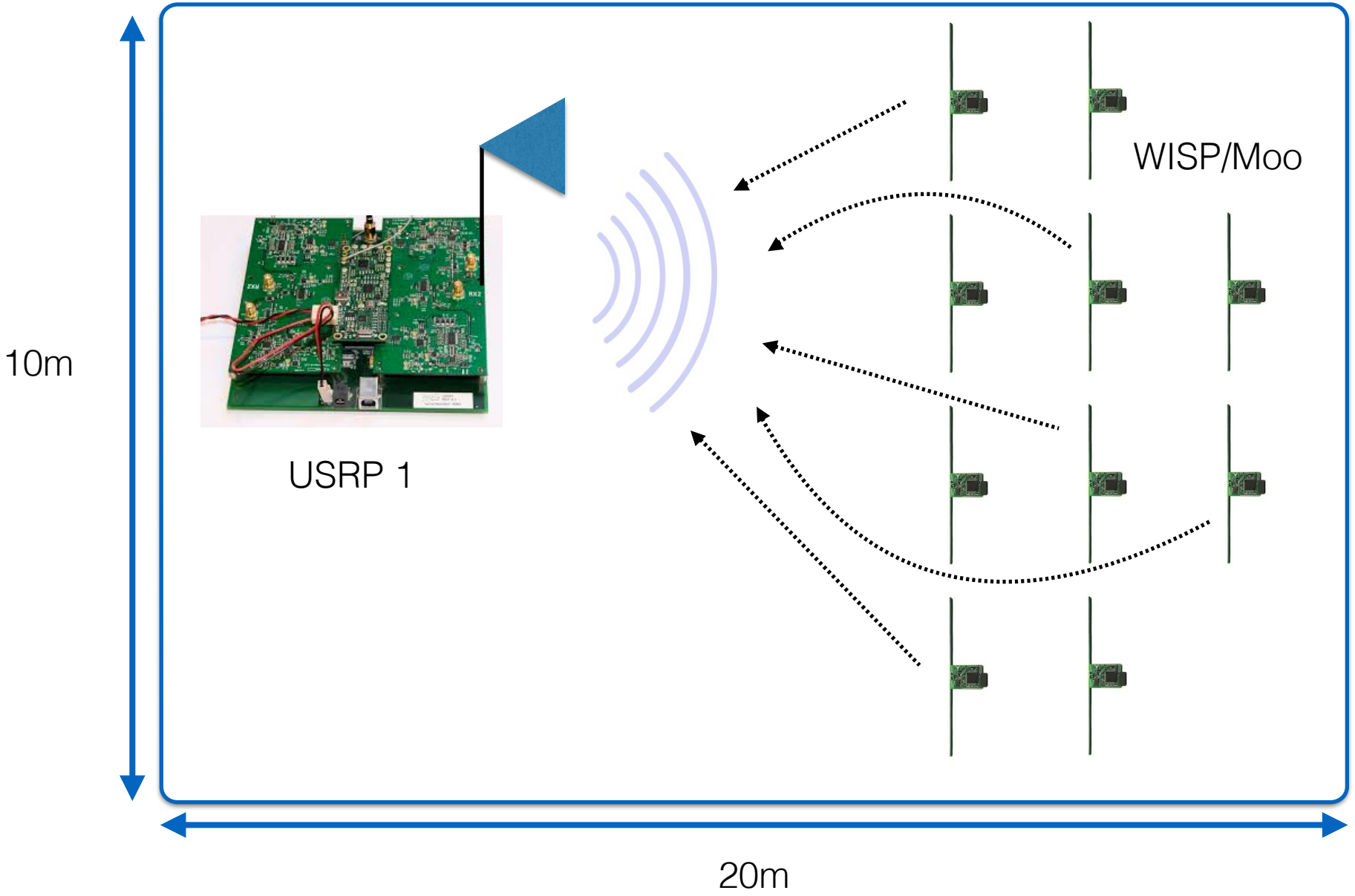
Estimated sleep time and TX bits



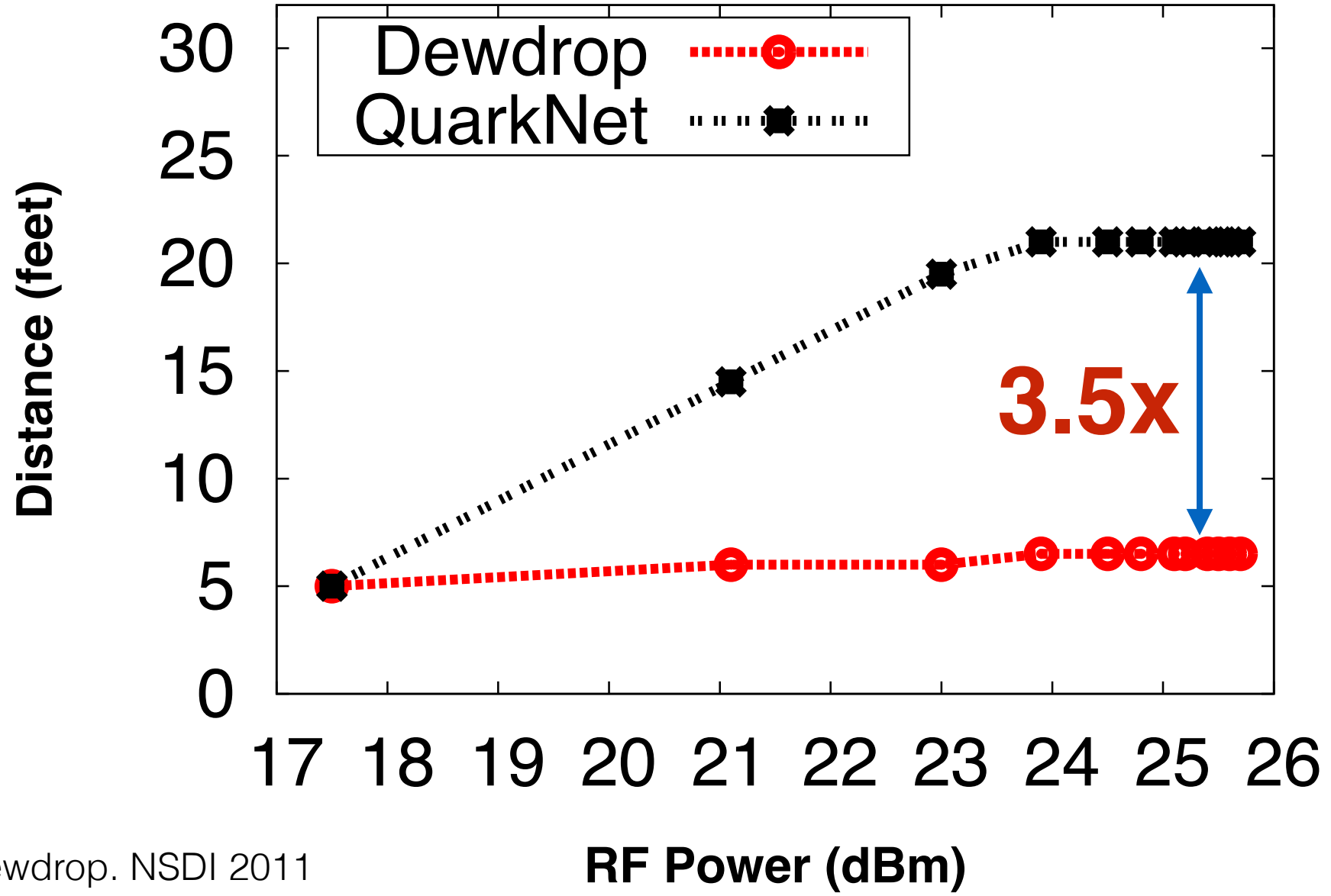


interleaving at μframes level

System Implementation

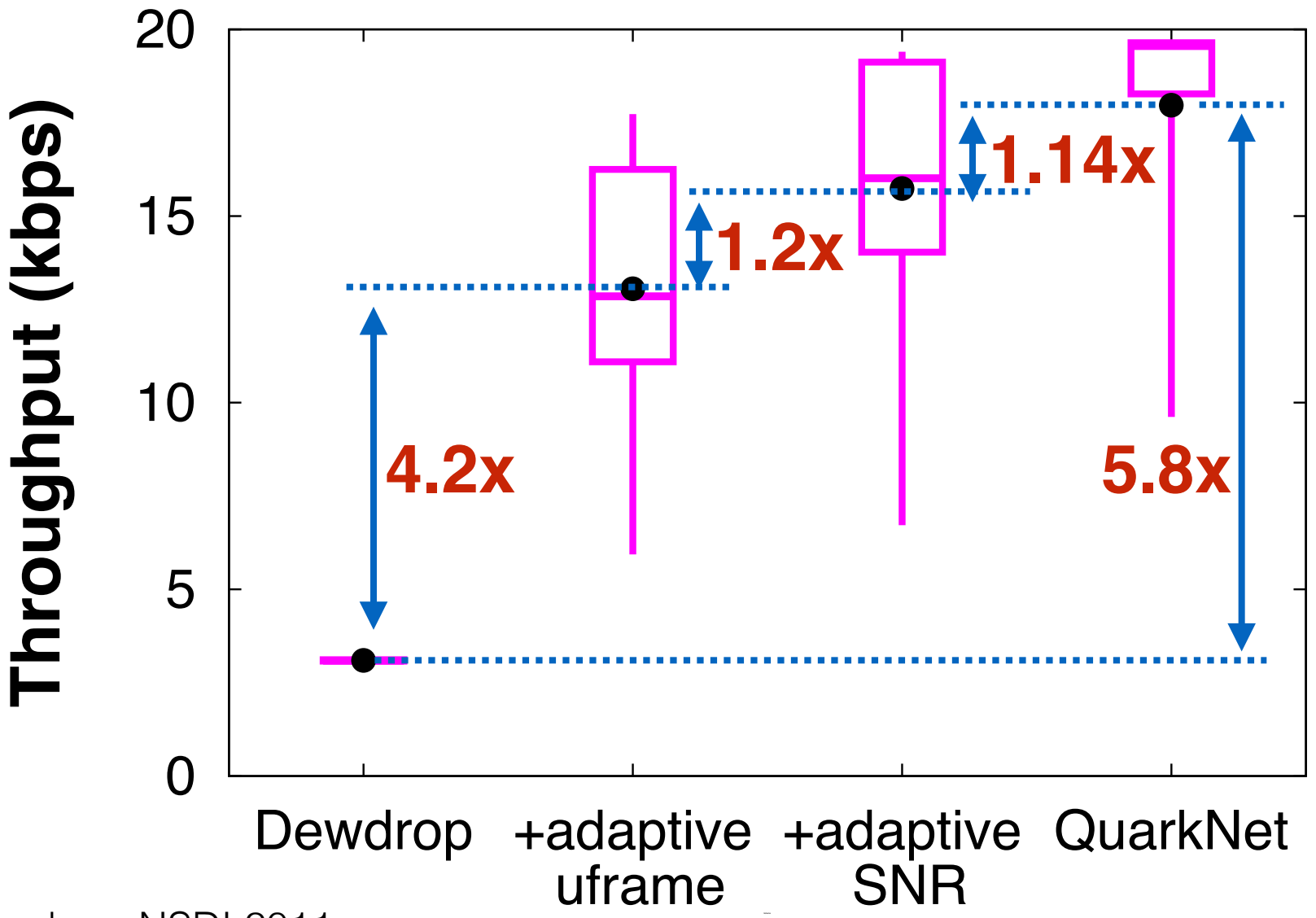


Benefit on the Operational Range

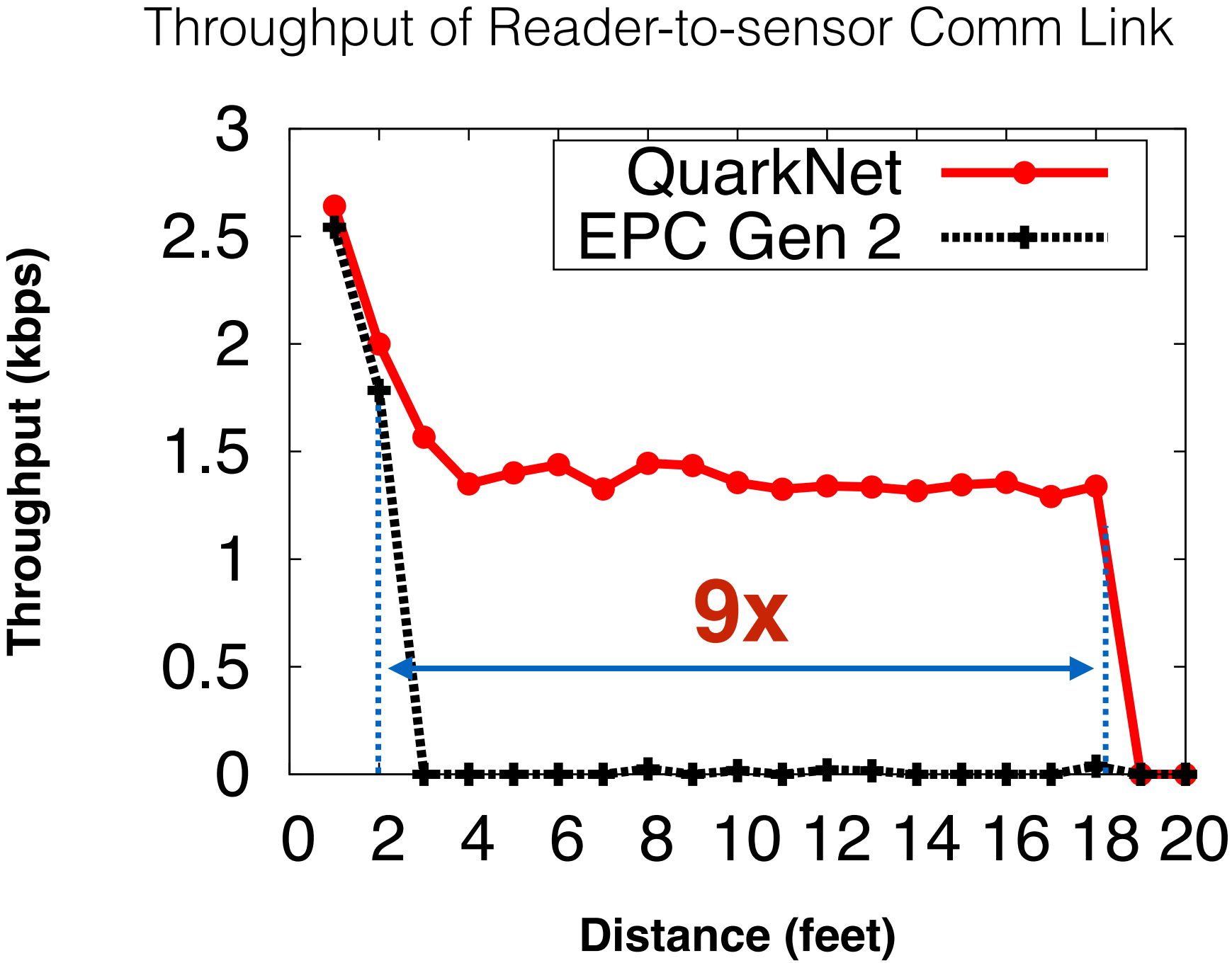


[1] Dewdrop. NSDI 2011

Big Increase on Communication Throughput



[1] Dewdrop. NSDI 2011


Throughput of Reader-to-sensor Comm Link
Throughput (kbps)
Distance (feet)
QuarkNet
EPC Gen 2
9x
0
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10
12
14
16
18
20

Conclusion

QuarkNet enables a network stack to seamlessly scale down to severe energy harvesting conditions.

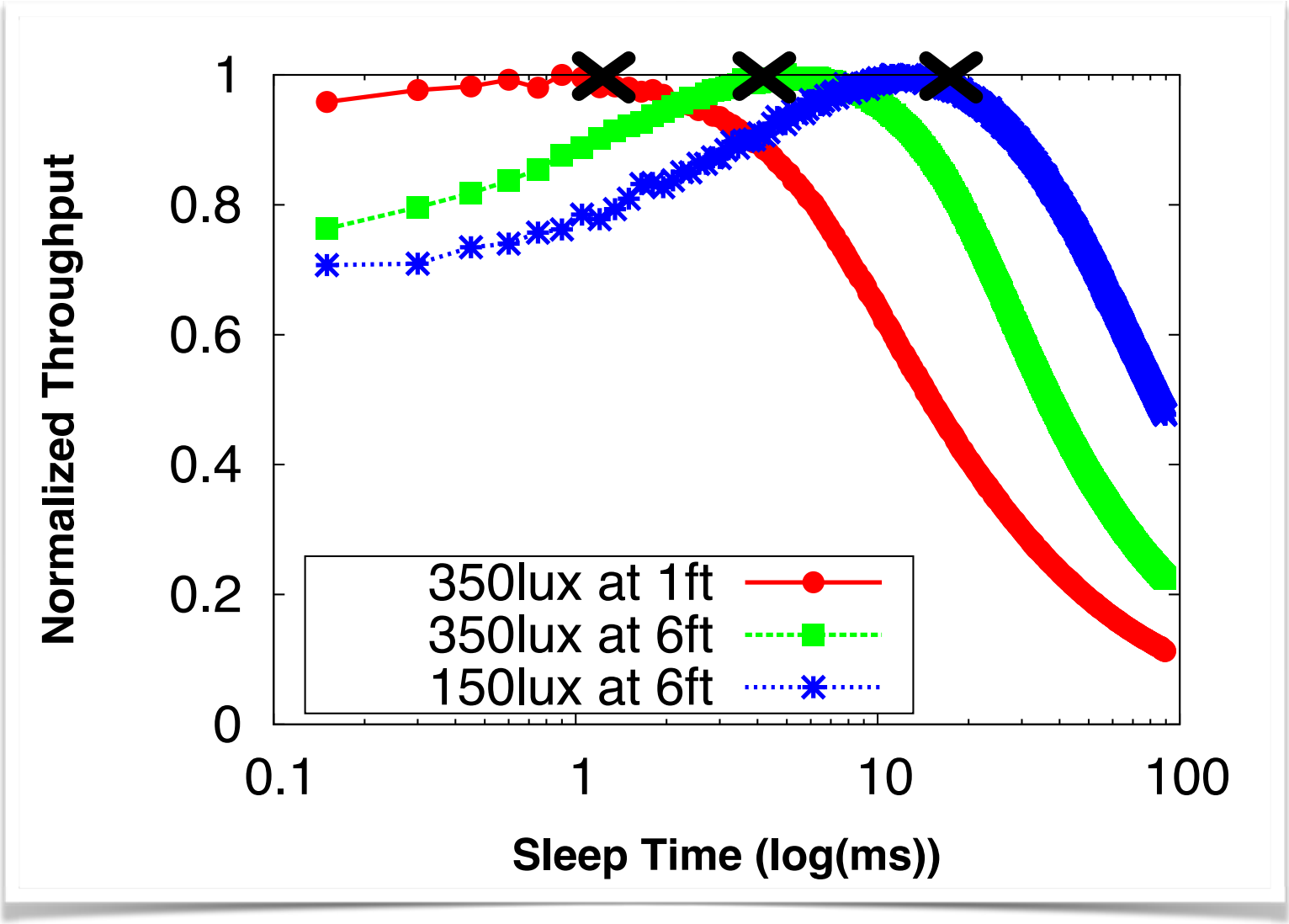
Key contribution is a novel packet fragmentation abstraction that can scale down to frame sizes as small as a few bits while adapting to harvesting and network conditions.

QuarkNet addresses a fundamental limitation of backscatter, which is operating range, and simultaneously improves throughput.

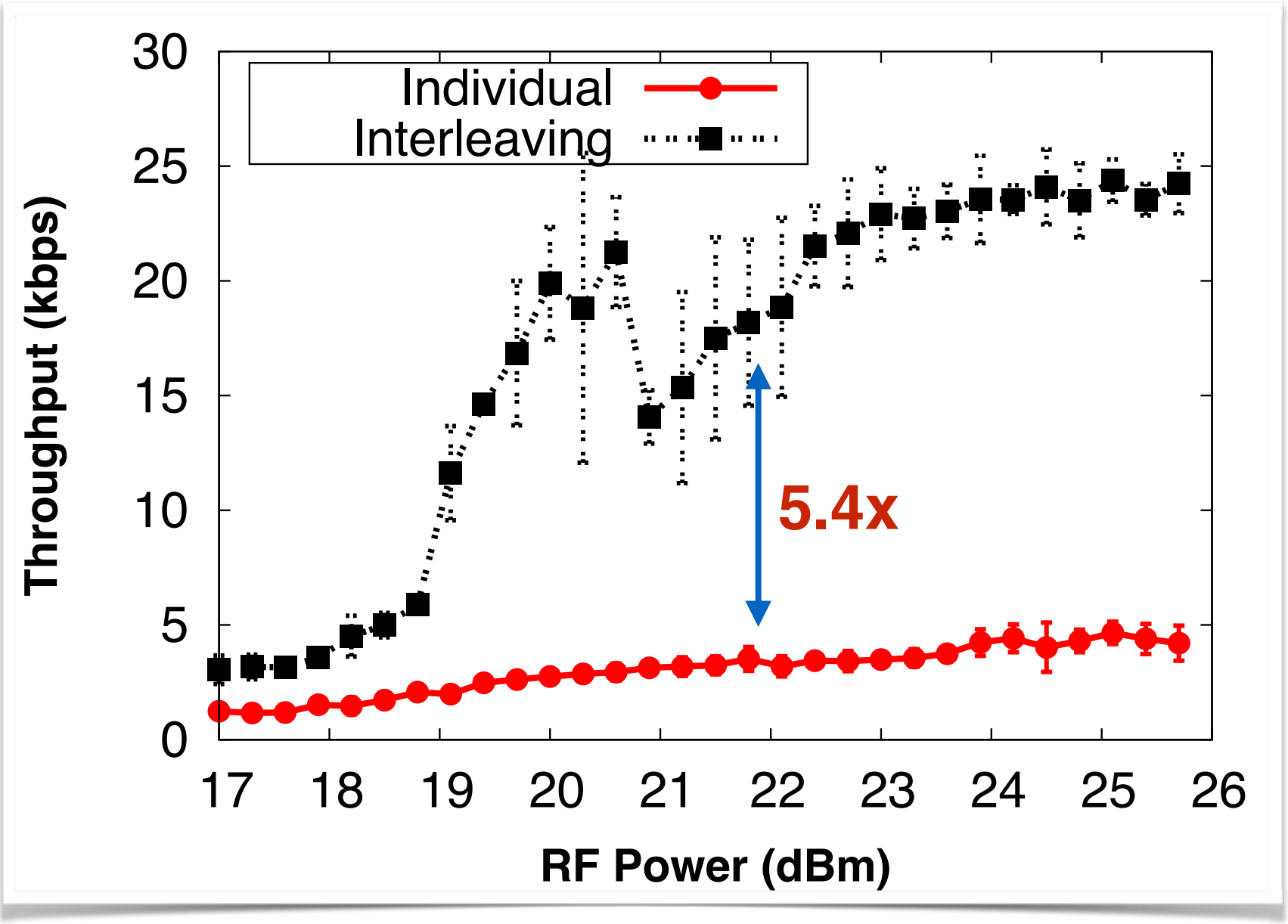
- Maximum operational range 21 feet, 3.5x higher than Dewdrop.
- Maximum throughput 18 kbps, 5.8x higher than Dewdrop.

Backup Slides

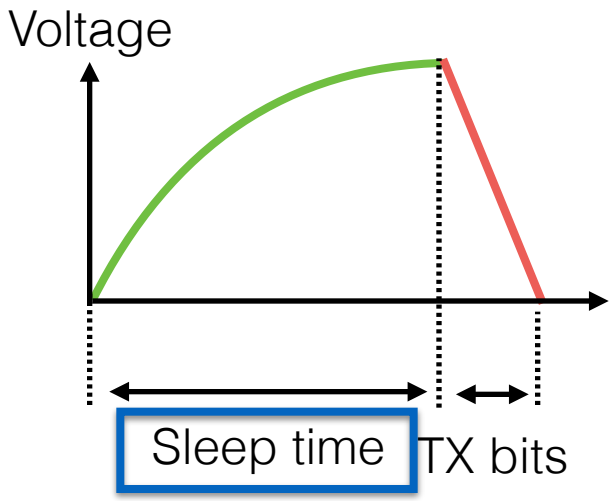
Results: selecting optimal sleep time



Throughput of Interleaving Sensors



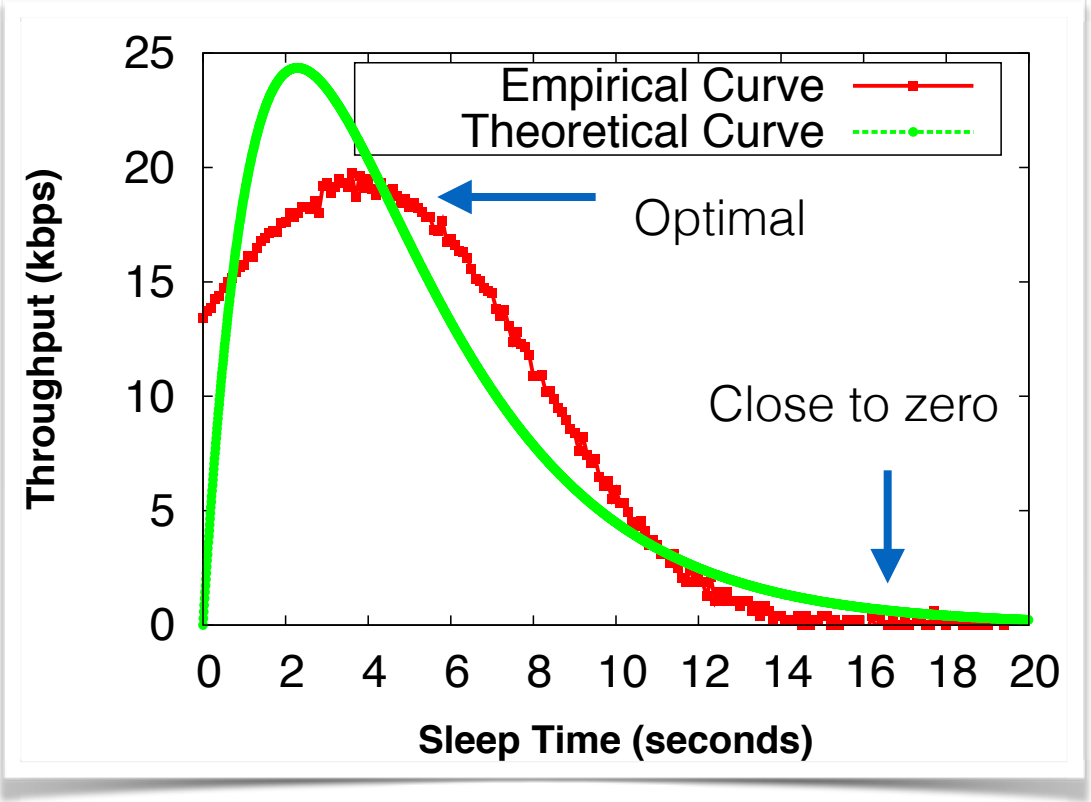
How to choose the sleep time?



Gradient search

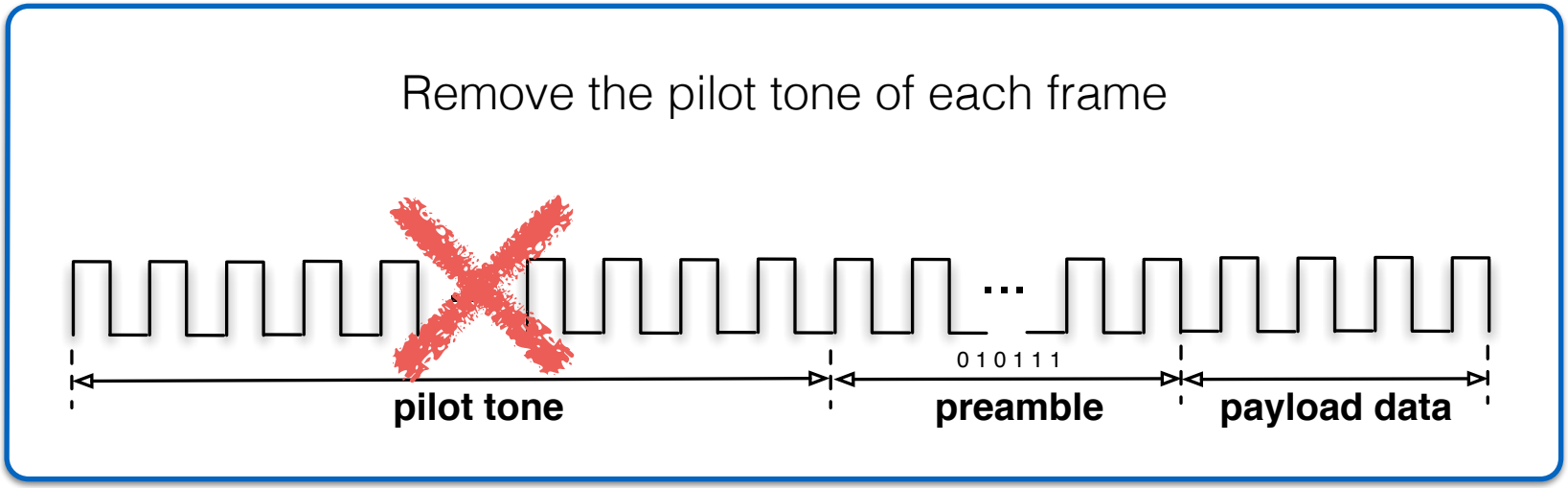
$$V = V_{max}(1 - e^{-t_s/\tau})$$

$$H = C \times V_{max}^2 \times \tau^{-1}(1 - e$$



Sleep time should be chosen for optimizing energy harvesting rate.

Trim the overhead of each transmission



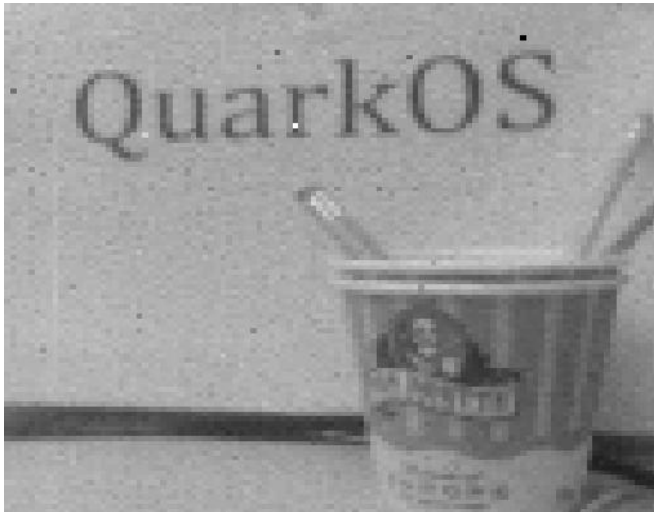
Trim the overhead of each transmission

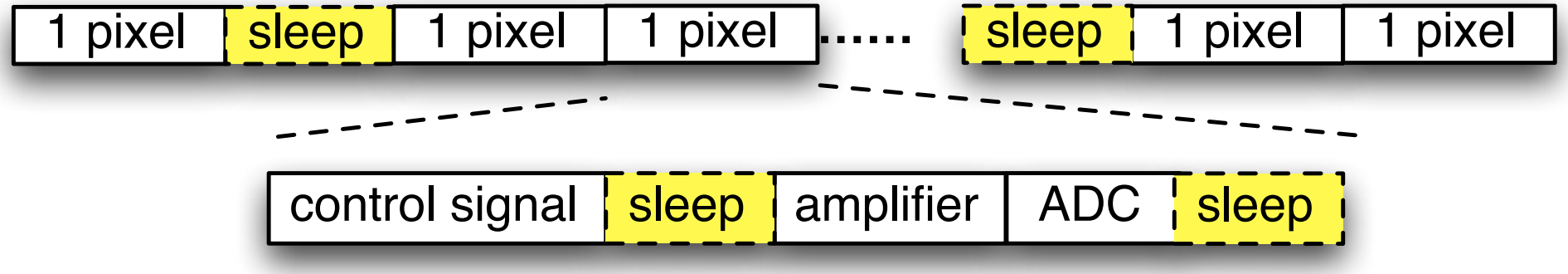
Fixed Cost (us)		QuarkNet Overhead (us)	
TX to inactive	9.9	interrupt config	10.58
inactive to TX	47.5	handle interrupt	9.3
RX to TX	4.08	frame adaptation	24.3
sleep to wakeup	9.83	voltage detection	3

71.31us **>** **47.18us**

Application

Task fragmentation can be used for operating a micro powered image sensor and transmitting the sensor data back via backscatter.





Decoding variable length μframes