Research Challenges for Intermittently Powered Wireless Embedded Systems

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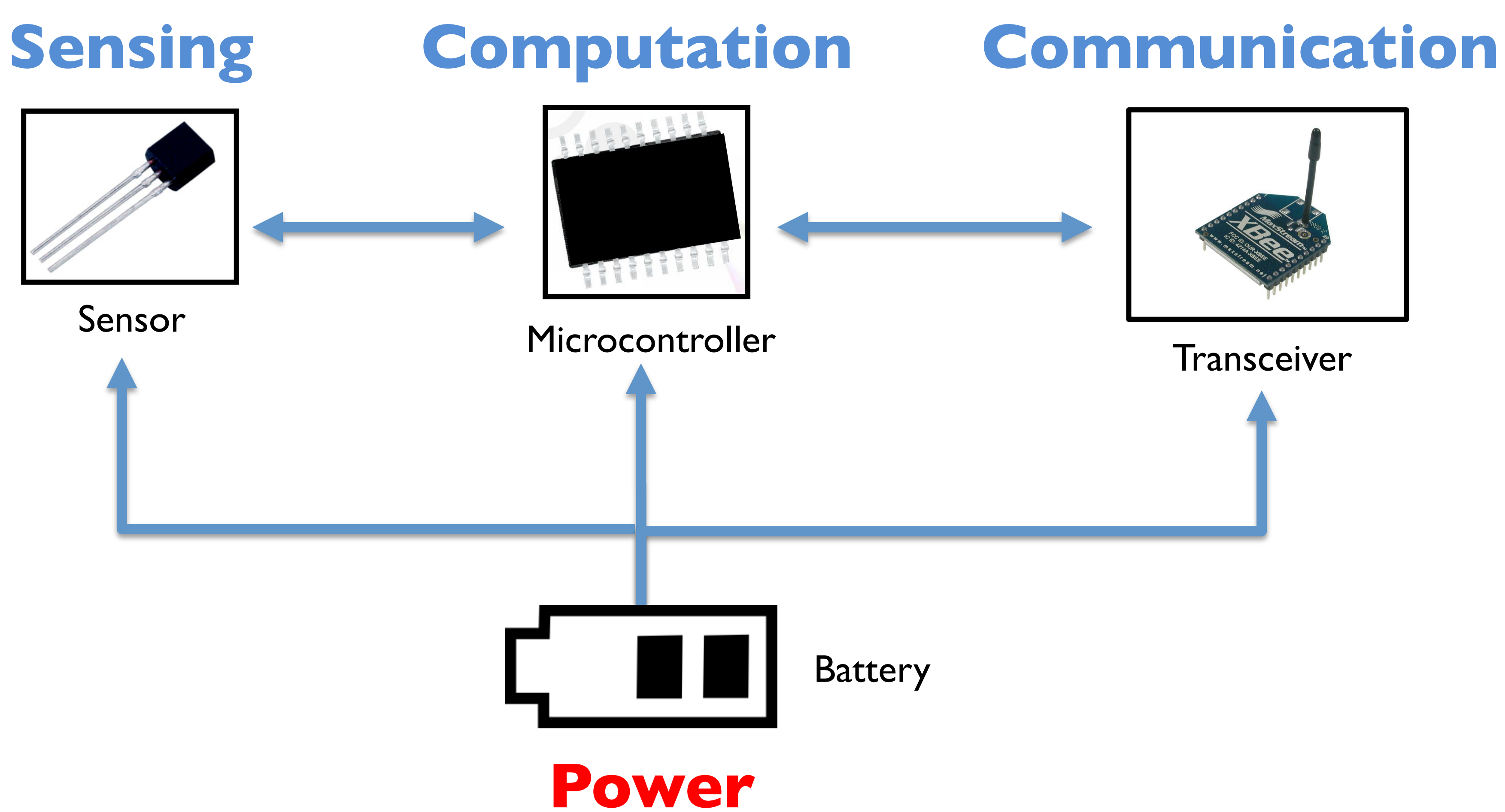
IoT – Wireless Embedded Systems



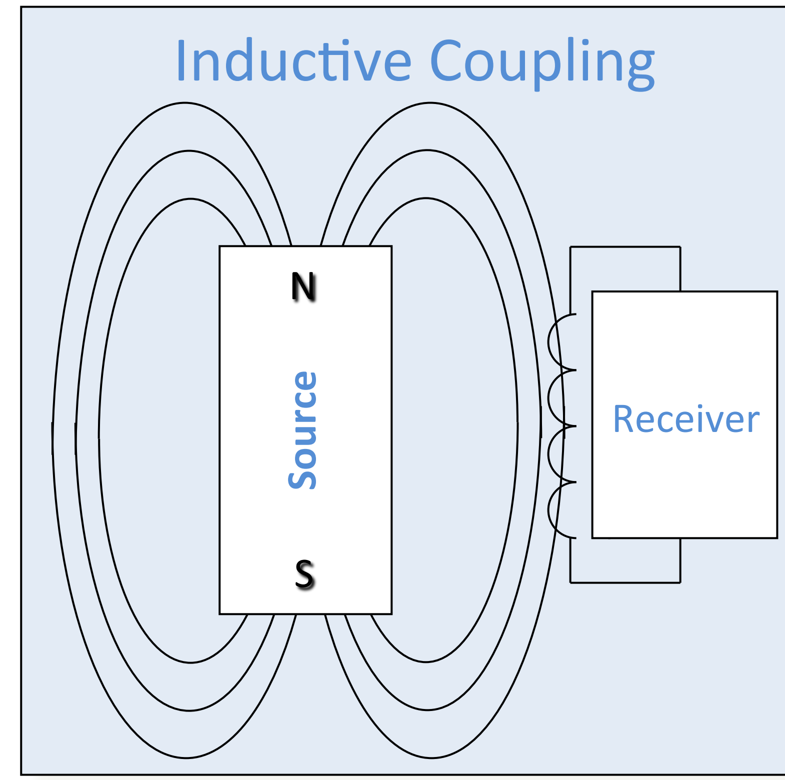
Powering IoT

- Powering cyber-physical systems is a challenge
  - **By 2025**: >100 billion IoT devices
  - sustainable operation
  - large-scale deployment
- Batteries
  - increase weight, cost of the hardware
  - replenishment is generally impractical
  - ecological footprint
- Transfer of electromagnetic energy
  - from a power source to receiver devices over the air
  - wireless power transfer

Iris Mote

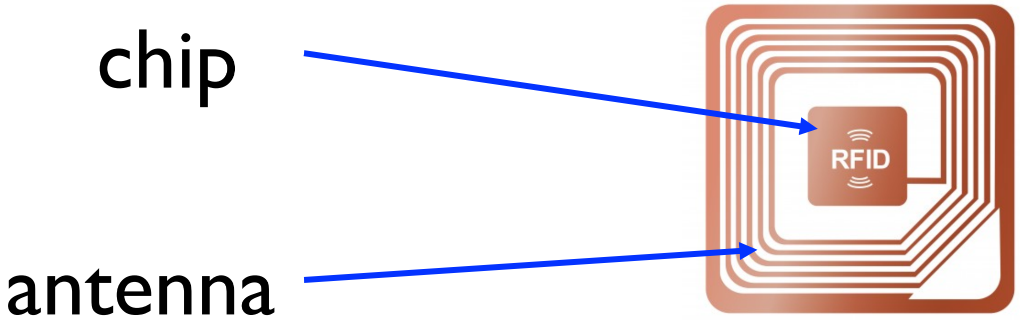
Wireless Power Transfer (WPT) - I

- Non-radiative techniques
  - either inductive or magnetic resonant coupling
    - varying magnetic flux induces current
  - transfer power over short distances



Wireless Power Transfer (WPT) - II

- Radiative techniques
  - use the electric field of the electromagnetic waves
    - radio frequency (RF) waves as an energy delivery medium
  - transfer power over longer distances
  - provision of energy to many receivers simultaneously
    - broadcast nature
  - low complexity, size and cost for the energy receiver hardware
  - suitability for mobility
  - charge low-power embedded devices
    - RFID (Radio Frequency Identification) tags



Outline

- RF-Powered Embedded Systems
  - Current Technologies
  - Communication Stack Requirements
  - Programming Platforms
- Wireless Power Transfer Networks (WPTNs)
  - Safety Issues in WPTNs
  - Security Issues in WPTNs

RF-Powered Embedded Systems

RF-Powered Computing

- A new class of low-power battery-less embedded systems
  - Intermittently Powered Devices (IPDs)
- CRFIDs (Computational RFIDs)
  - RFID technology as a foundation
  - Allow sensing, computation and communication without batteries
    - Charge a super capacitor using harvested rf energy
  - Equipped with a backscatter radio
    - simple circuitry for the receiver
    - allows communication to come almost for free

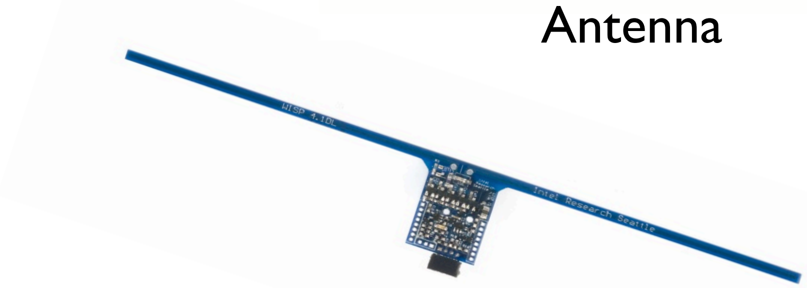
A CRFID platform: WISP - Wireless Identification and Sensing Platform
(University of Washington)

Ultimate goal: replacing existing battery-powered wireless sensor networks

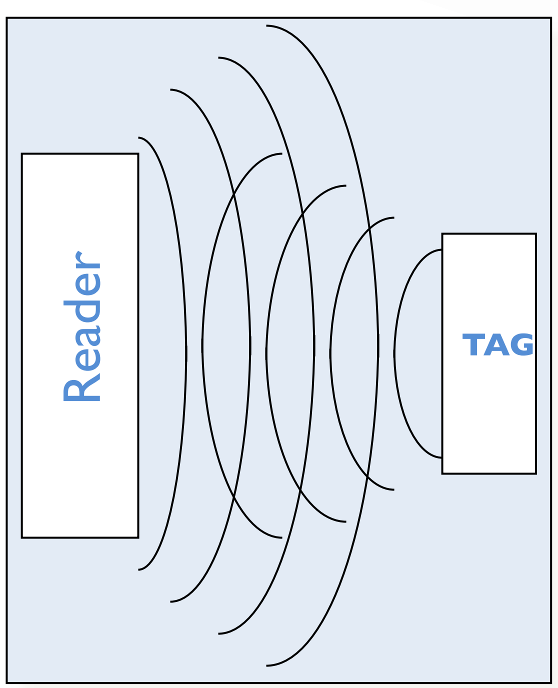
WISP Hardware - Overview

RFID reader

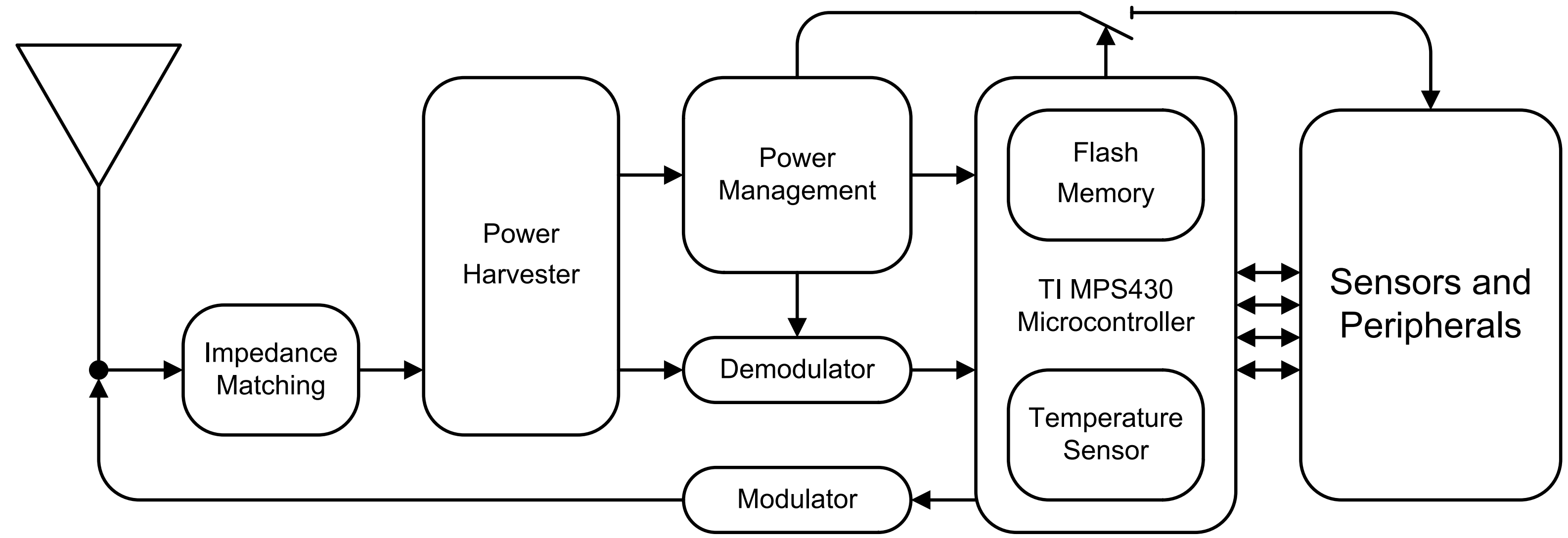
Antenna

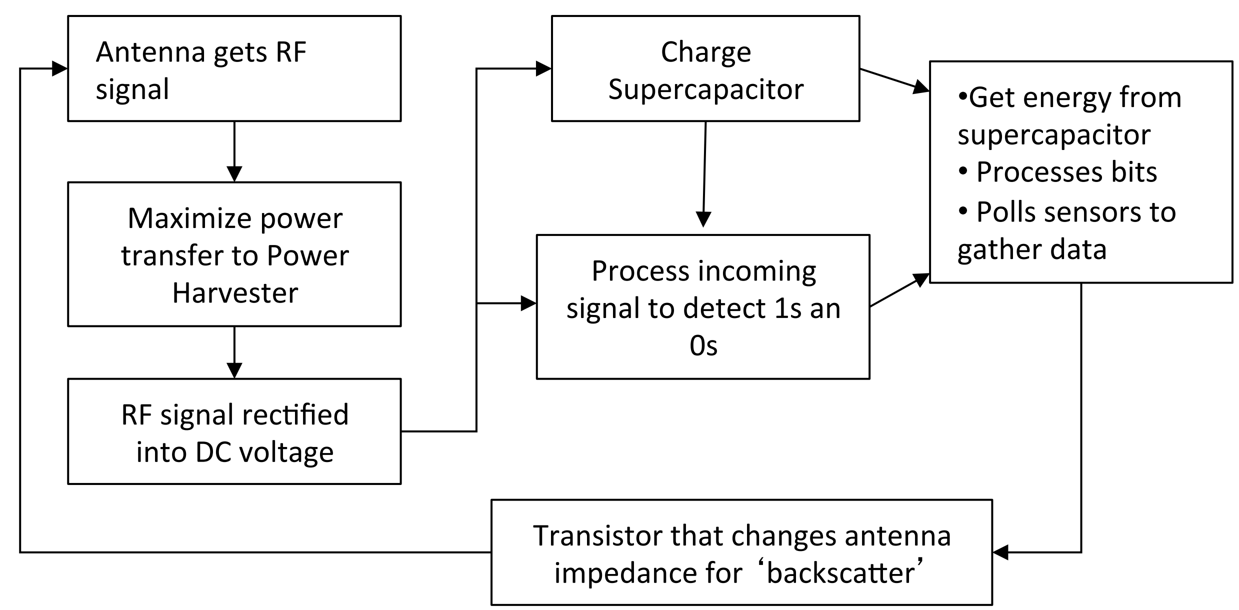


WISP



Backscatter

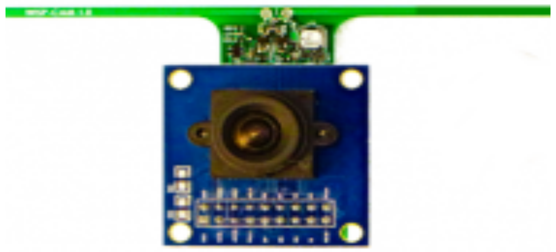


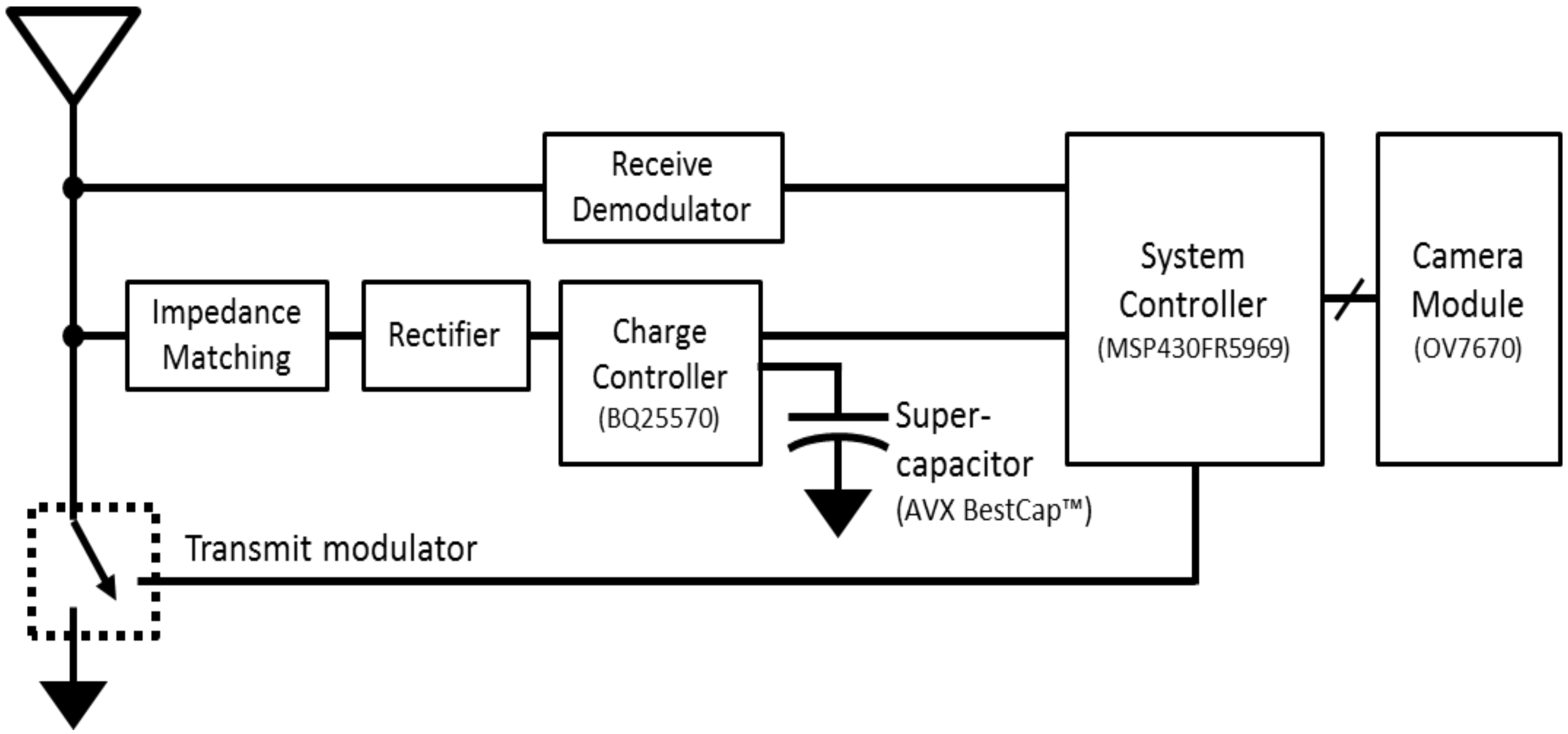


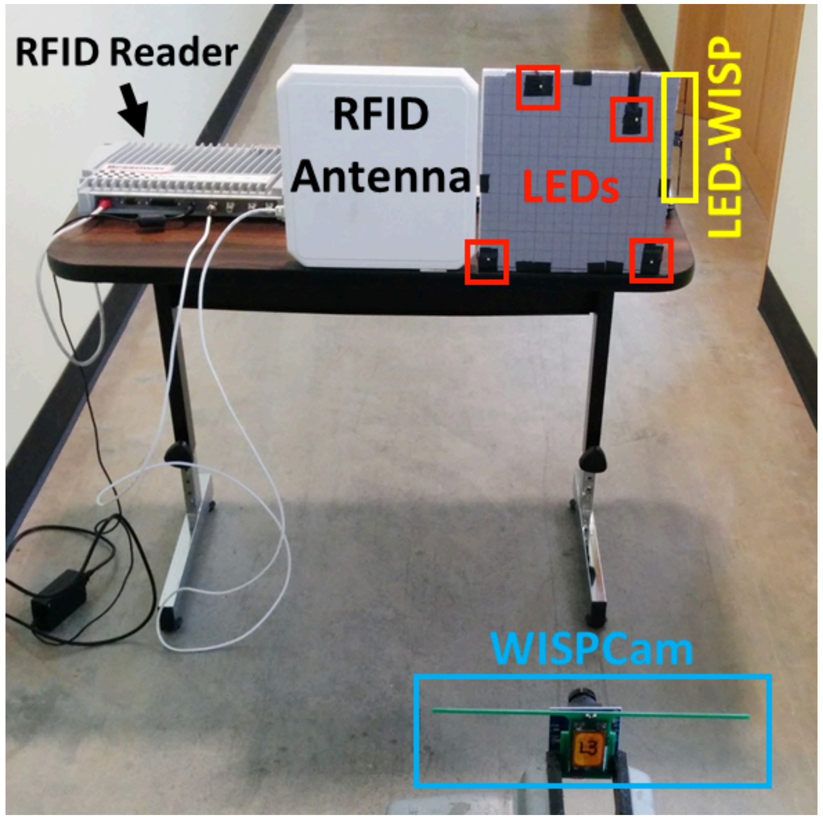
Sample, Alanson P., et al. "Design of an RFID-based battery-free programmable sensing platform." IEEE Transactions on Instrumentation and Measurement 57.11 (2008): 2608-2615.

WISPCam: Battery-less Camera

- WISPCam - University of Washington





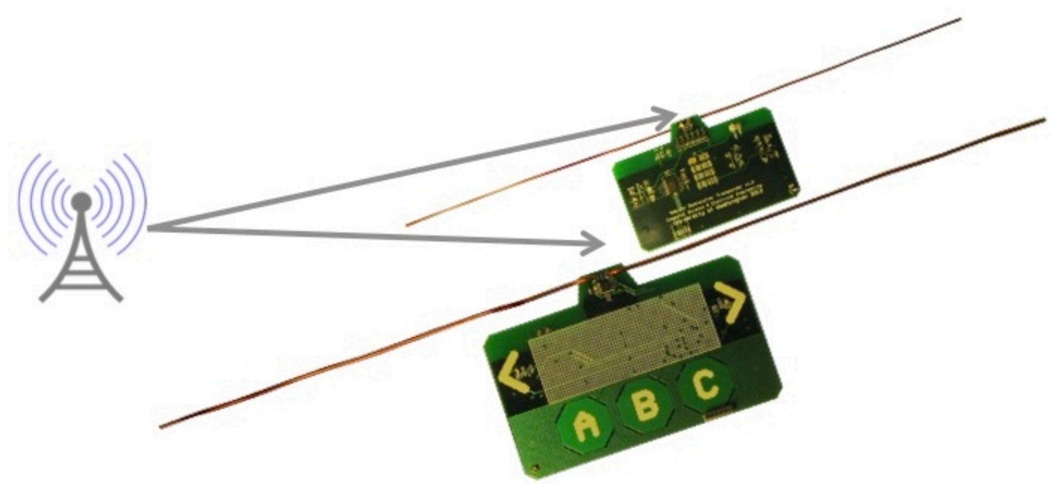


WISPCam captures a 160x120 low resolution image for face detection

Naderiparizi, Saman, et al. "Wispcam: A battery-free rfid camera." 2015 IEEE International Conference on RFID (RFID). IEEE, 2015.

Ambient Backscatter

- Traditional backscatter communication, (e.g. in RFID)
  - a device communicates by modulating its reflections of an incident RF signal - not by generating radio waves
- Ambient backscatter
  - Communicate using ambient RF signals as the only source of power
    - Ambient RF from TV and cellular communications



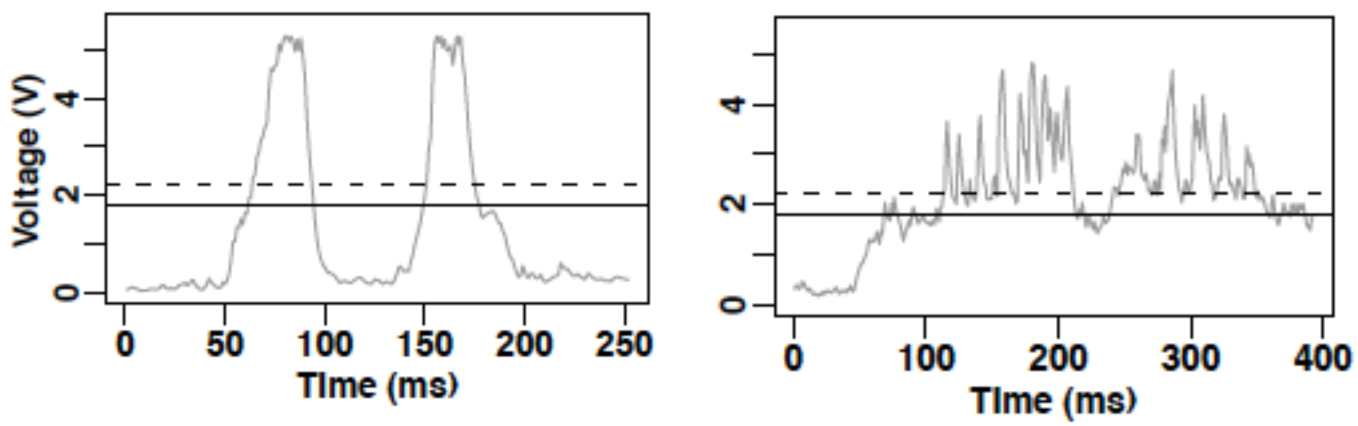
Vincent Liu et al. "Ambient Backscatter: Wireless Communication Out of Thin Air ", ISIGCOMM, August 2013

WISP tags vs WSN nodes - I

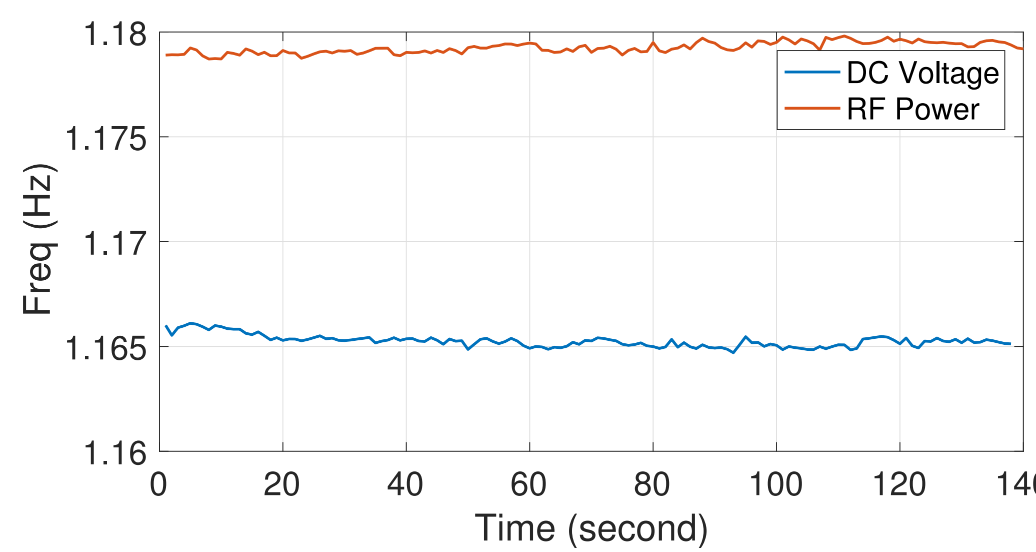
- Continuously varying voltage level
  - WSNs: stable voltage levels in the short term (battery-powered)
  - WISP: fluctuating input voltage[1]

[1]Benjamin Ransford et al., "Mementos: system support for long-running computation on RFID-scale devices." Acm Sigplan Notices 47.4 (2012): 159-170.

Different voltage levels at different distances to the reader



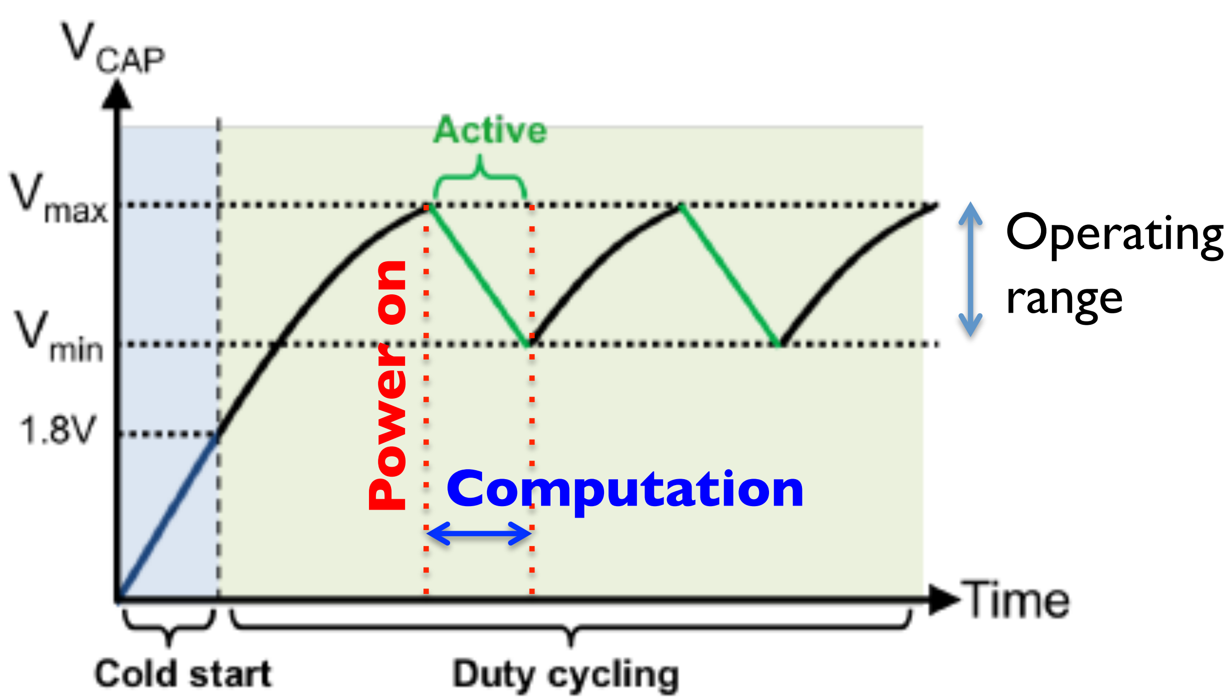
  - Different side-effects
    - E.g. prevents short-term stability of the clock hardware[2]



[2]Yıldırım, Kasım Sinan, et al. "On the Synchronization of Intermittently Powered Wireless Embedded Systems." arXiv preprint arXiv:1606.01719 (2016).

WISP tags vs WSN nodes - II

- Frequent loss of computation state
  - frequently ``die'' due to power loss
    - need to save the computation state into the non-volatile memory
    - recover when they harvested sufficient energy to start up
    - saving computational state to non-volatile memory is also energy consuming



Energy is available intermittently

Computation is intermittent

[1]Naderiparizi, Saman, et al. "Wispcam: A battery-free rfid camera." 2015 IEEE International Conference on RFID (RFID). IEEE, 2015.

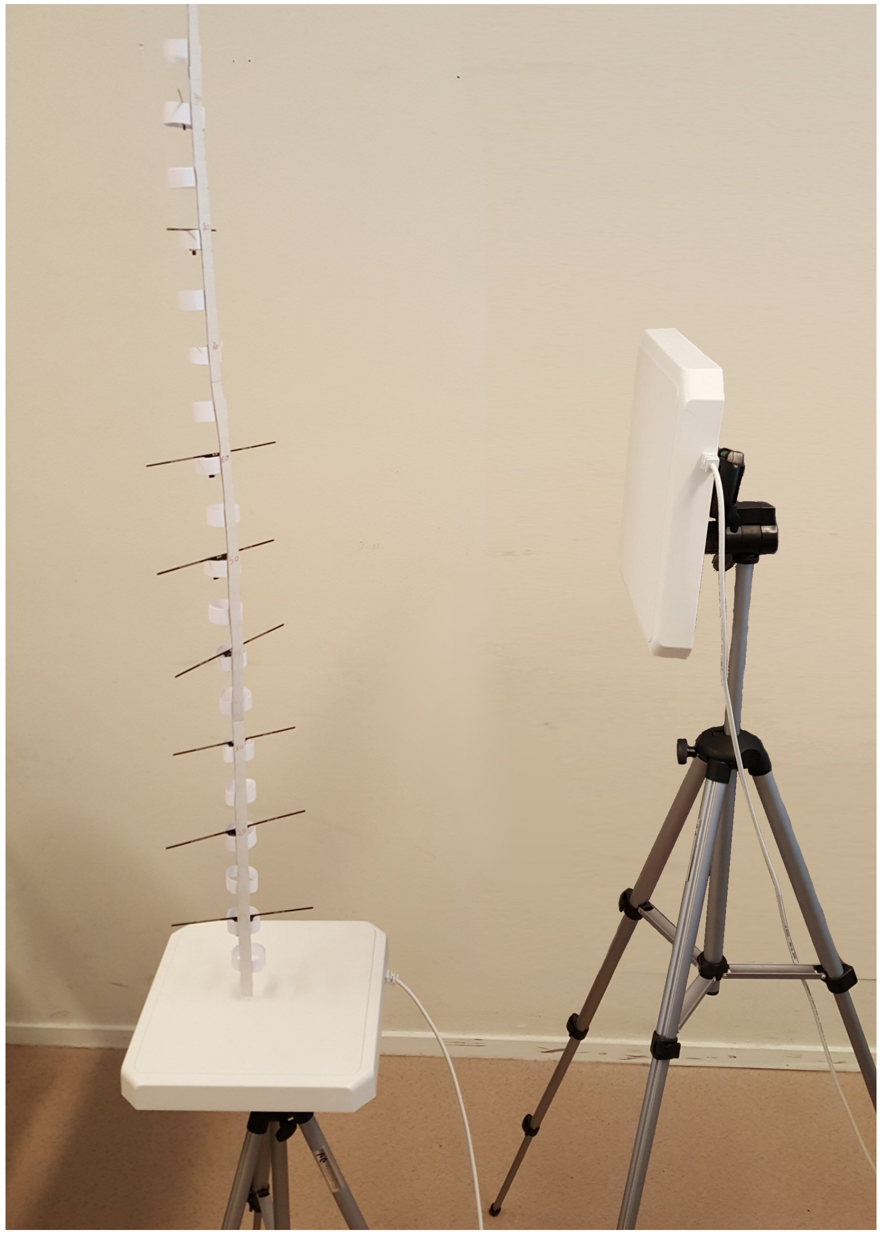
WISP tags vs WSN nodes - III

- The classical motto of WSNs
  - ``compute instead of communicate whenever possible''
  - No longer valid for the WISP platform
    - backscatter communication comes almost for free
- Intermittent power
  - lightweight methods in terms of computation are desirable
  - E.g. least-squares regression
    - computationally heavy ?
    - require considerable amount of memory ?

Communication Protocols

IPD – Communication Middleware

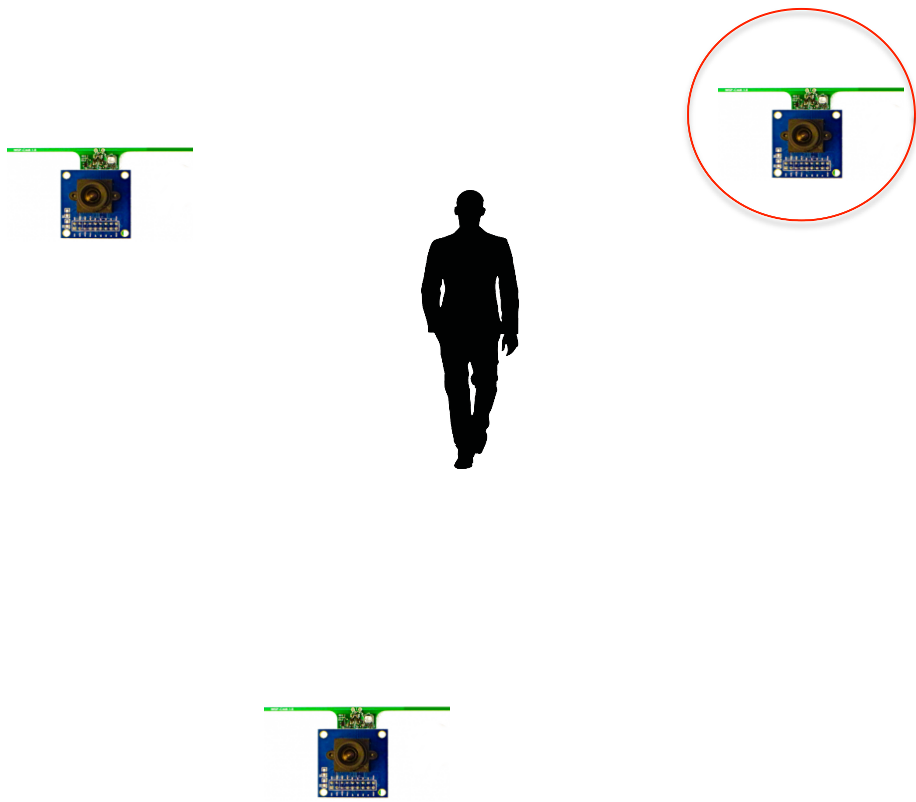
- CRFID applications are developing
  - extremely small energy budgets to spare.
  - operate on short distances (less than 5 m)
  - very low throughput (in the order of kB/s).
- Basic building blocks are missing
  - E.g. time synchronization in wireless sensor networks
- Currently EPC Gen 2 Communication Standard
    - No multi-hop network
    - No Routing



Case Study – Synchronizing CRFIDs

Battery-less cameras (WISPCams) deployed to capture images of an object from different angles simultaneously.

Each battery-less camera has its own built-in clock whose oscillator generate pulses at slightly different speeds.

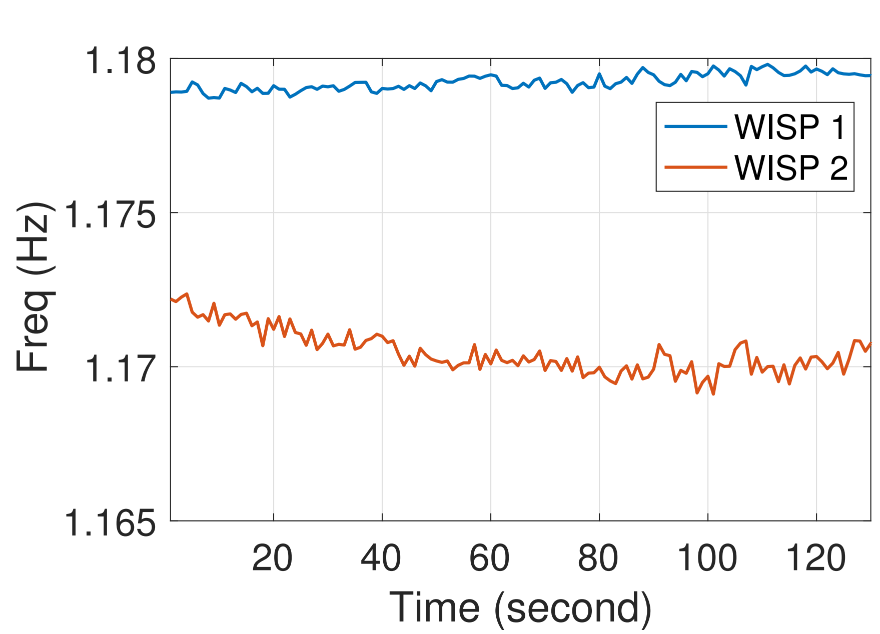


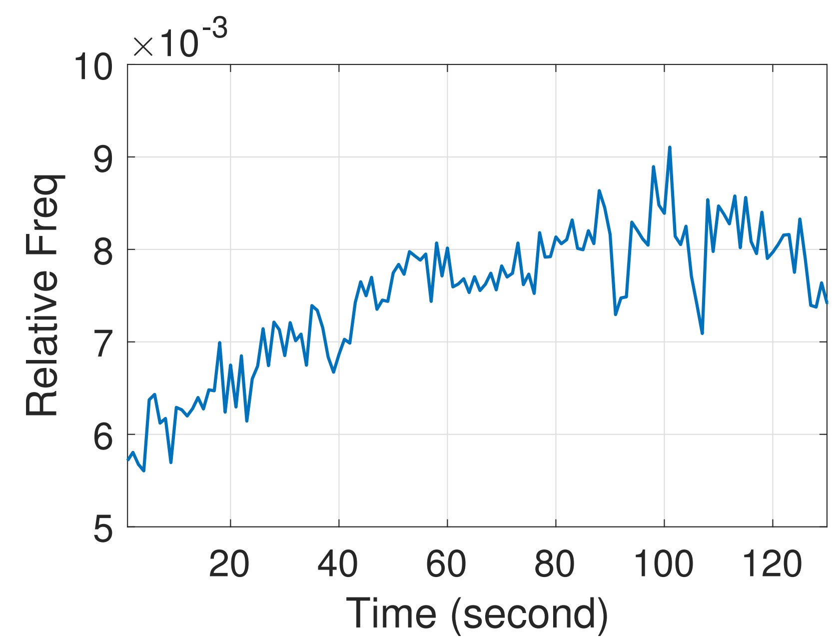
How to obtain a common time notion for such collaborative and coordinated actions?

A network of battery-less cameras

Challenges - I

- Continuously varying voltage level in short-term
  - The prominent factor affecting the frequency of the crystal oscillator
  - Prevents short-term stability and introduces significant drift.





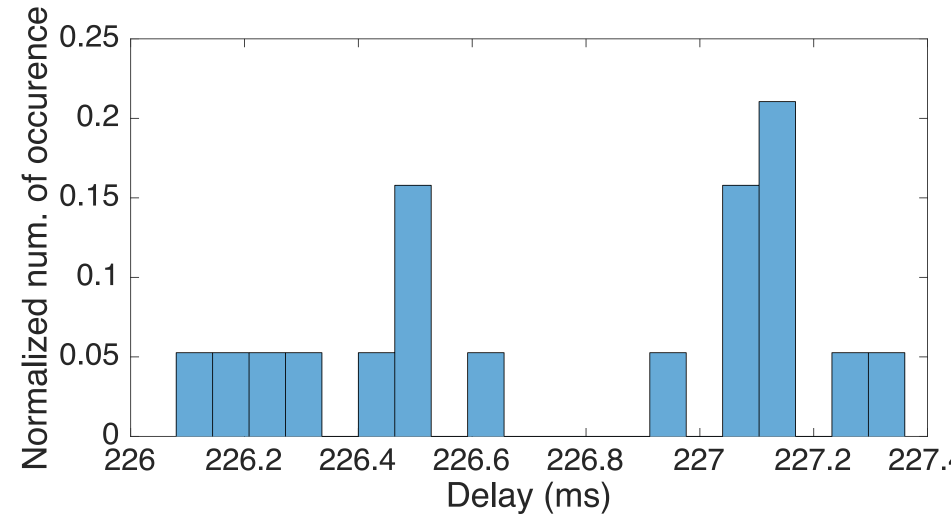
- Frequent loss of synchronization state
  - WISP tags frequently “die”
  - Need to save synchronization state
    - Saving computational state is also an energy consuming task

Challenges - II

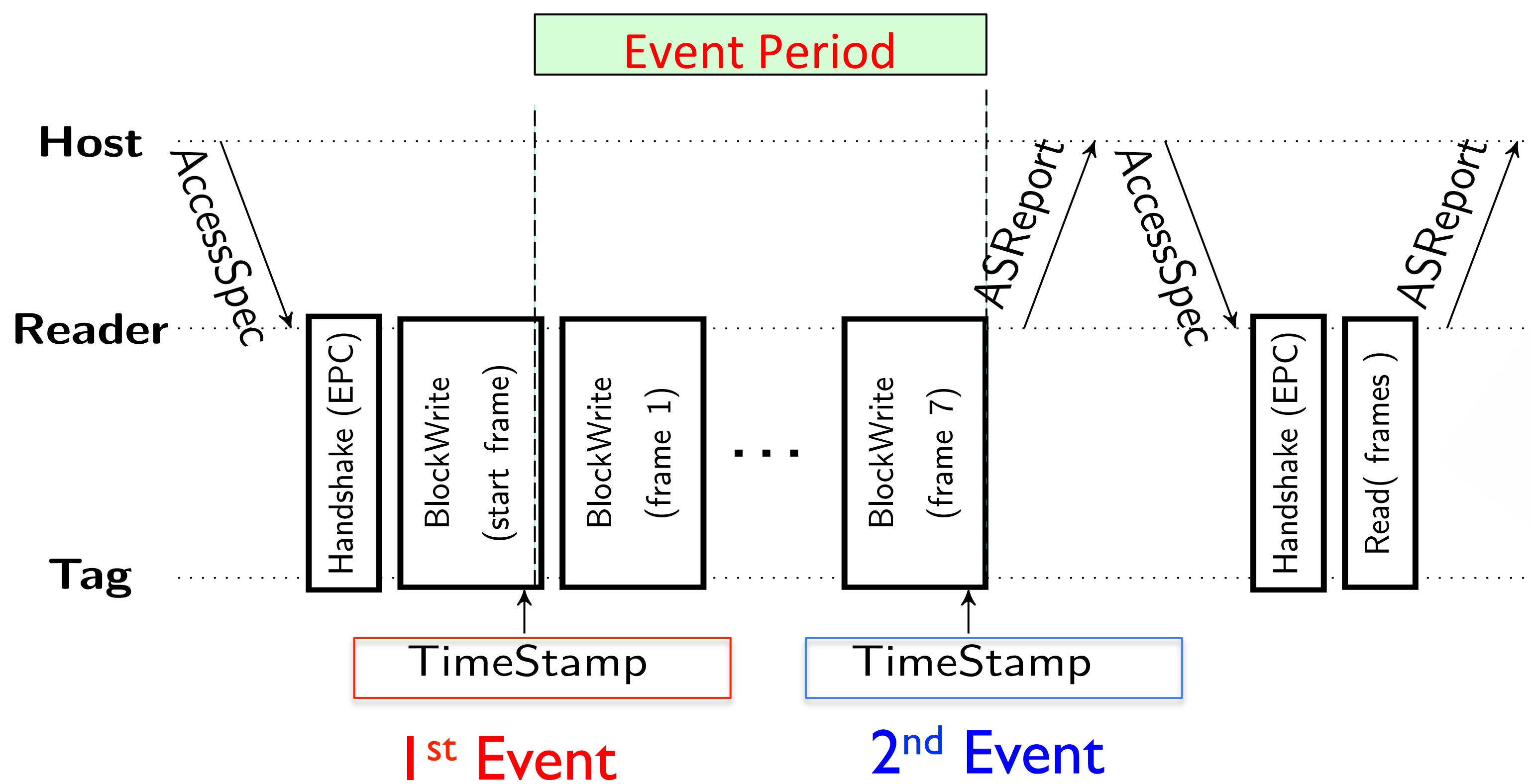
- Computation and memory overhead sensitivity
  - computationally lightweight methods
- Communication is free
  - backscatter communication
- Single-hop architecture
  - RFID reader itself is the natural reference
- Limitations of EPC Gen 2 standard
  - does not assign timestamps to the radio packets
    - a fundamental requirement
  - communication delays between the reader and tag
    - RFID reader dependent

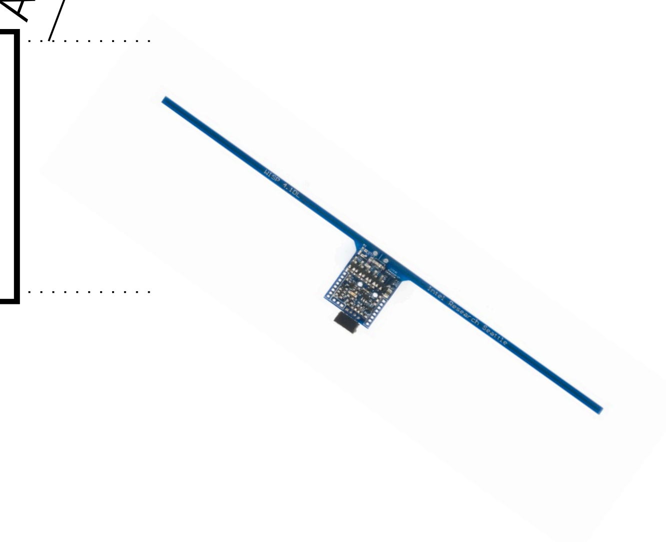
WISPSync - I

- RFID reader
  - generates events at regular intervals.
- WISP tag
  - adjust the speed of its software clock
  - predicts the occurrence of the next event



The event period is distributed with a mean of 226.76 ms and standard deviation of 0.41 ms; respectively.



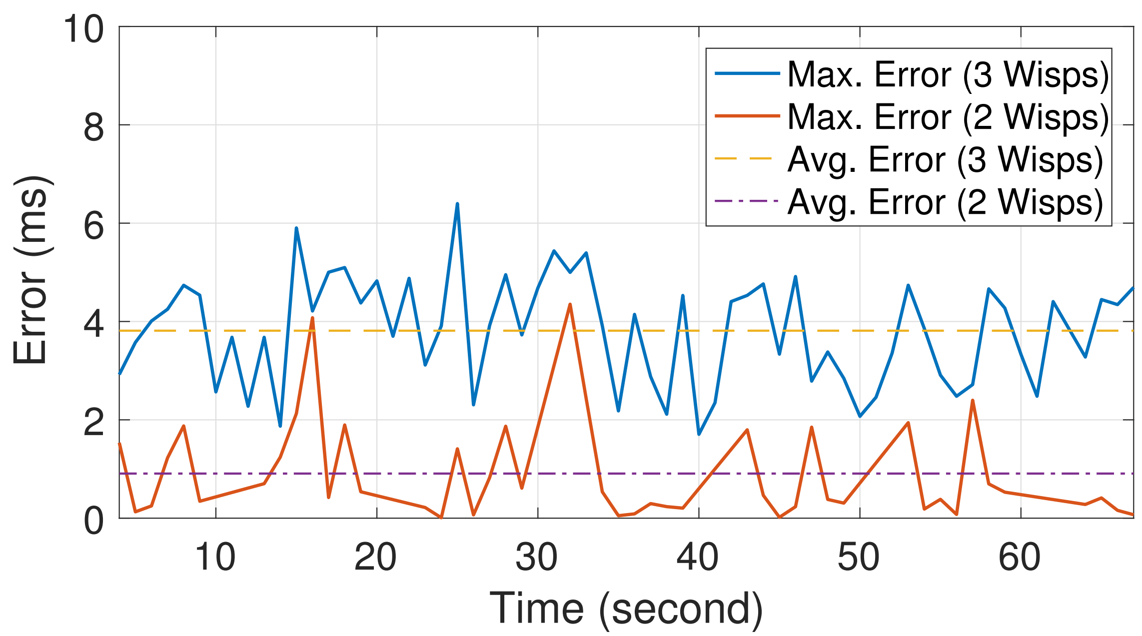


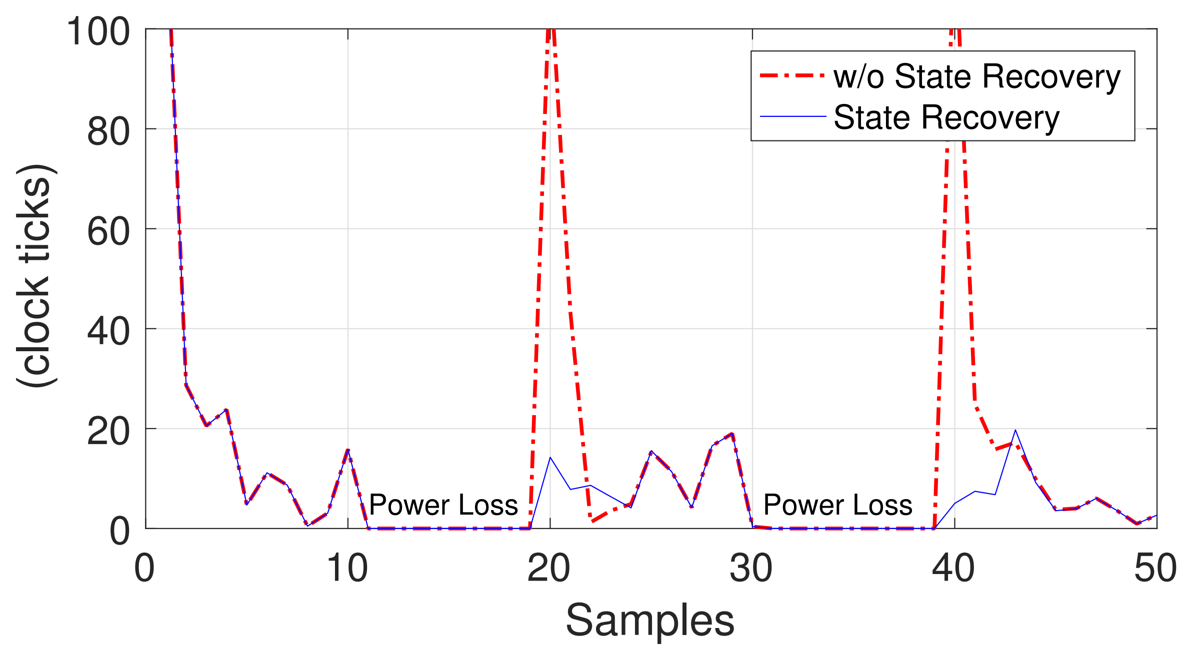
[1]Yıldırım, Kasım Sinan, et al. "On the Synchronization of Intermittently Powered Wireless Embedded Systems." arXiv preprint arXiv:1606.01719 (2016).

WISPSync - II

- Inspired from PI controllers
  - performs only a few computation steps
    - runs efficiently under limited harvested energy
  - keeps a few variables to hold the synchronization state
    - recovers from power interruptions with minimum overhead
  - adaptive to react to short-term clock instabilities
    - fast (depending on the integral gain).

[1] *Yıldırım, Kasım Sinan, Ruggero Carli, and Luca Schenato. "Adaptive control-based clock synchronization in wireless sensor networks." Control Conference (ECC), 2015 European. IEEE, 2015.*

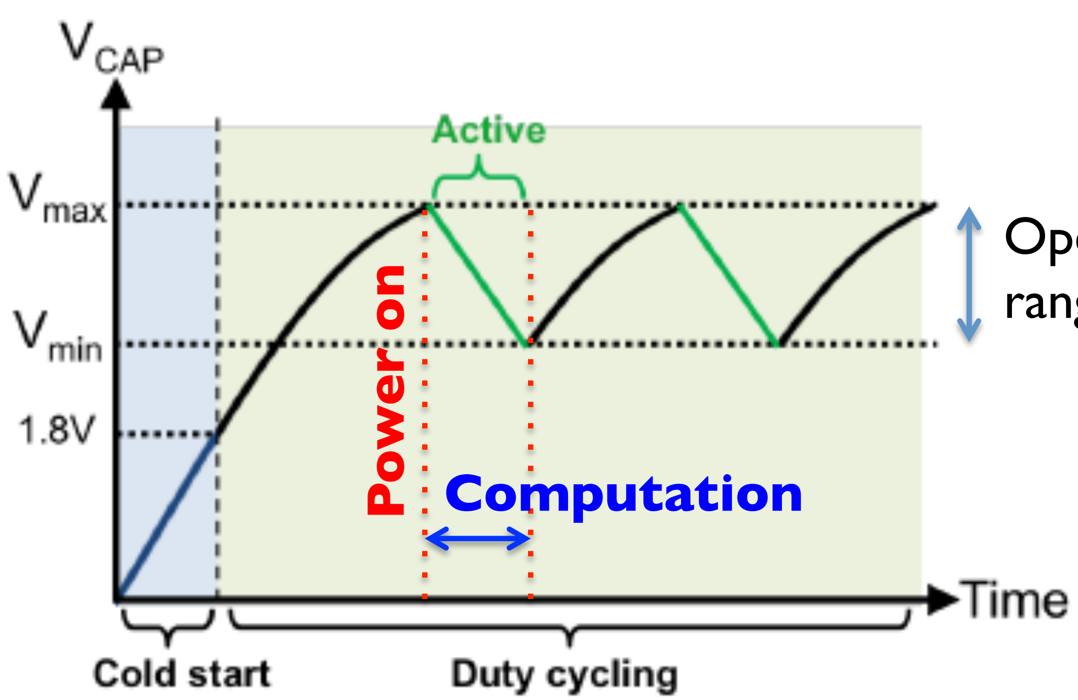


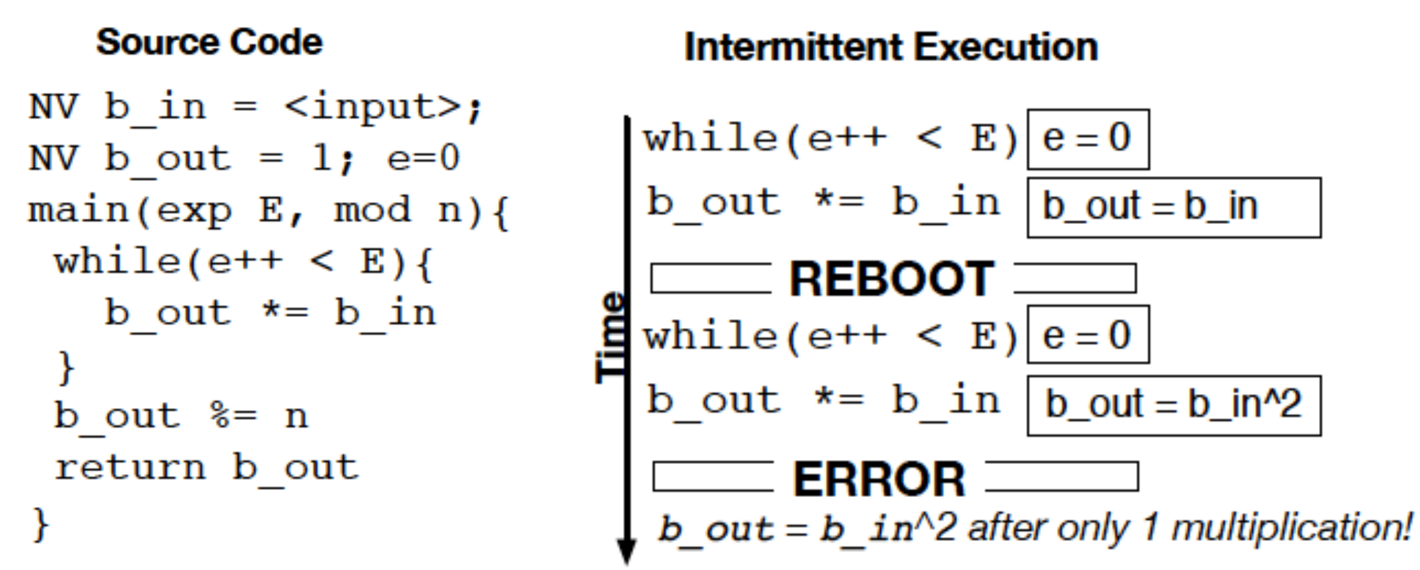


Programming Challenges

IPD – Programming Platforms

- How to design programs under power interruptions?
  - How to ensure
    - Consistency of the non-volatile memory?
    - Correctness of the program?
- How to determine when and what to save in non-volatile memory
  - Energy consuming

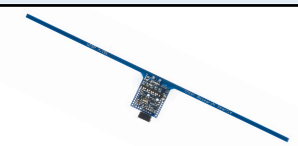




[1] *Chain: Tasks and Channels for Reliable Intermittent Programs Alexei Colin, Brandon Lucia, OOPSLA 2016*

Future…

	Active	Passive	Ideal
Power Source	Battery-powered	RF-powered (battery-free)	RF-powered (battery-free)
Physical Operating Range	Unlimited	Requires proximity to RF power source	Unlimited
Lifespan	Months to years	No fundamental limitation	No fundamental limitation

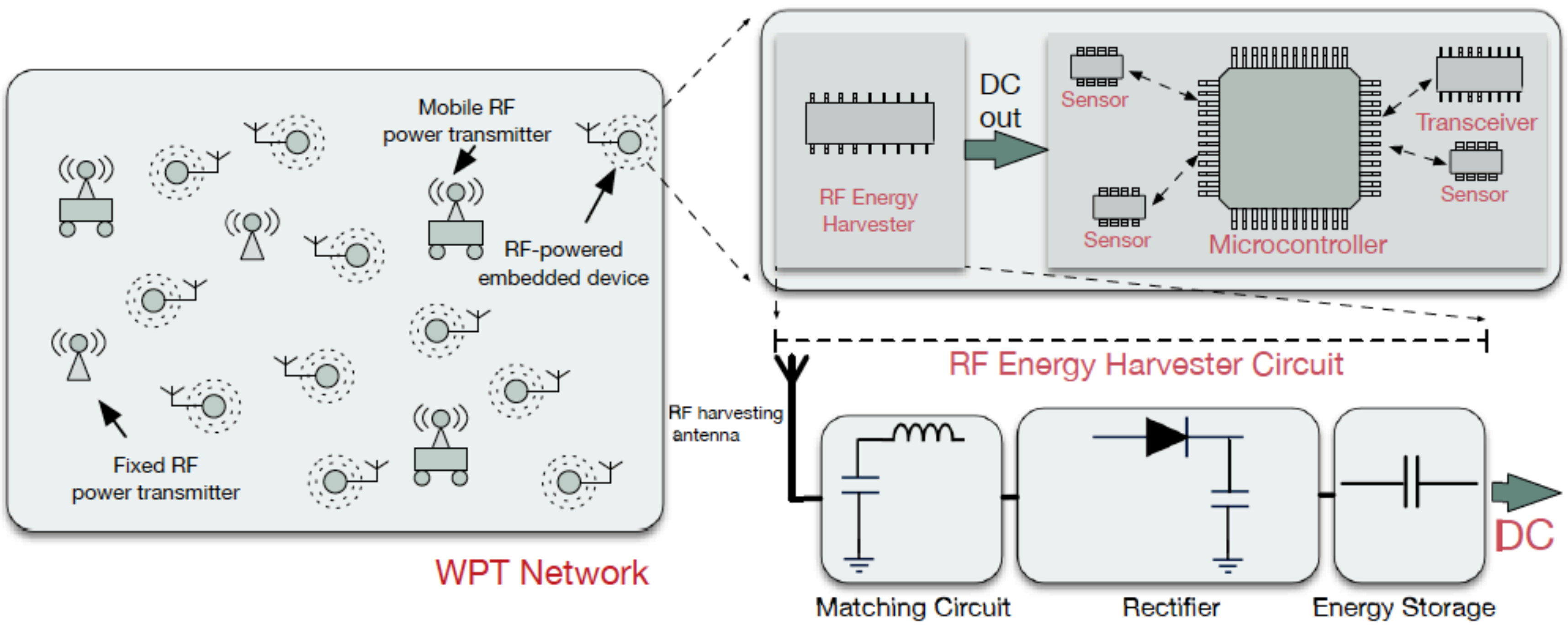


Not Yet

Wireless Power Transfer Networks

Provision of Energy to IPDs

- Wireless power transfer networks (WPTNs)
  - Energy transmitters (ETs)
    - charge different types of energy receivers (ERs)
    - controlling their transmit power and time/frequency of the waveforms
  - Each ER is equipped with a harvester circuit
    - converts the received RF signal to a DC signal
    - charges built-in capacitor/energy storage



Safety and Security Issues in WPTNs

- Wirelessly transmitted energy can be neither encrypted nor authenticated
  - cannot ensure charging a specific harvester
  - power transfer channels are open to attacks
- Radiated power from commercial WPTNs
  - radiation safety thresholds are more likely to be exceeded
- Conventional security mechanisms
  - demand non-negligible computational resources.
  - Challenging under limited harvested energy

[1] *Liu, Qingzhi, et al. "Safe and Secure Wireless Power Transfer Networks: Challenges and Opportunities in RF-Based Systems." arXiv preprint arXiv:1601.05648 (2016).*

Safety Issues

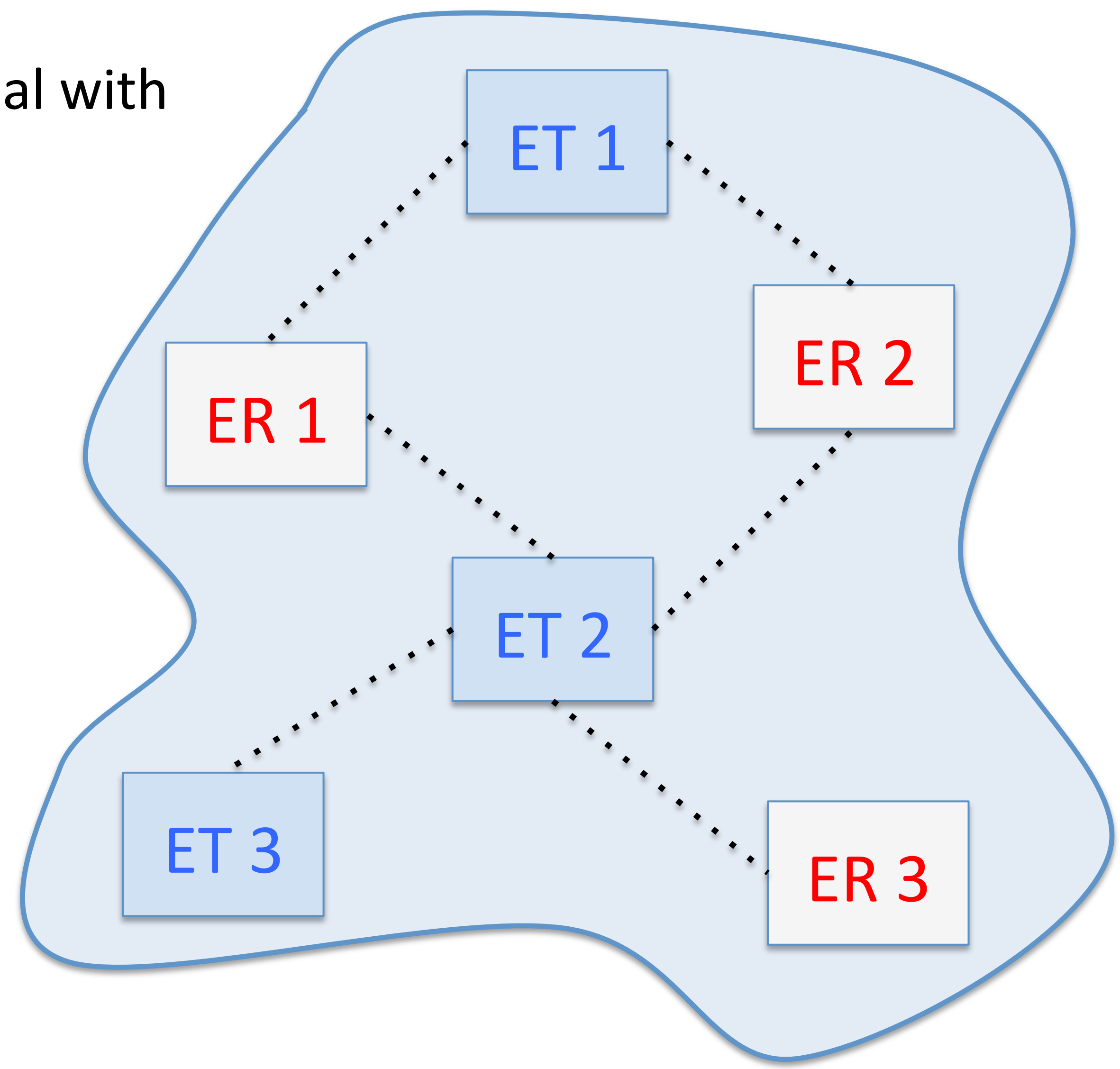
Safe power transfer in WPTNs - I

- Several ETs can be active simultaneously
  - aimed at charging ERs collaboratively
    - charge as fast as possible (reduce charging delay)
    - optimize the transferred energy
- A safe-charging WPTN
  - electromagnetic radiation (EMR) under a safety threshold
  - a power transfer schedule
    - maximize total transmitted power and ensure EMR safety
    - an NP-hard problem[1]
  - quite challenging
    - end-users are allowed to deploy new ETs and modify the locations
    - as more ETs are deployed, users might be exposed to more radiation

[1] *H. Dai, Y. Liu, G. Chen, X. Wu, and T. He, "Safe charging for wireless power transfer," in Proc. IEEE INFOCOM, Toronto, Canada, Apr. 27 – May 2, 2014.*

Safe power transfer in WPTNs - II

- A dynamic system should
  - guarantee the safety
    - considering run-time influence of unpredictable end-user actions.
  - maximize total transmitted power
    - Received power is is inversely proportional with the distance
  - ensure EMR safety at each point
    - EMR is linearly proportional with the received power



Wireless power density

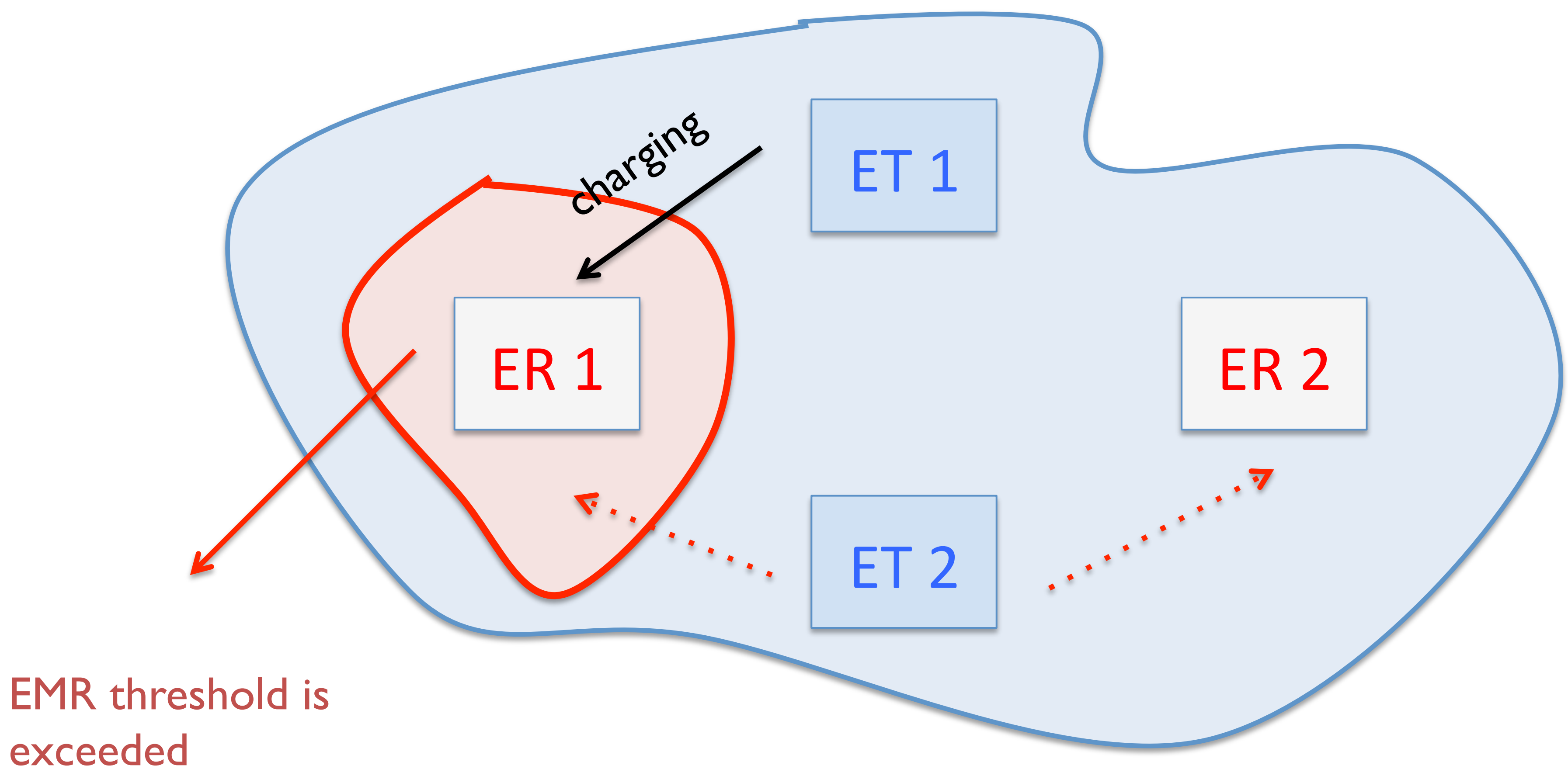
Hard to estimate and control due to reflection and refraction of the signals.

Centralized/Distributed Control of ETs

Security Attacks

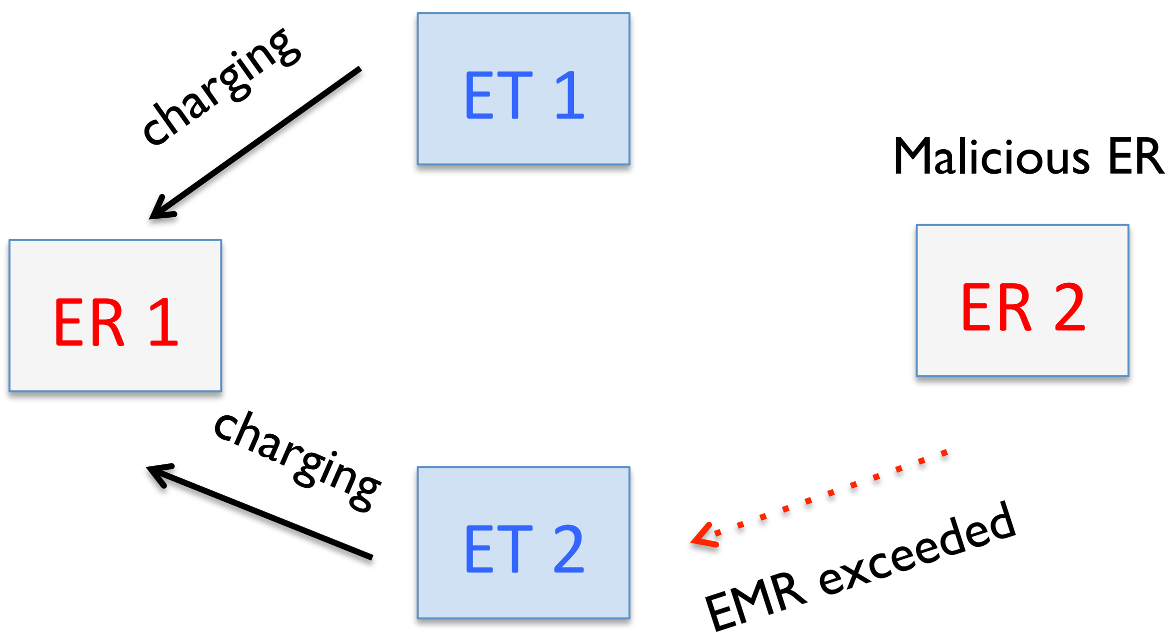
Charging Deadlocks

- Suppose that an ER 1 is being charged by ET 1.
- Let ER 2 with an almost depleted battery sends a charge request to ET 2.
  - ET 2 is turned on and starts transmitting energy
    - RF exposure exceeds the safety threshold for ER 1.
  - ET 2 remains turned off
    - ER 2 might stop operating.



Safety Attacks

- Safety regulations can be abused - denial of service
  - to degrade charging performance of ETs
  - even to force them to stop working
- A malicious ER can report that the RF exposure is over the safety limit.
  - ETs should
    - either turn-off their transceivers
    - reduce their transmission power.
- The more safety attacks are done
  - the less efficiently ERs are charged
  - the shorter their operation time.



Better measurement and estimation techniques are required
to obtain the radio power distribution without feedback from ER.

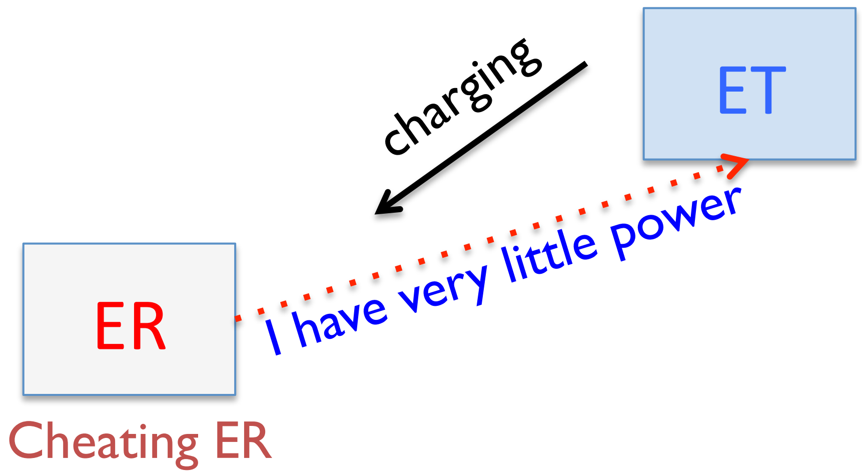
Freerider ERs

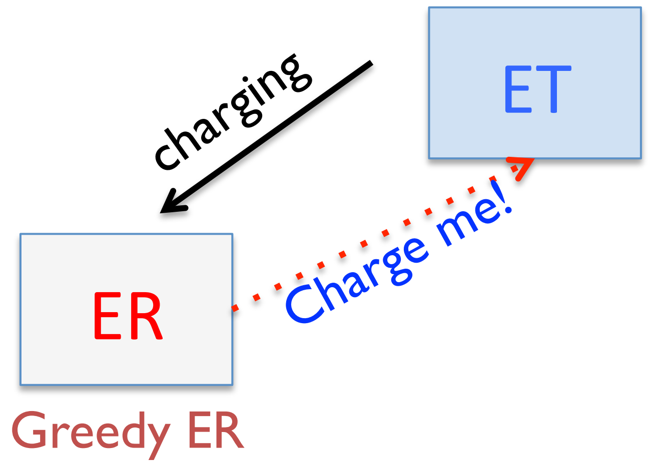
- ETs equipped with omni-directional antennas - public energy sources
  - any ER inside their coverage can harvest energy.
    - although they did not request it.
- Freerider ERs
  - do not send charging requests & receive energy for free.
  - ETs are unaware of which ERs they are charging.
  - How to charge only registered or authorized ERs?

ETs can modify their RF transmission parameters at run-time, e.g. frequency and power.

Greedy – Cheating ERs

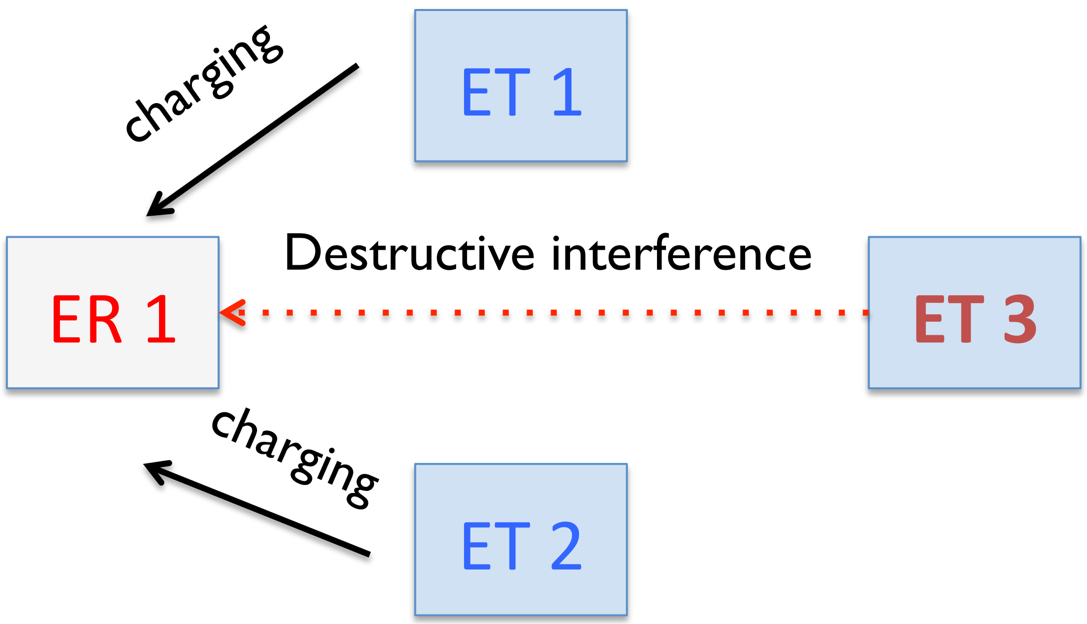
- Greedy ERs send charging requests to ETs continuously
  - may lead to other ERs receiving less power.
- ETs should implement fair power transfer mechanisms.
  - challenging to estimate harvested energy precisely
  - receive feedbacks from ERs
    - to get their energy levels
    - to optimize their power transmission parameters.
- Cheating Ers report their current energy level is low
  - receive more power from ETs.





Beamforming Attacks

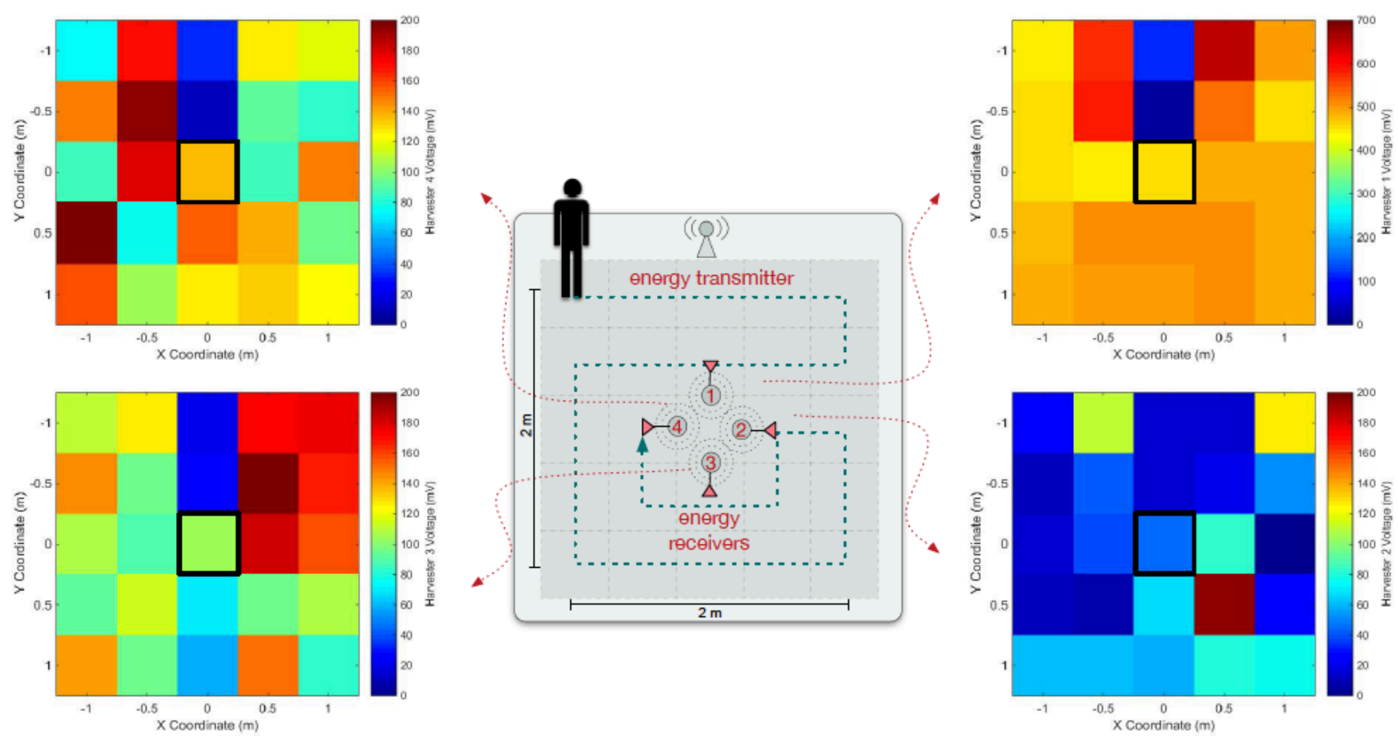
- Multiple ETs emit RF waves at the same frequency band simultaneously
  - constructive interference: the phase differences of signals are negligible
    - the received power is greater than that of individual energy waves
  - destructive interference: the phase difference is large
    - leading to less harvested power
- Destructive interference is a potential threat
  - an attacker deliberately to decrease or destroy harvested energy at ERs



Turning off and listen the network, dynamically adapt their transmission parameters

Monitoring Attacks

- WPTNs can also be considered as wireless monitoring networks
  - malicious ERs that receive energy from ETs
    - disclose private information
- Example:
  - a malicious ER can be equipped with sensors
    - collect measurements
    - Localize people



Conclusions

- IPDs and RF-based WPTNs are emerging
- There are lots of research opportunities in this domain
  - Communication Protocols
    - Physical layer
    - MAC layer
    - Routing
    - Synchronization
  - Programming Platforms
  - Operating Systems
  - Safe and secure power transfer
  - Many more…

Thank You!