Low Power (Battery-Free) Systems

Vamsi Talla

CTO

Jeeva Wireless

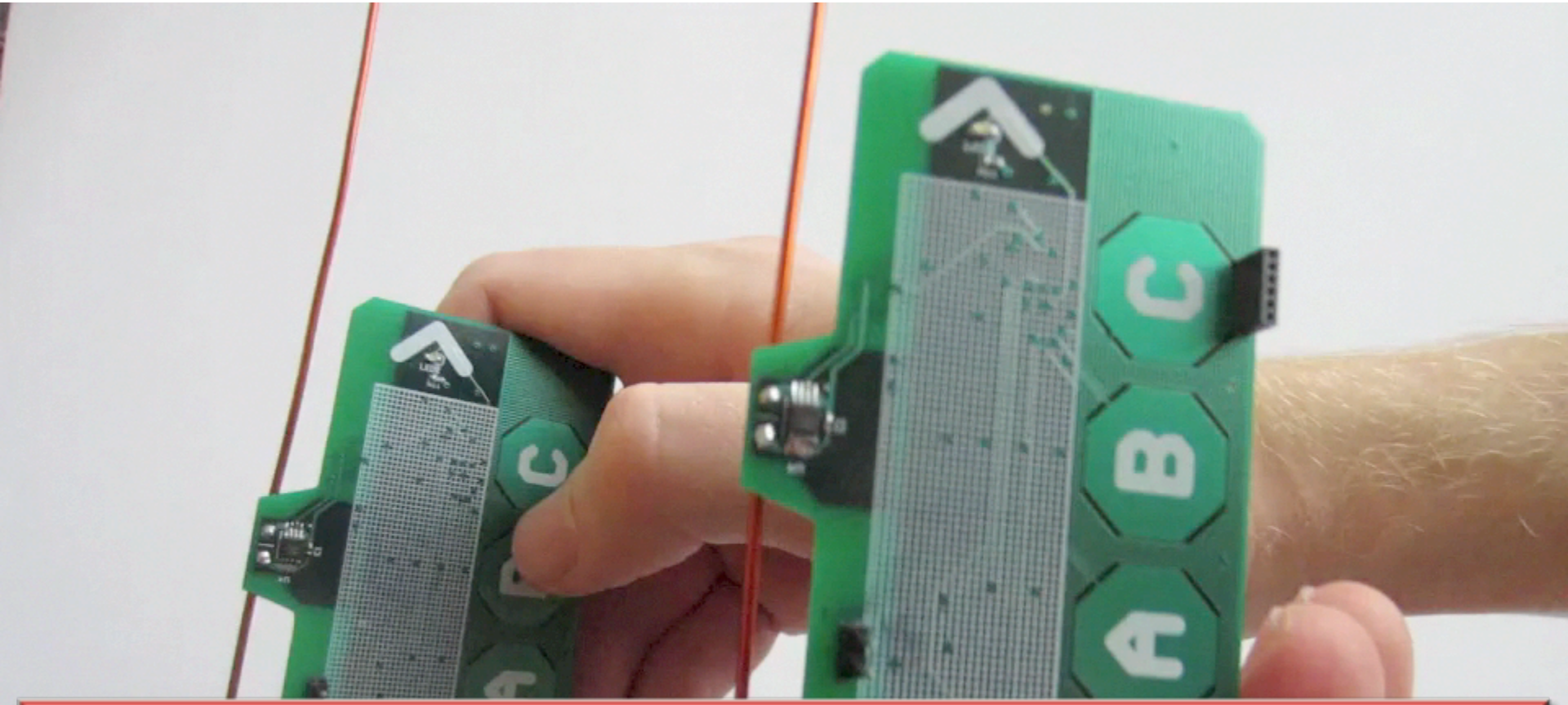
Ambient Backscatter

Vincent Liu,Aaron Parks, Vamsi Talla,
Shyam Gollakota, David Wetherall, Joshua Smith

Our Goal

Interactive devices that compute and communicate without batteries

What We Are After



How to power computation, sensing, and communication?

Leverage Existing Wireless Signals

TV

Cellular

Wi-Fi

Available at almost any time and place, rain or shine

Recent Work Harvests 10s of µW [‘09]

- Enough for computation and sensing

- Orders of magnitude less power than needed for radio communication [‘13]

Challenge: Communication Between Battery-Free Devices

- Generating radio signals is expensive

- Could duty cycle
  - Limits interactive applications

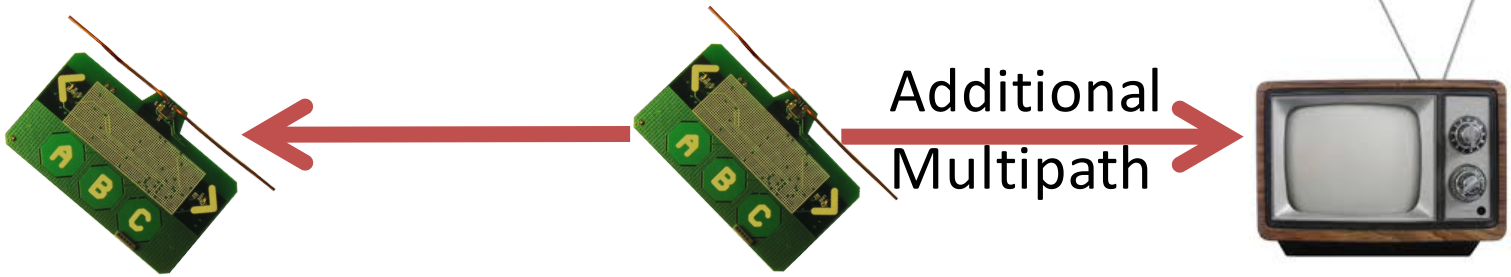
Can we communicate without either device generating radio signals?

Ambient Backscatter

Use existing signals instead of generating our own

TV Tower

Works with only ~5% of the harvested power!

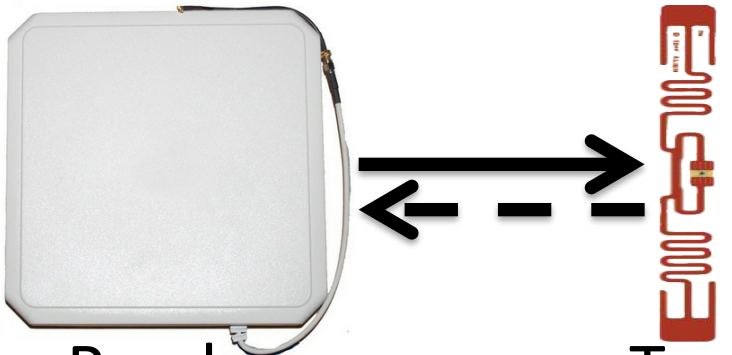


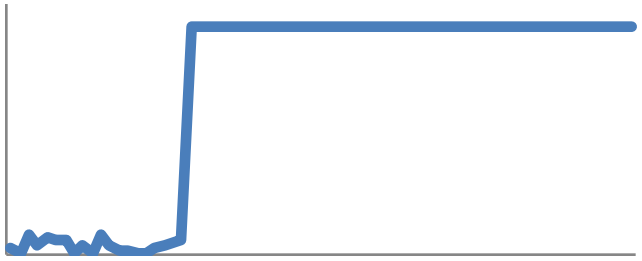
‘0’ bit – Absorb TV Signals

‘1’ bit – Reflect TV signals

Challenges

RFID

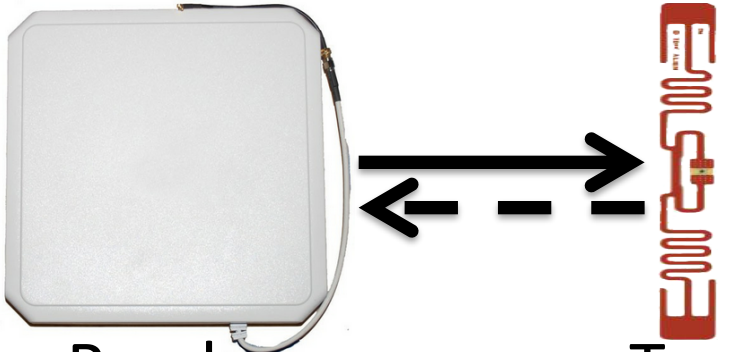




- Reader sends constant wave
- Receive chain: 100s of mW
- Reader centrally coordinates

Ambient Backscatter

RFID



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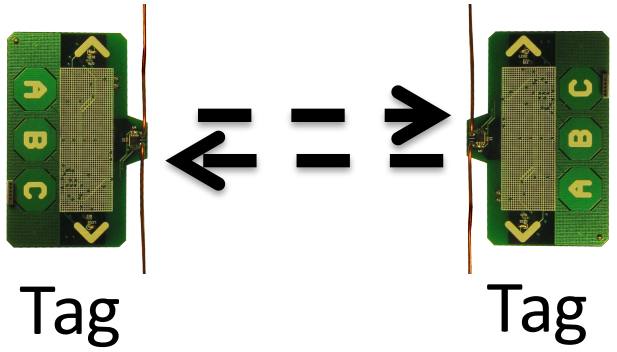
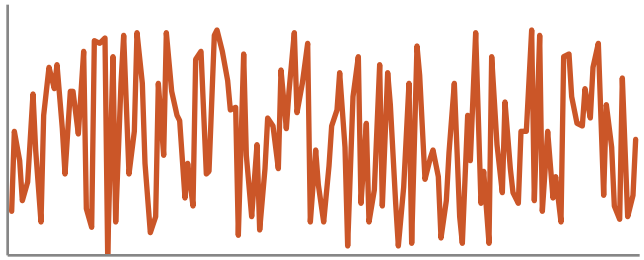
Ambient Backscatter





- Uses uncontrollable signals
- Receive chain: 0.5 µW
- Need distributed MAC

Challenges

- Extracting backscattered signals from ambient signals we don’t control
- Decoding on a battery-free device
- Designing distributed MAC for battery-free devices

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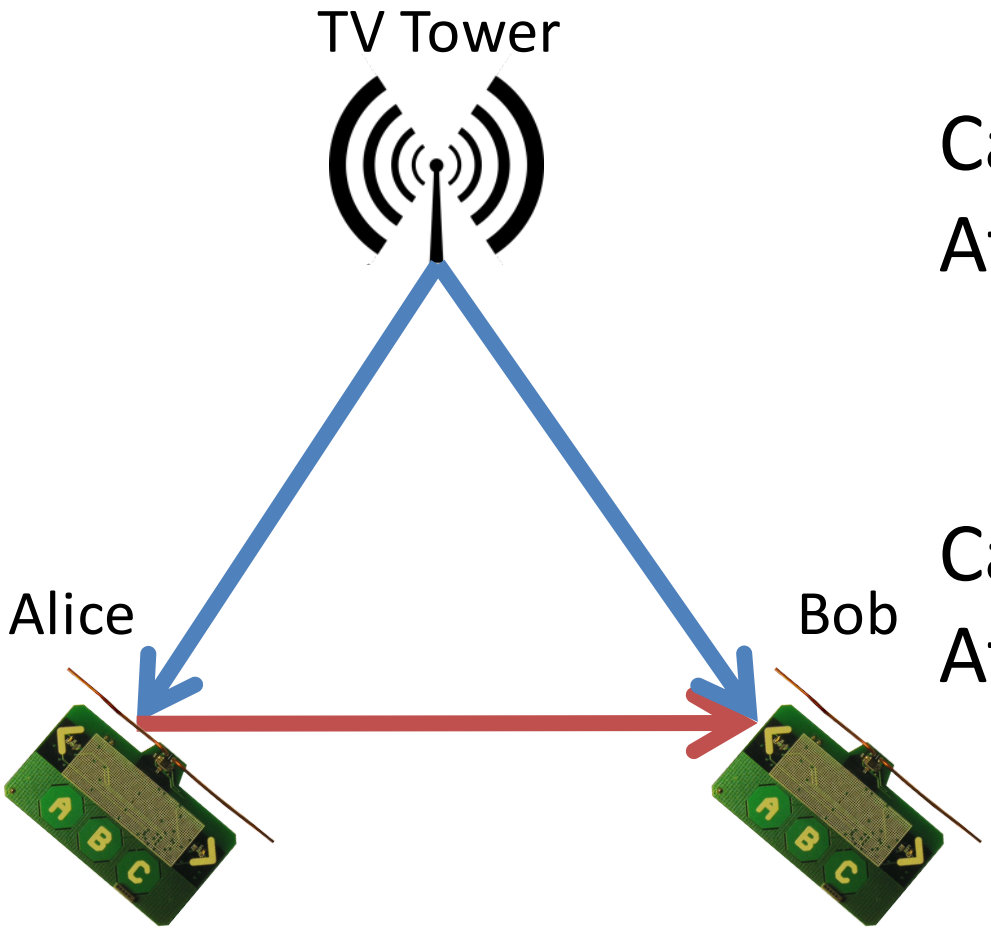
How Do We Extract The Backscattered Signals?



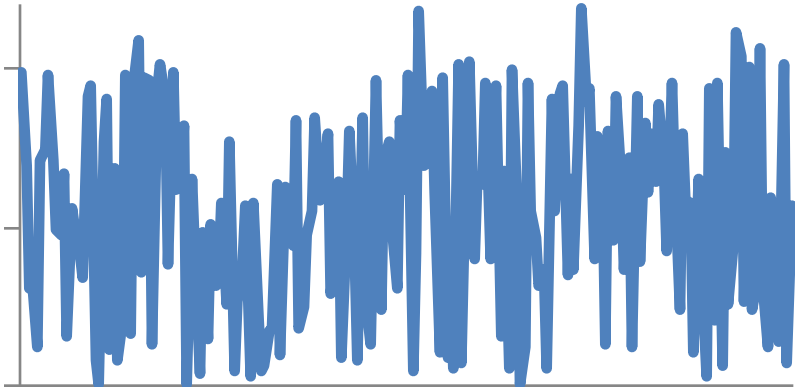
Case 1: Alice absorbs
At Bob: TV signal

Case 2: Alice reflects
At Bob: TV signal
+ Weak Reflection

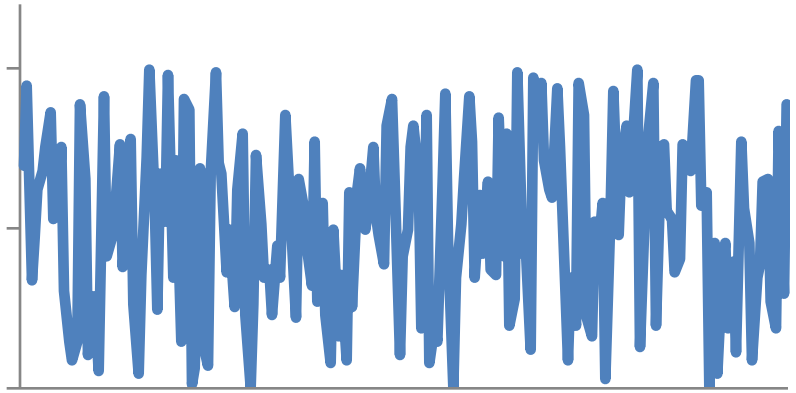
Alice's reflections change the average amplitude

Solution: Detect Changes in Average Amplitude

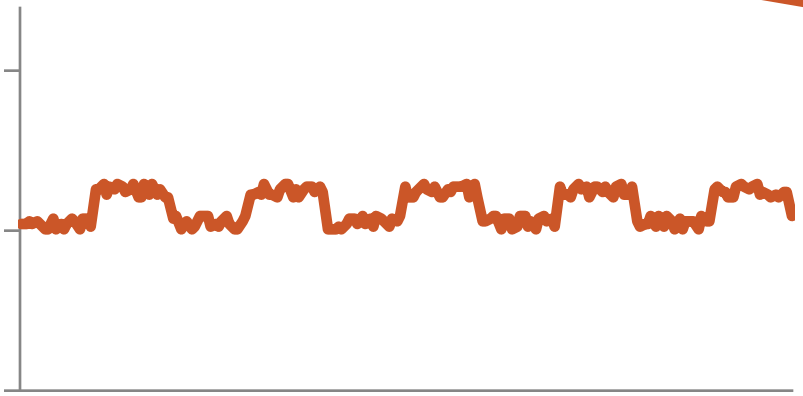
Alice Sends 1010…

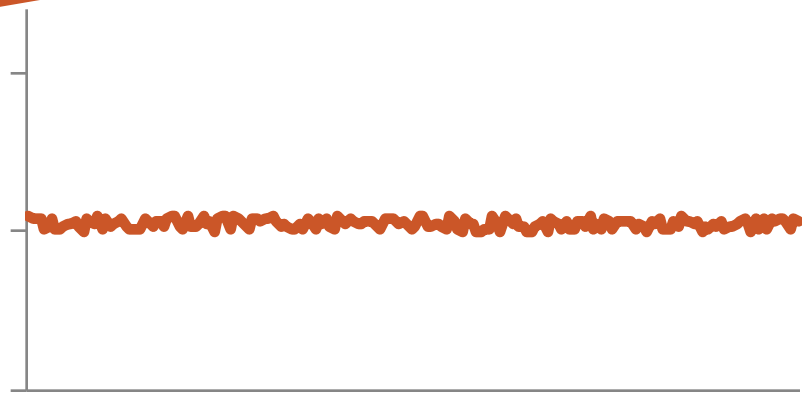


Alice Inactive

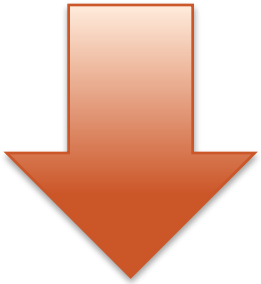


Moving Window Average





If we had digital samples, averaging would be easy

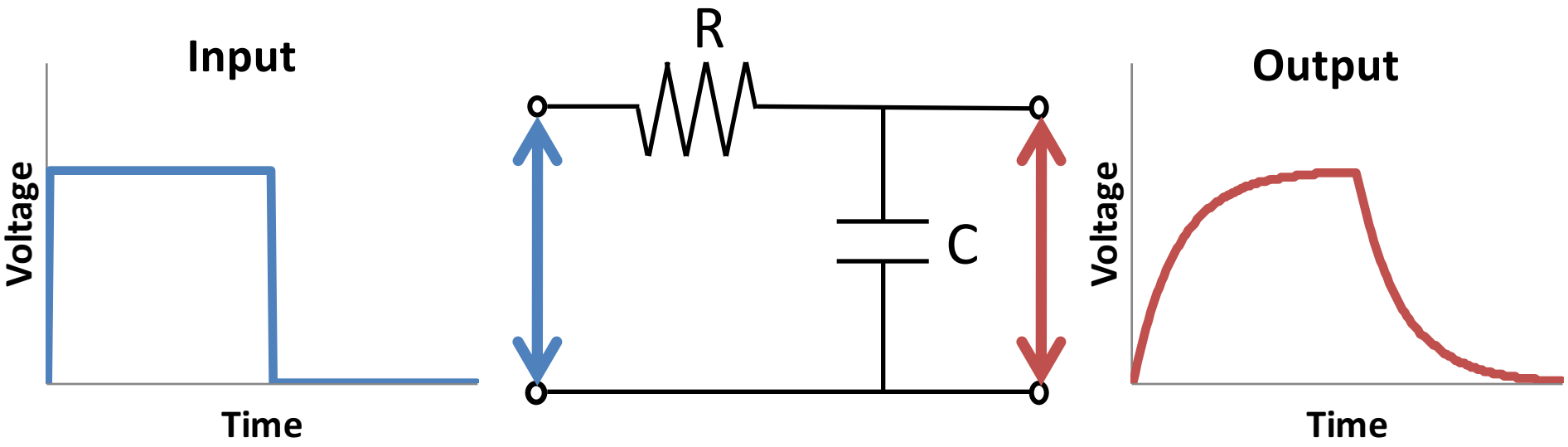


Need power-hungry analog-to-digital converters

Challenges

- Extracting backscattered signals from ambient signals we don't control
- Decoding on a battery-free device
- Designing distributed MAC for battery-free devices

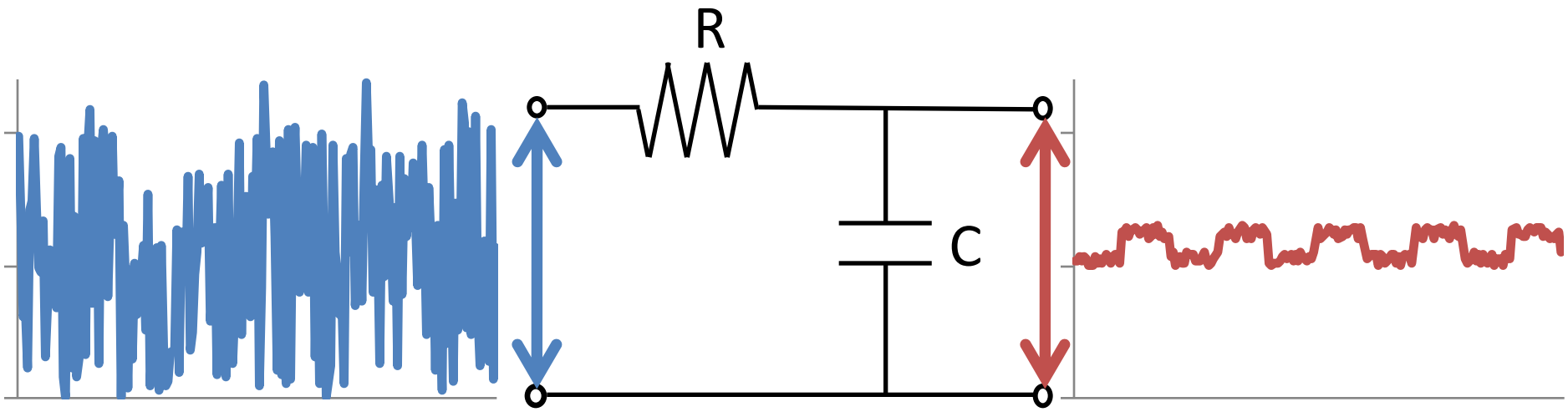
Use RC Circuits to Average



- Capacitor slowly charges/discharges when voltage is applied/removed

Provides a cheap, analog, exponential moving average

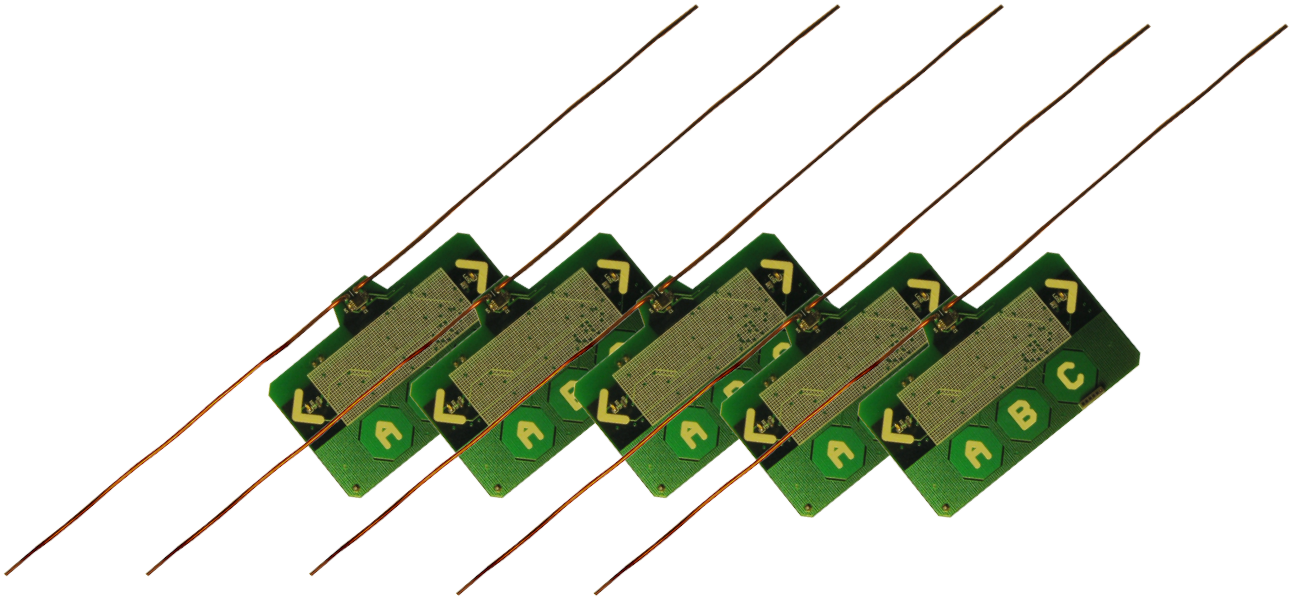
Use RC Circuits to Average



- Capacitor slowly charges/discharges when voltage is applied/removed

By picking the right RC values,
we can selectively filter out the high TV frequencies

Now that we can decode bits…



Link Layer
Physical Layer

Distributed MAC?

Challenges

- Extracting backscattered signals from ambient signals we don't control
- Decoding on a battery-free device
- Designing distributed MAC for battery-free devices

We Use CSMA

- CSMA uses carrier sense, i.e. energy detection

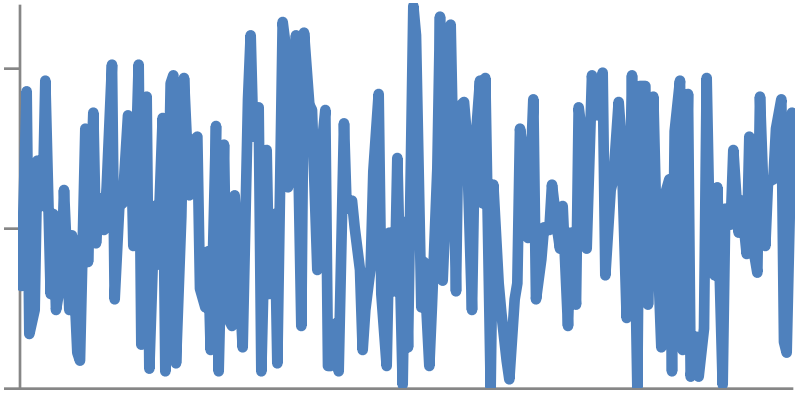
- Battery-free devices do not have energy levels
  - Requires power-hungry ADCs

Challenge: Energy detection without access to the energy levels

Solution: Leverage Hardware Properties for Energy Detection

1. RC circuit filters out the TV signals
   → Removes high-amplitude variations

In the absence of backscattering, we see a constant output



Solution: Leverage Hardware Properties for Energy Detection

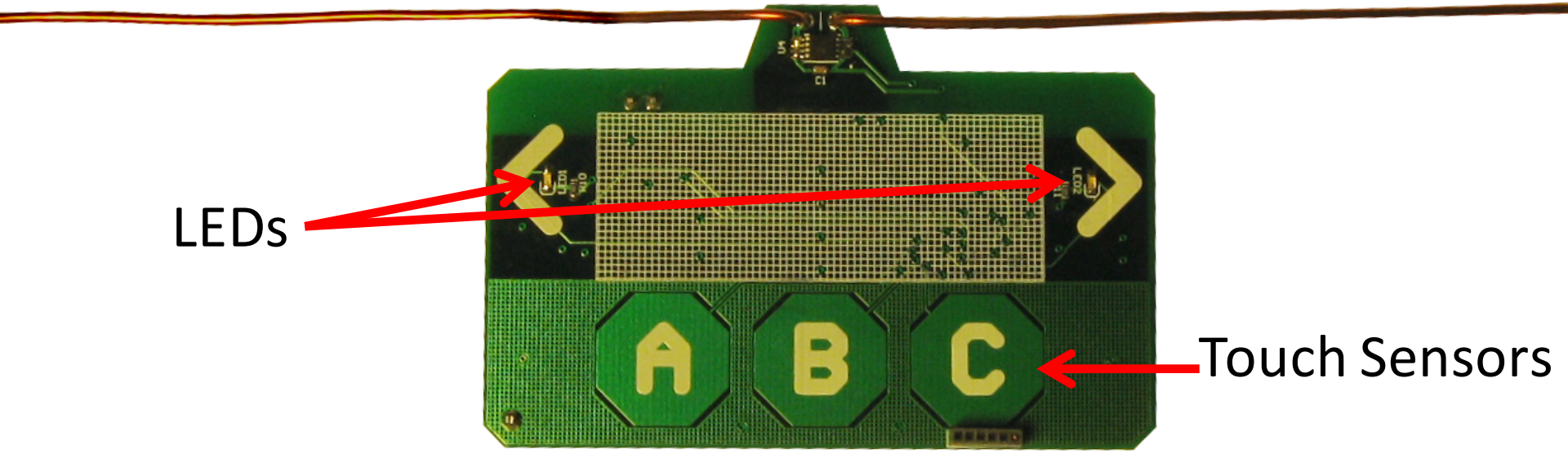
- No backscatter → See all 0s or all 1s
- Backscatter → See many transitions

Use bit transitions as proxy for energy detection

Evaluation

Prototype Using Off-the-Shelf Components

- Battery-free
- Harvests and backscatters TV signals at 539 MHz
- Microcontroller performs computation



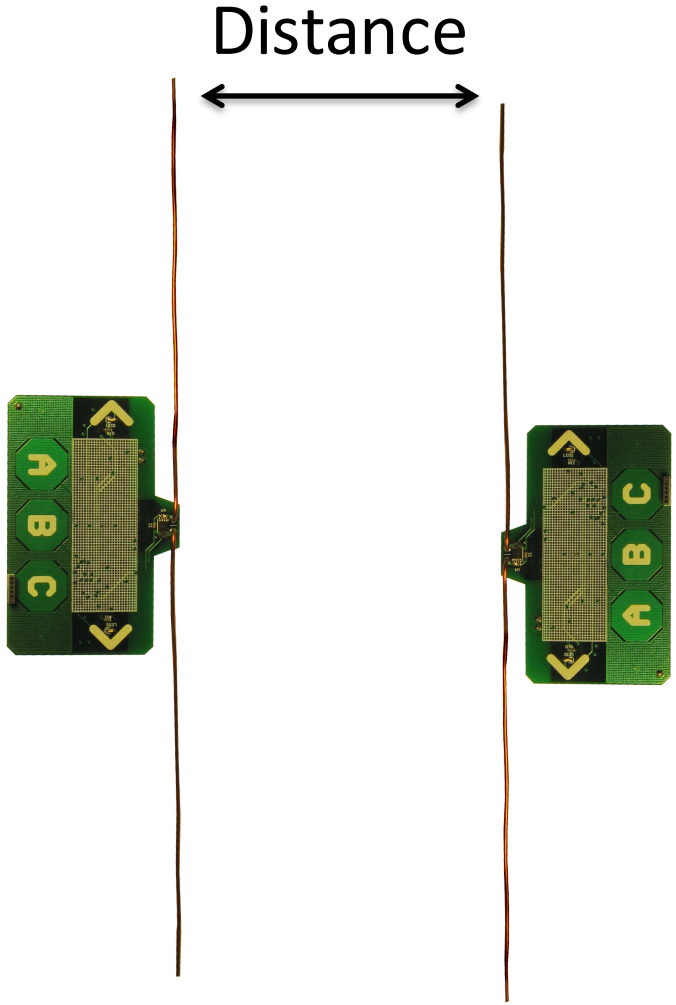
Tested Locations

- Seattle area with a 1MW TV tower at 539 MHz
- Indoor and outdoor environments
- Distances up to 10.5 km from the TV tower
  - TV power ranged between -24dBm and -8dBm

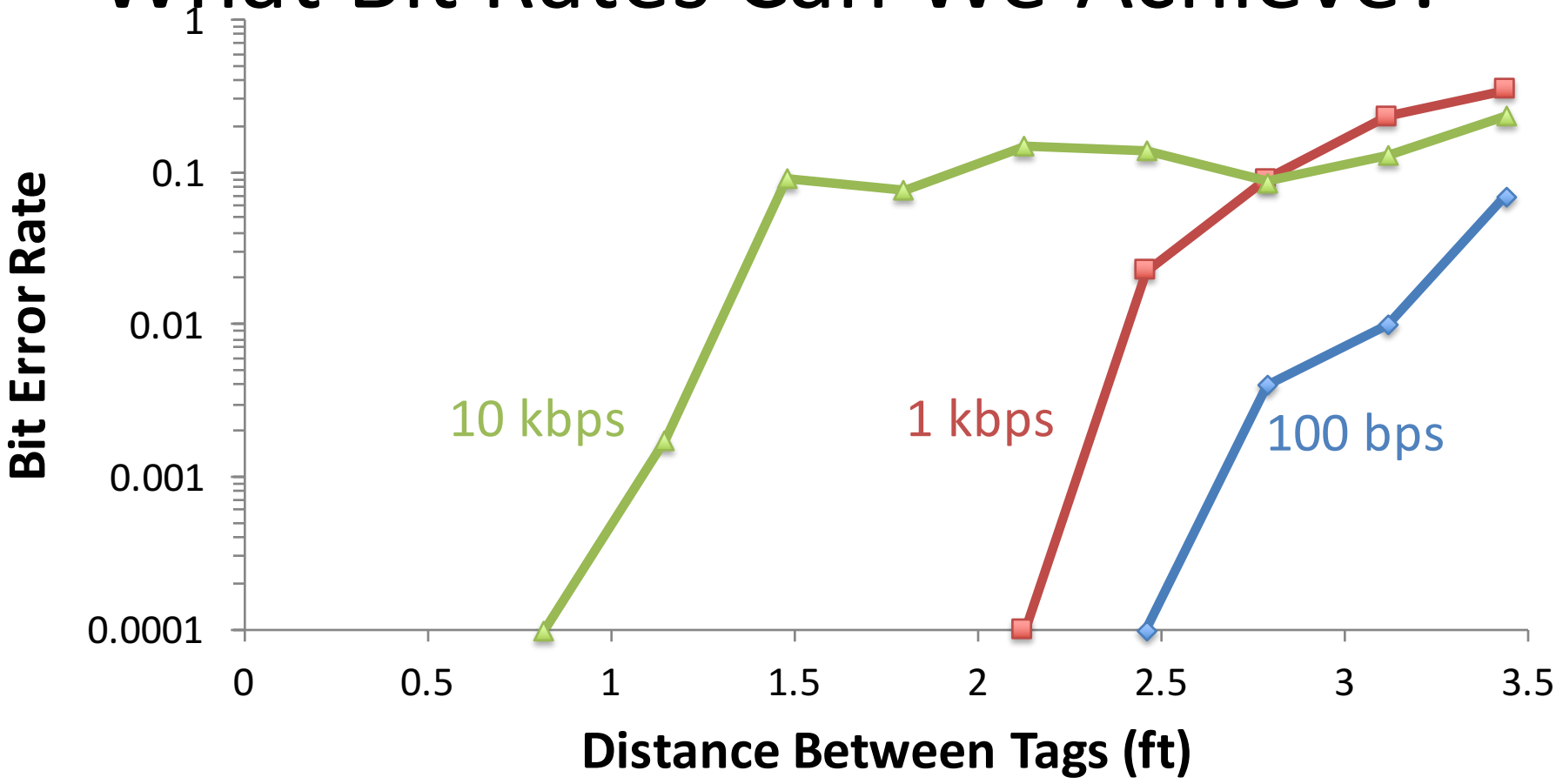
What Bit Rates Can We Achieve?

- Three bit rates:
  10kbps, 1kbps, 100bps

- BER versus distance
  between two devices



What Bit Rates Can We Achieve?



These results show the feasibility of Ambient Backscatter

Applications

Identifying Misplaced Items

In Grocery stores or Warehouses (e.g., Amazon)

- With ambient backscatter, devices can figure out they are misplaced on their own
- We built a preliminary system with cereal boxes

Identifying Misplaced Items

In Grocery stores or Warehouses (e.g., Amazon)

Works even if not all tags are in range of a reader

Conclusion

- We develop
  - The first primitive that enables communication without either device generating RF signals
  - A battery-free hardware prototype that computes and communicates using only TV signals

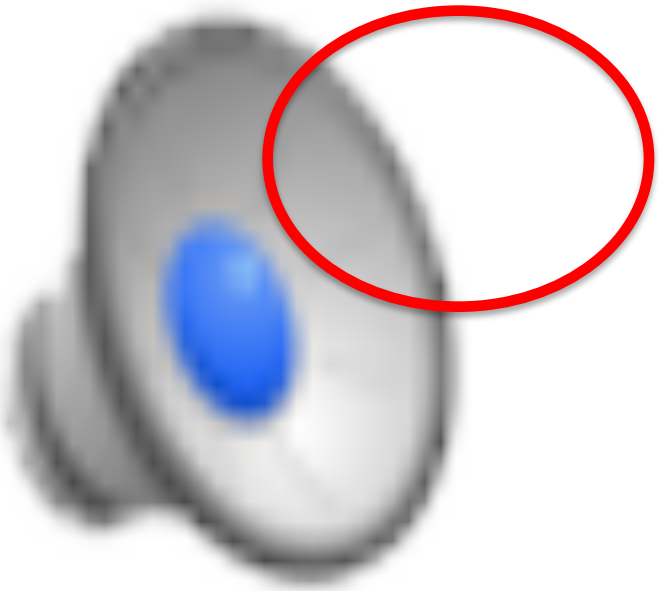
- We transform existing signals into both a power source and a communication medium
  - Opens up new research opportunities

abc.cs.washington.edu

Powering the next billion devices with Wi-Fi

Vamsi Talla, Bryce Kellogg, Ben Ransford, Saman Naderiparizi, Shyam Gollakota and Josh Smith

University of Washington

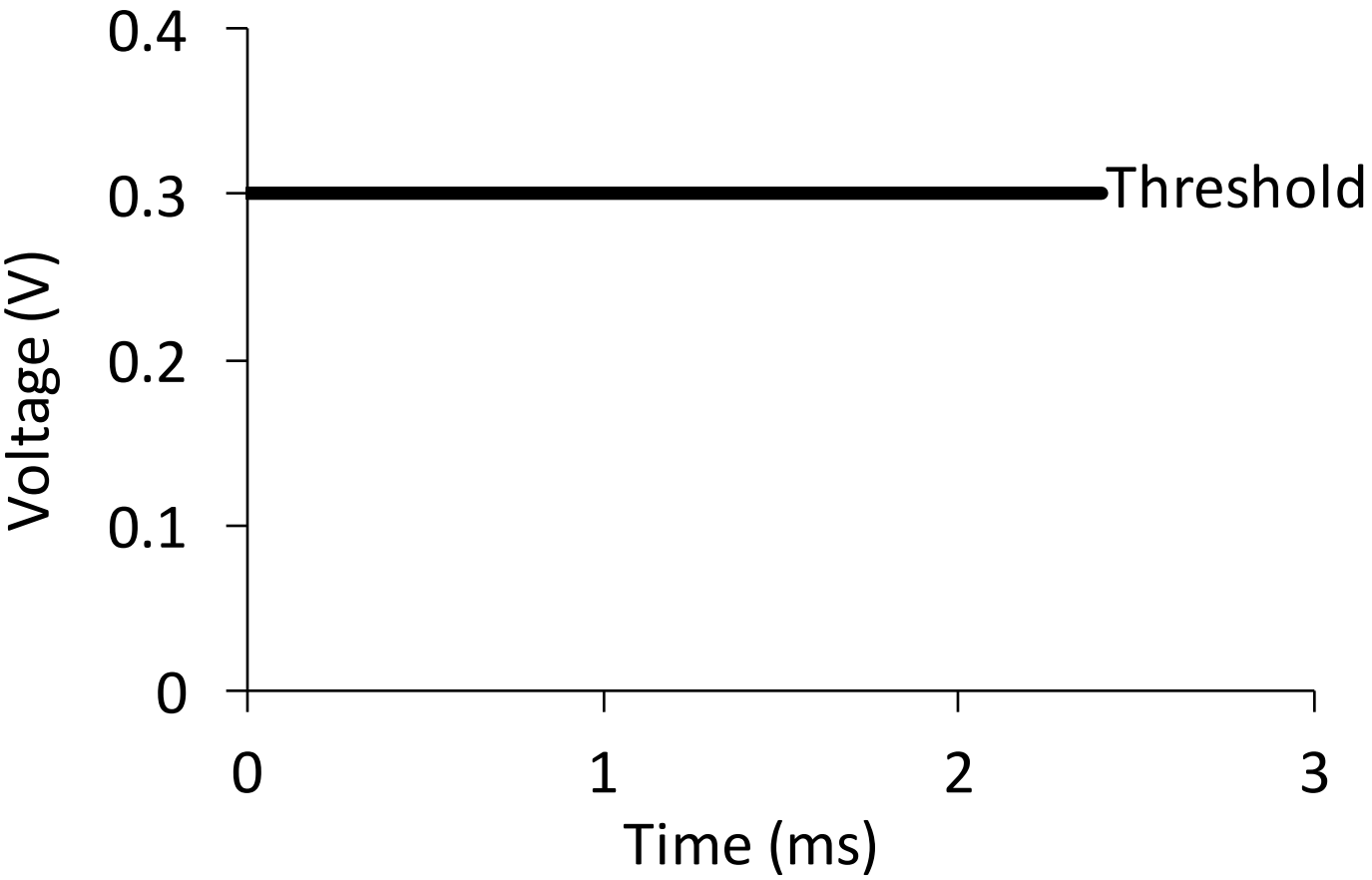


Wi-Fi is a great fit for power delivery

- Wi-Fi is ubiquitous in indoor environments
- Inexpensive given Wi-Fi's economies of scale
- Negligible size footprint, reuse 2.4 GHz antenna

Why is this hard?

Wi-Fi is designed for communication and not power delivery



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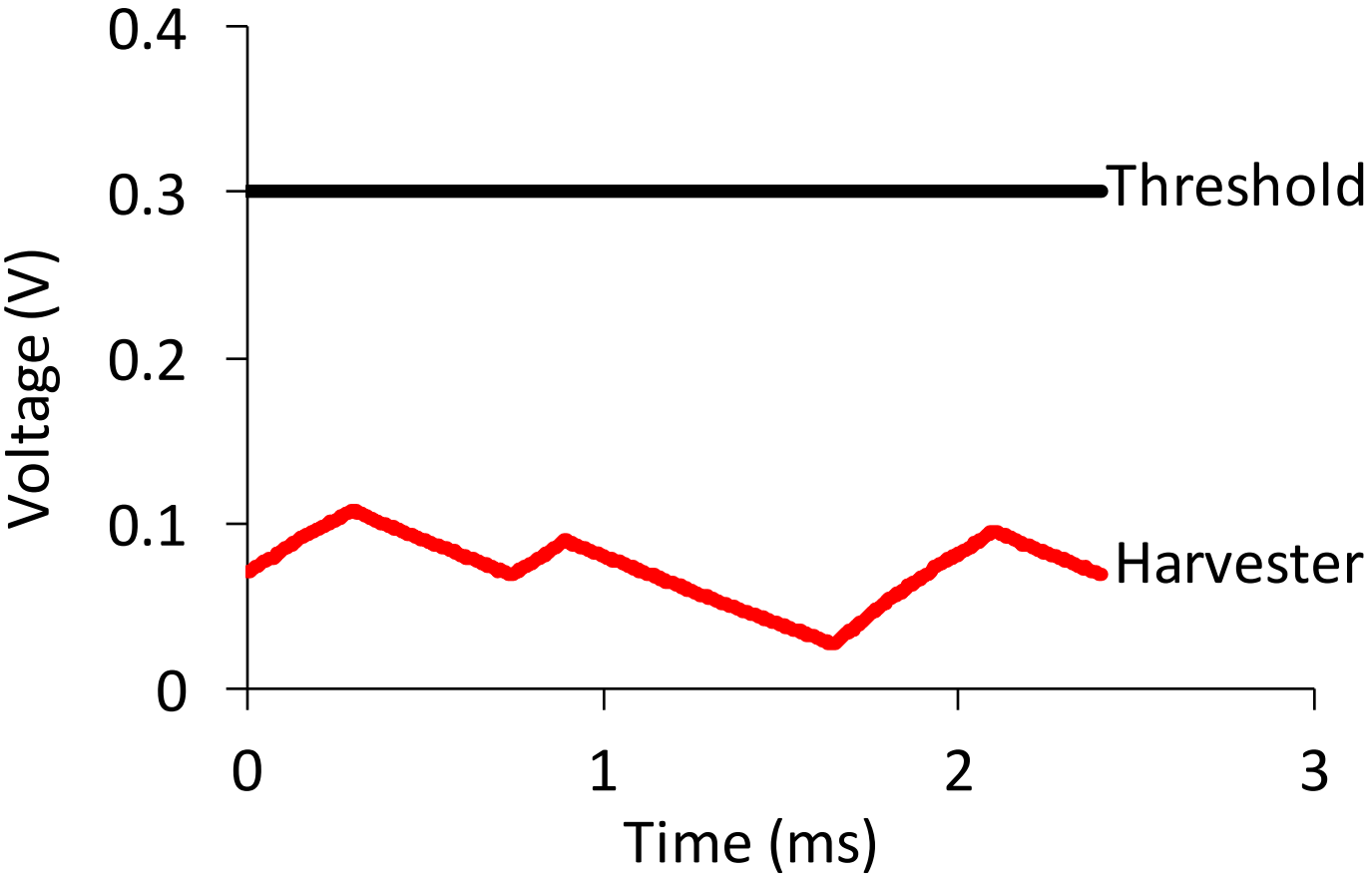

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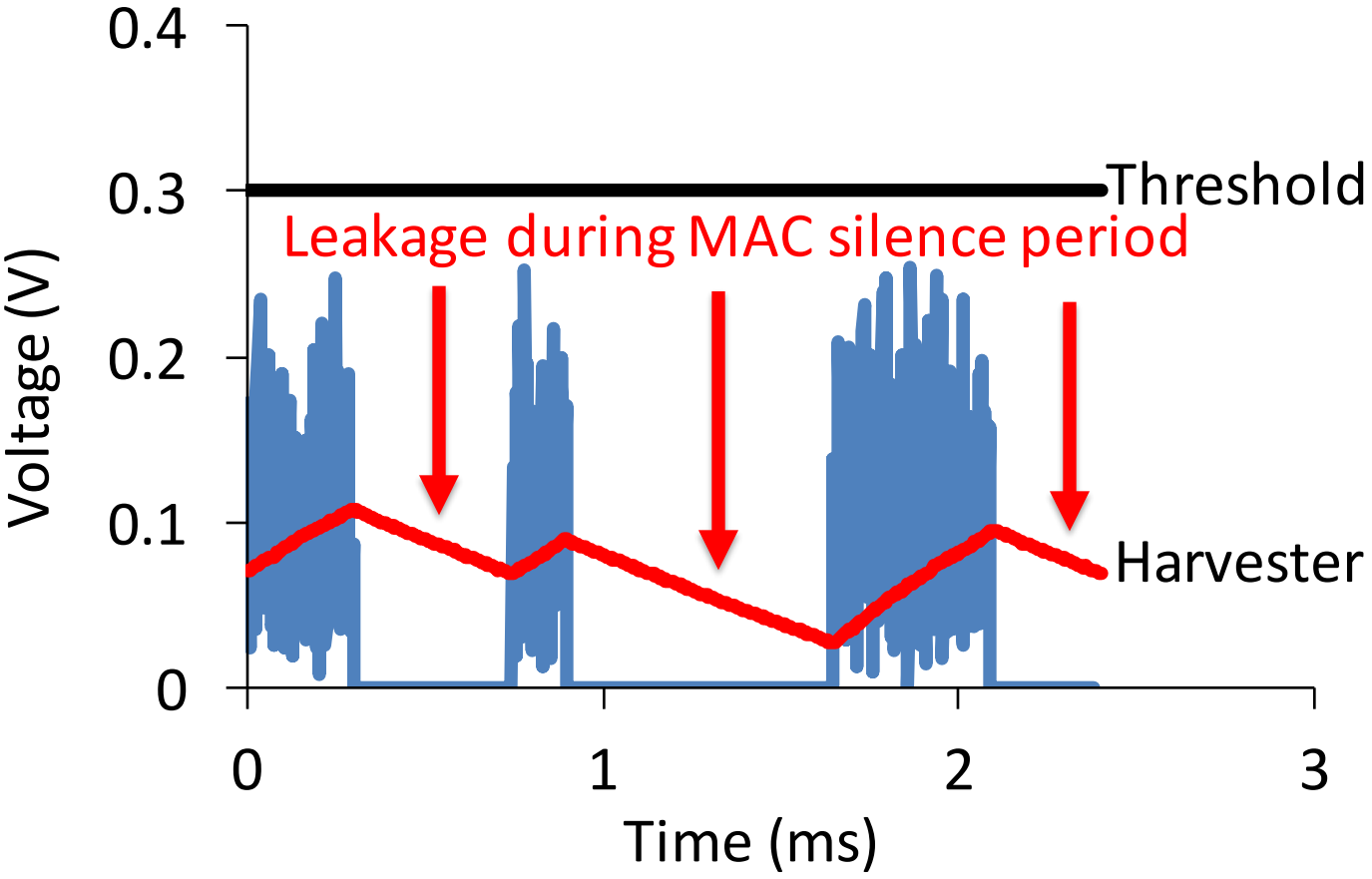
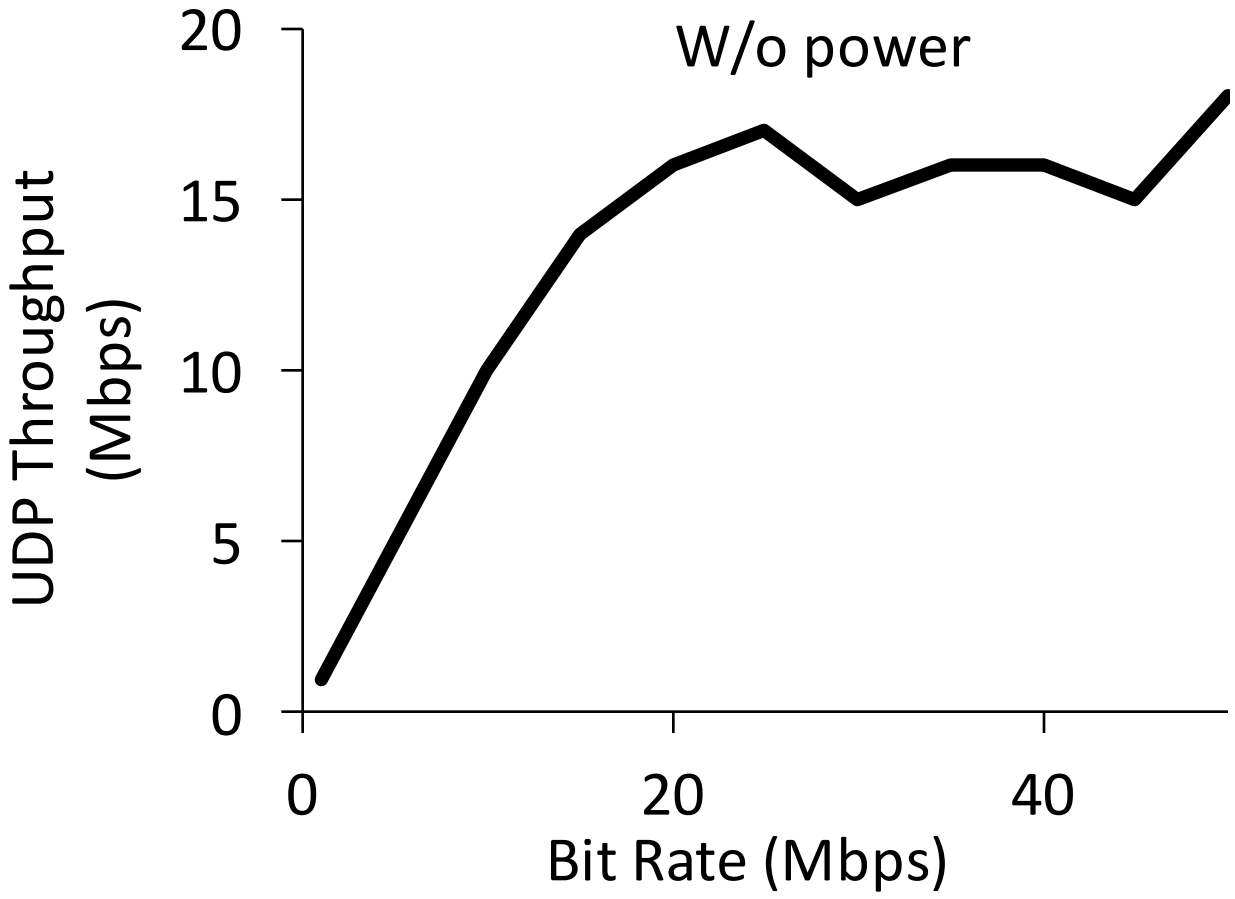


Power delivery requires continuous transmission

But, continuous transmissions jam Wi-Fi

UDP connection between Wi-Fi router and a client using iperf



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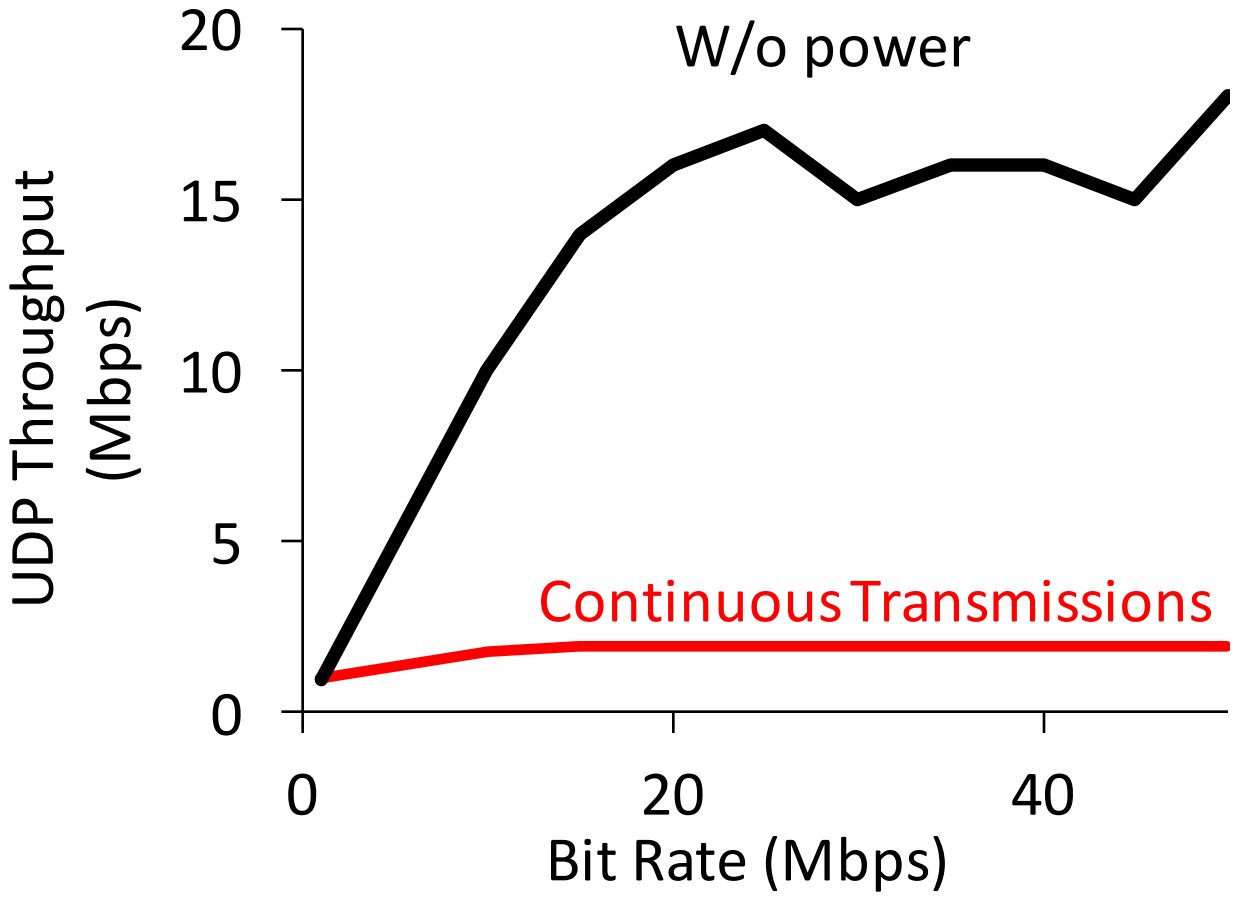


Fundamental tradeoff between power delivery and Wi-Fi performance

Power over Wi-Fi

- First system to deliver power to low-power devices using existing Wi-Fi chipsets
  - Imitate continuous transmission without degrading Wi-Fi
- Real world deployment in six homes without significantly degrading network performance
- Built the first Wi-Fi powered temperature sensor, camera, battery charger and USB charger

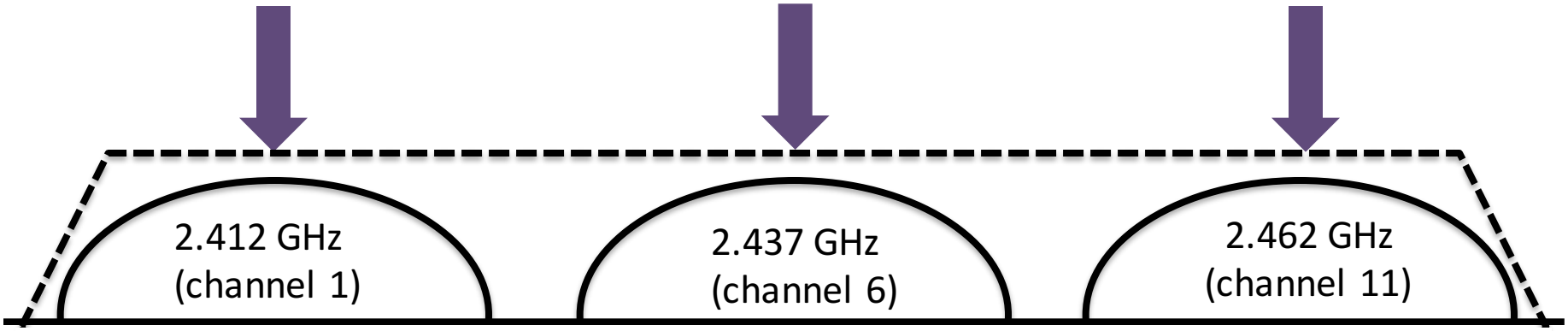
- **Opportunistic multi-channel transmissions:** Imitate continuous transmissions without affecting Wi-Fi network

- **Duty cycle aware transmissions:** Reduce channels occupancy due to power packet

- **Scalable power protocols:** Allows to scale with multiple PoWi-Fi routers

Opportunistic multi-channel transmission

Unlikely that all frequencies are occupied at the same instance



Imitate continuous transmission across 3 Wi-Fi channels

Our harvester design efficiently harvests across multiple Wi-Fi channels

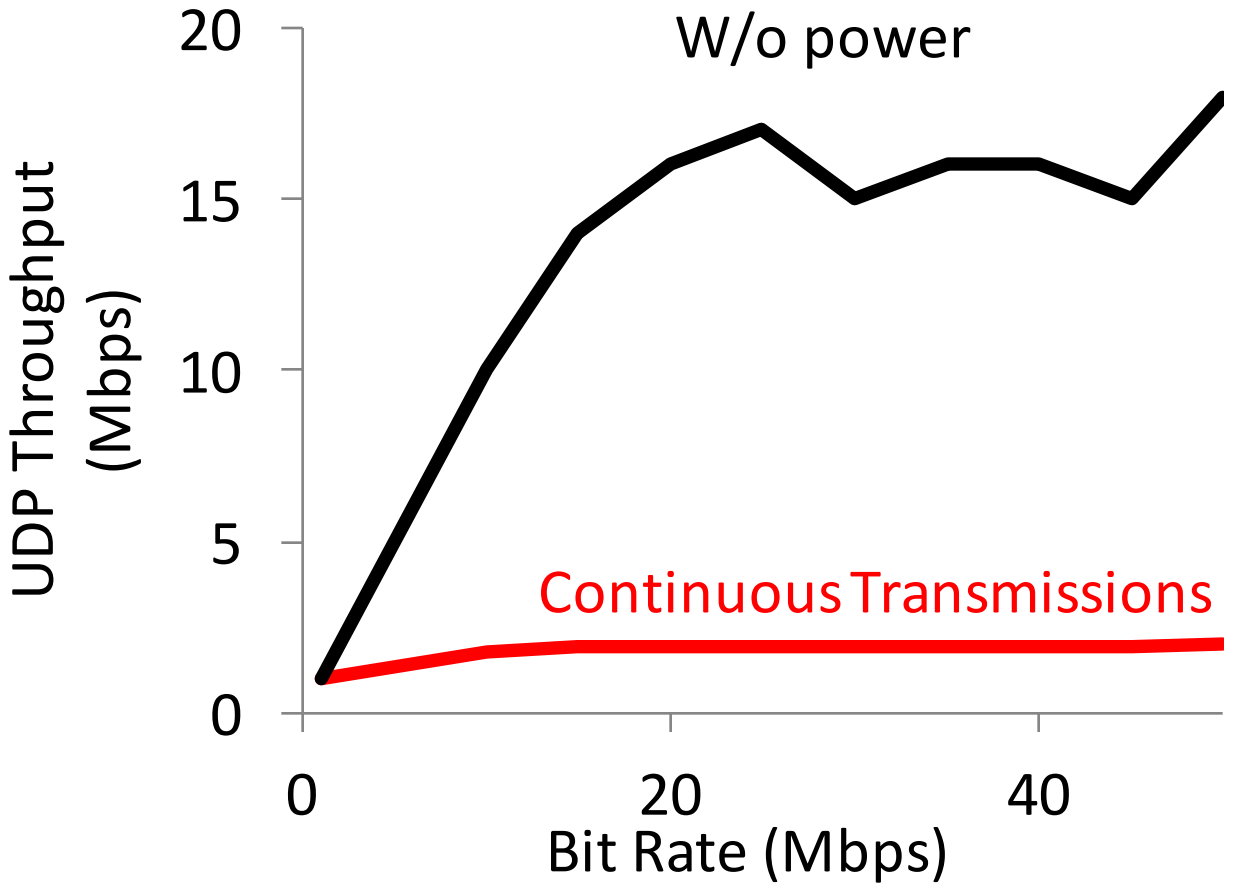
Opportunistic multi-channel transmission

- 1500 byte power packet at 54 Mbps with 100 us inter-packet delay
- When queue depth < threshold, add power packets

Set threshold value to prioritize actual traffic and have negligible impact on Wi-Fi performance

Opportunistic multi-channel transmission

UDP connection between Wi-Fi router and a client using iperf



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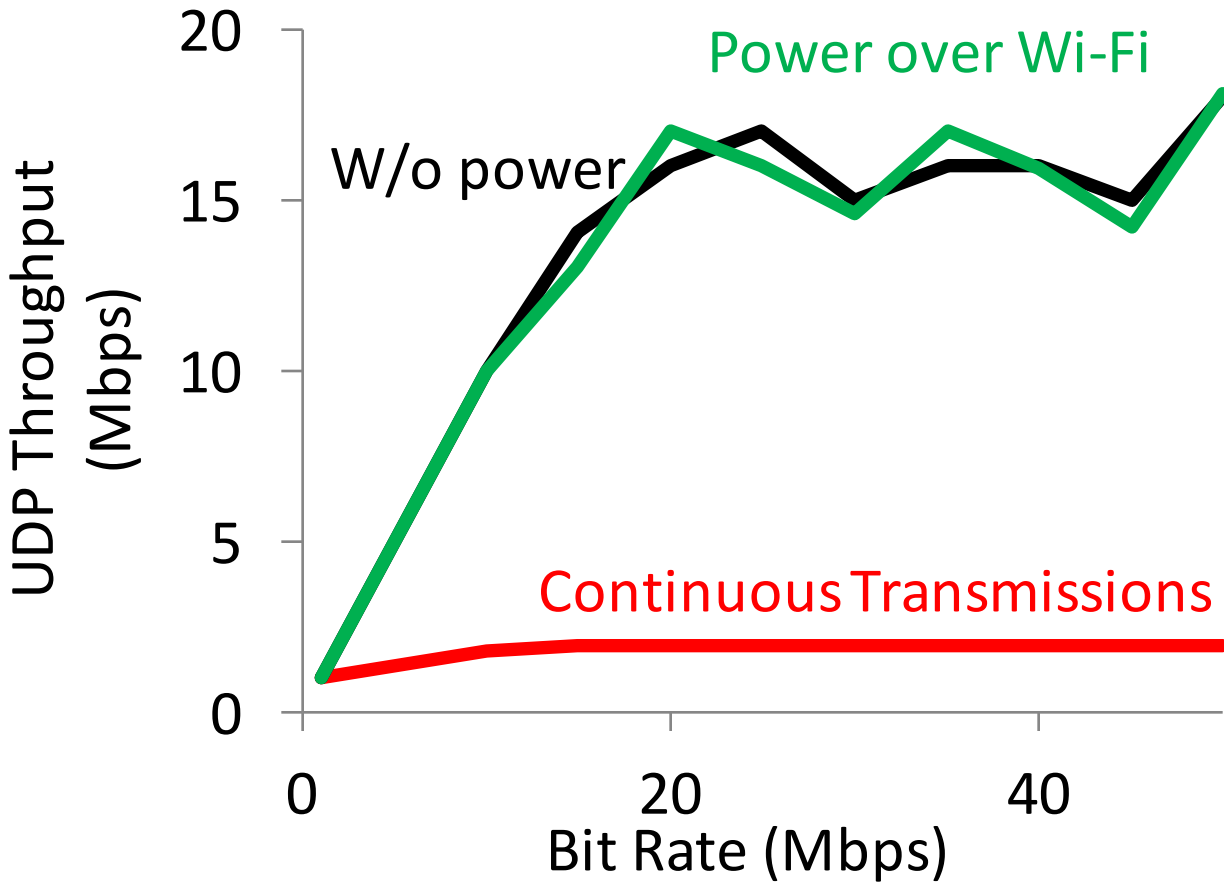


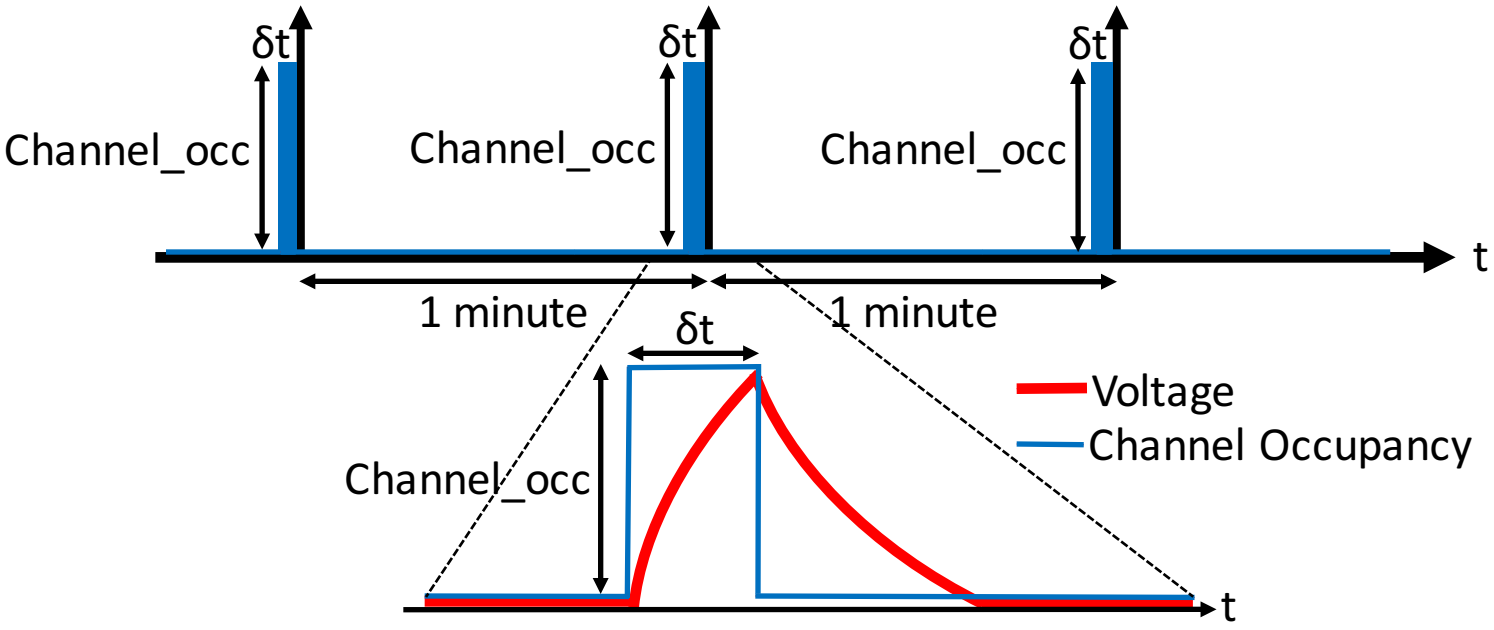
Cumulative channel occupancy of 97.6%

- **Opportunistic multi-channel transmissions:** Imitate continuous transmissions without affecting Wi-Fi network

- **Duty cycle aware transmissions:** Reduce channel occupancy due to power packet

- **Scalable power protocols:** Allows to scale with multiple PoWi-Fi routers

Duty cycle aware transmissions



Joint non-linear optimization problem between Wi-Fi performance and harvester behavior

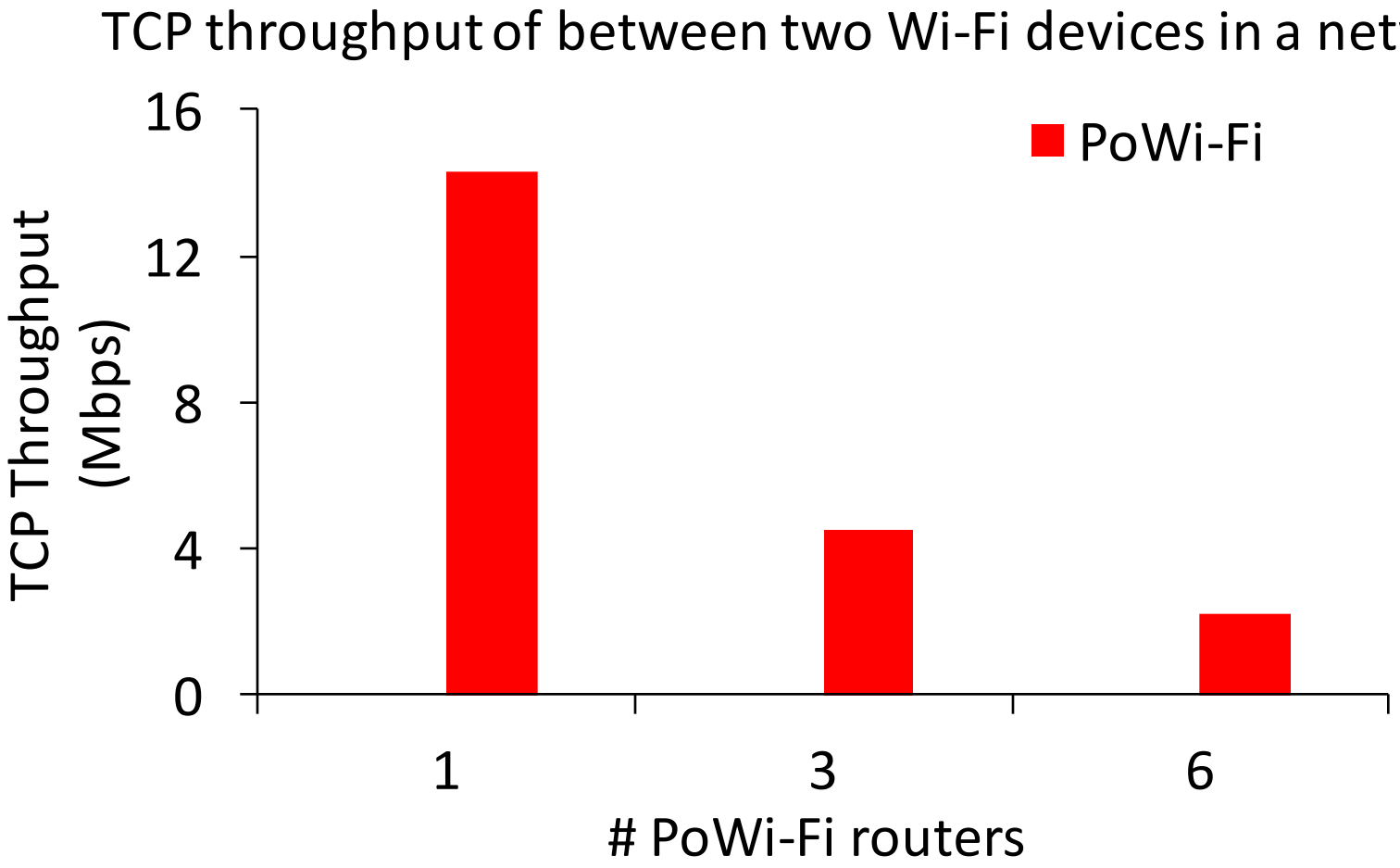
Average channel occupancy reduced to 3.3%, a 10x reduction

- **Opportunistic multi-channel transmissions:** Imitate continuous transmissions without affecting Wi-Fi network

- **Duty cycle aware transmissions:** Reduce channel occupancy due to power packet

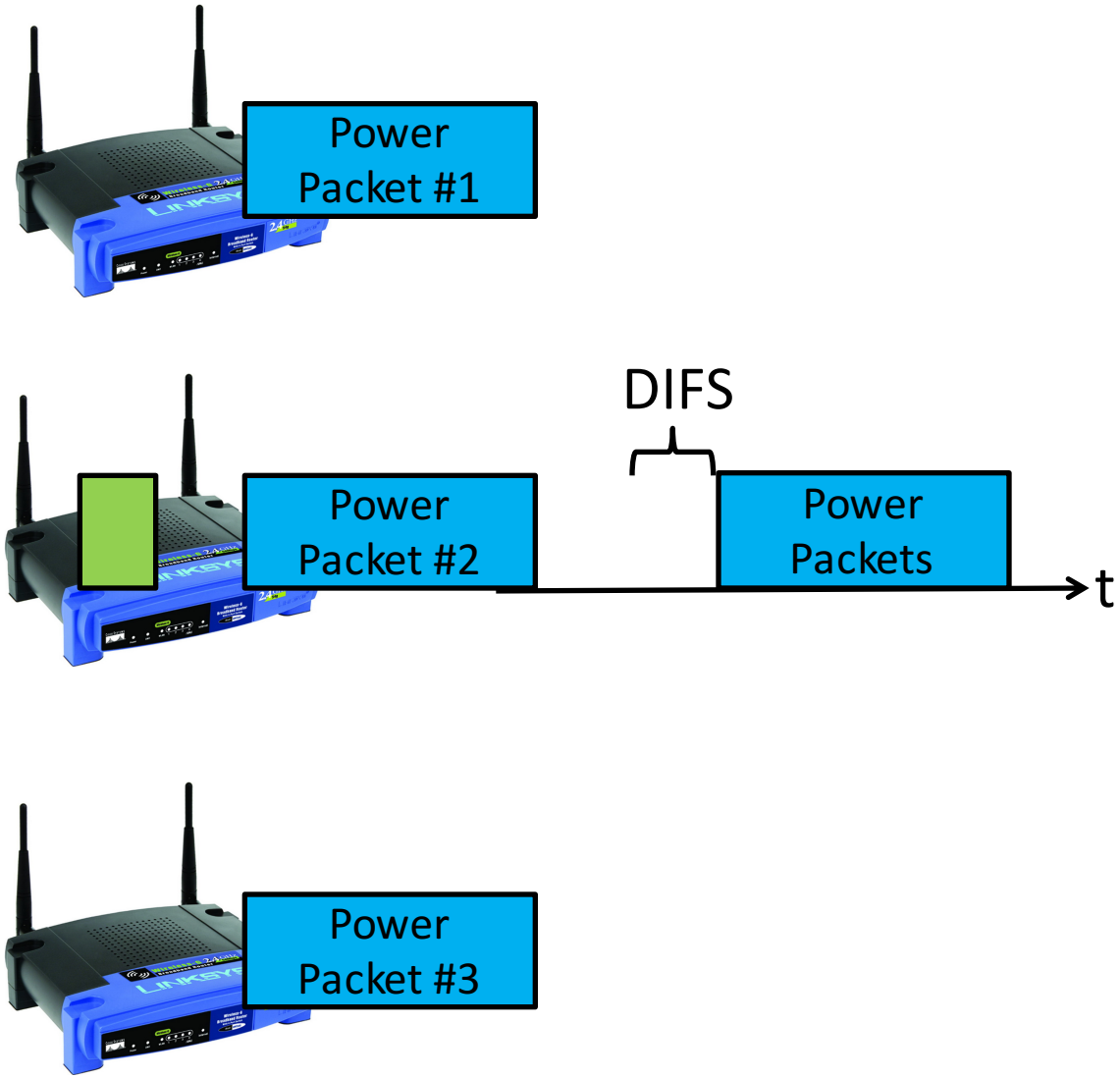
- **Scalable power protocols:** Allows to scale with multiple PoWi-Fi routers

Scaling with PoWi-Fi routers

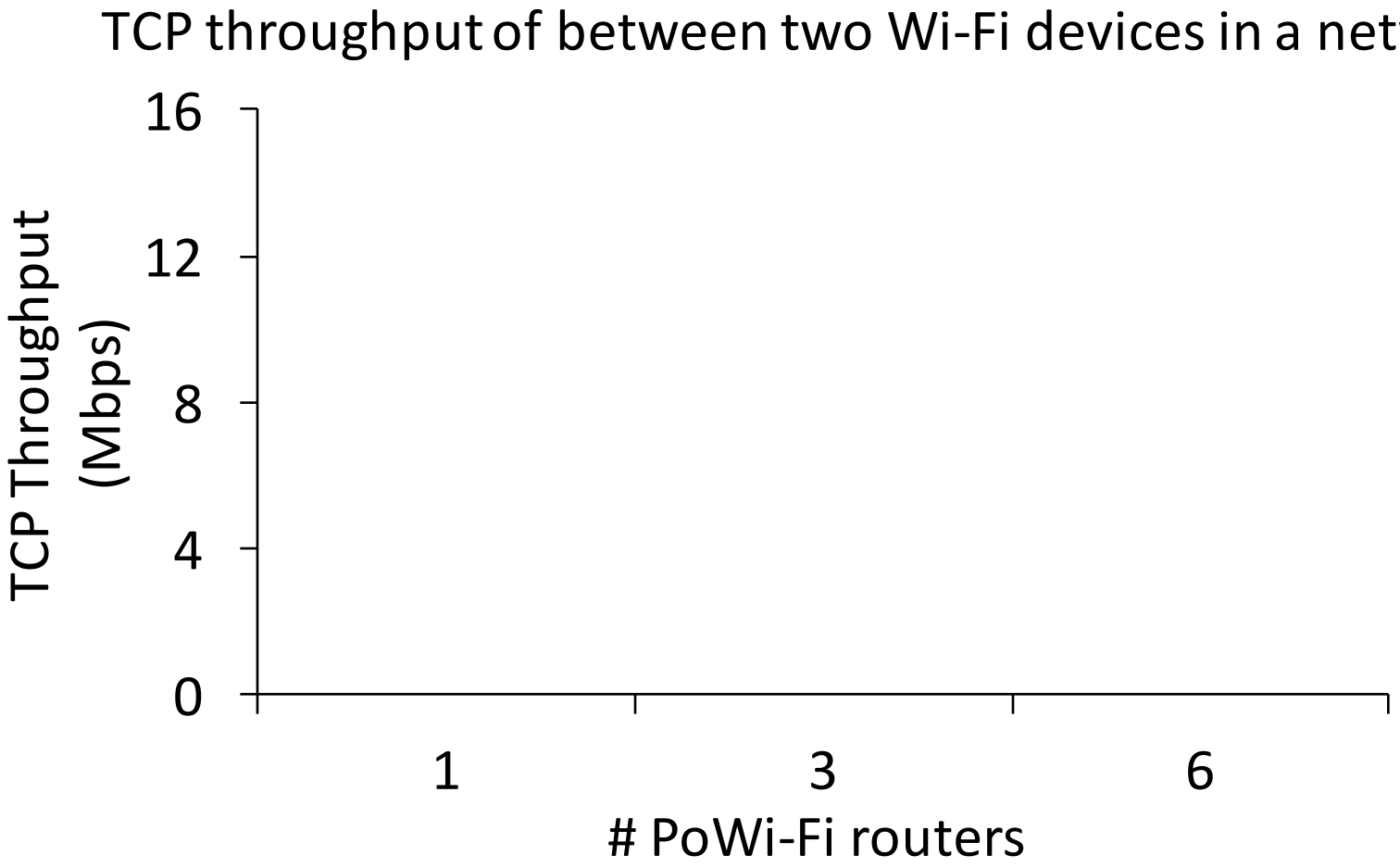


PoWi-Fi design does not scale with number of routers

Solution: Concurrent PoWi-Fi transmissions



Concurrent PoWi-Fi transmissions



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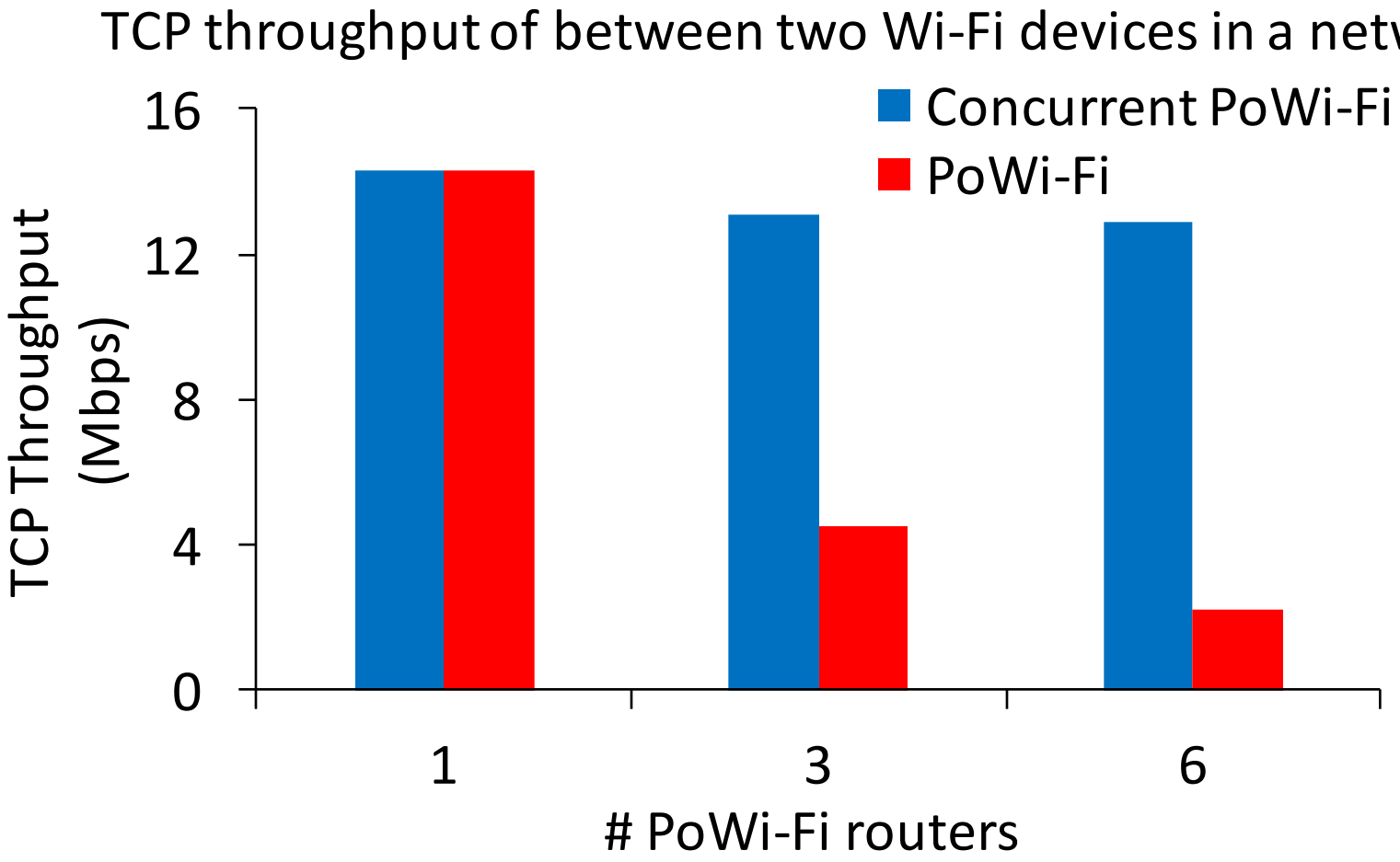

Our design scales with number of PoWi-Fi routers

- **Opportunistic multi-channel transmissions:** Imitate continuous transmissions without affecting Wi-Fi network

- **Duty cycle aware transmissions:** Reduce channel occupancy due to power packet

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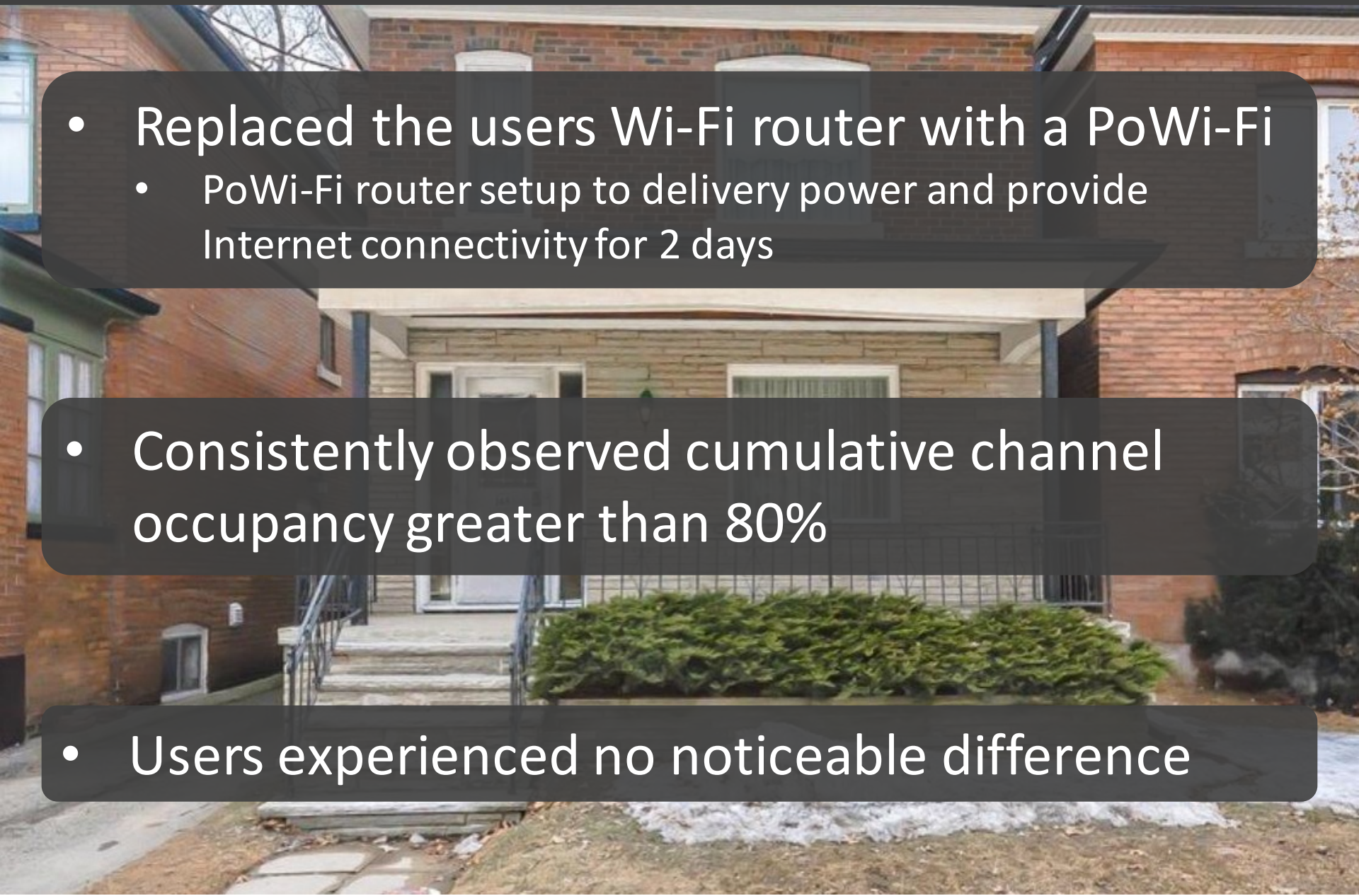
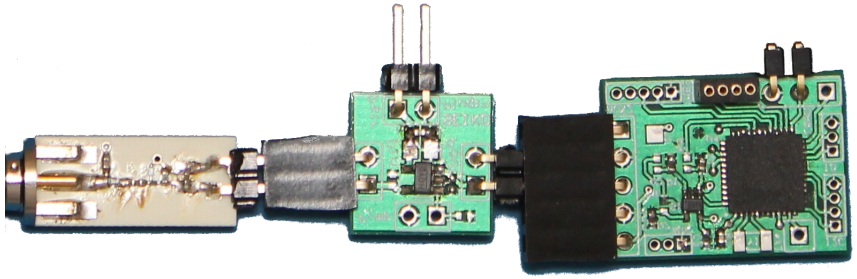
Real world deployment in 6 homes



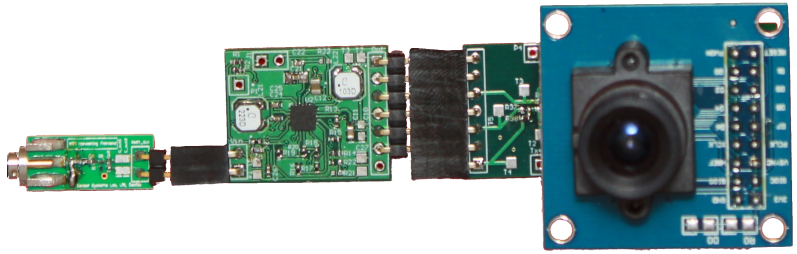
- Replaced the users Wi-Fi router with a PoWi-Fi
  - PoWi-Fi router setup to delivery power and provide Internet connectivity for 2 days
- Consistently observed cumulative channel occupancy greater than 80%
- Users experienced no noticeable difference

Wi-Fi powered devices

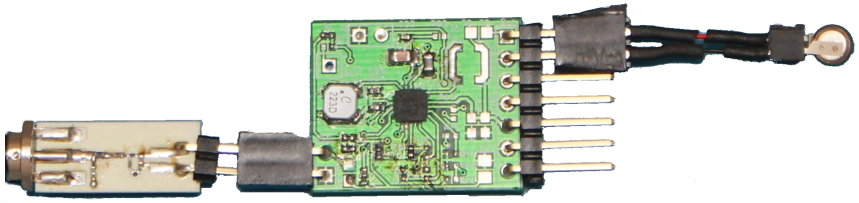
Wi-Fi powered sensors



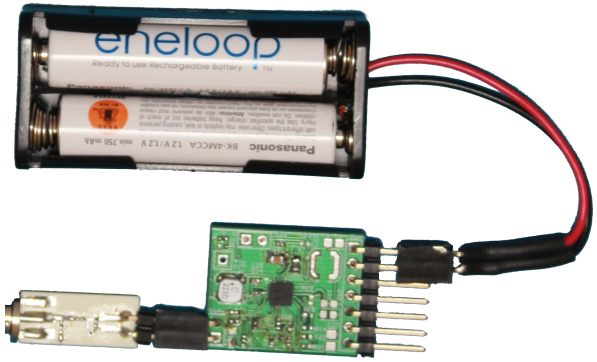
Battery-free temperature sensor



Battery-free camera

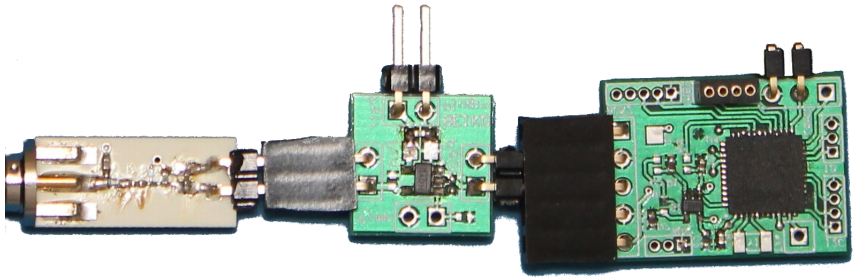


Li-Ion battery charger

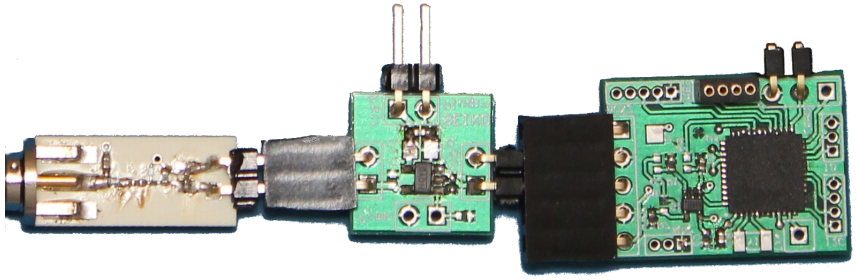


NiMH battery charger

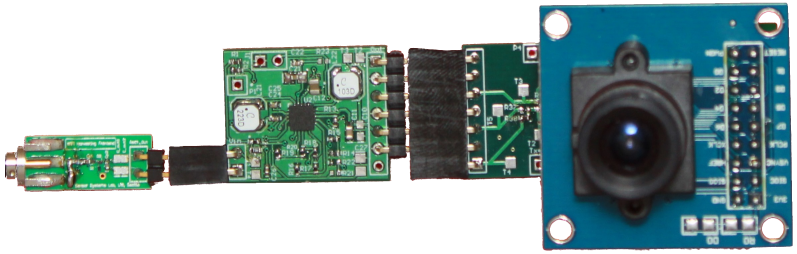
Wi-Fi powered temperature sensor



Wi-Fi powered temperature sensor



Wi-Fi Powered Camera



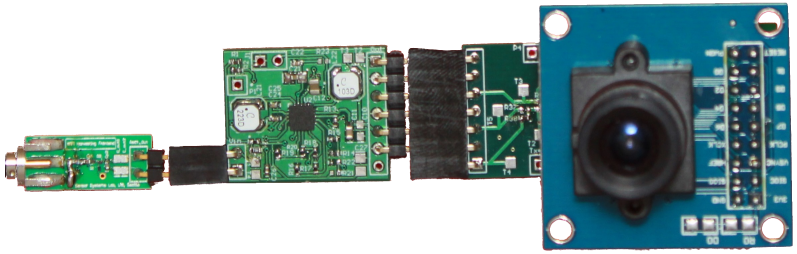
Inter-frame time (minutes)

40
35
30
25
20
15
10
5
0

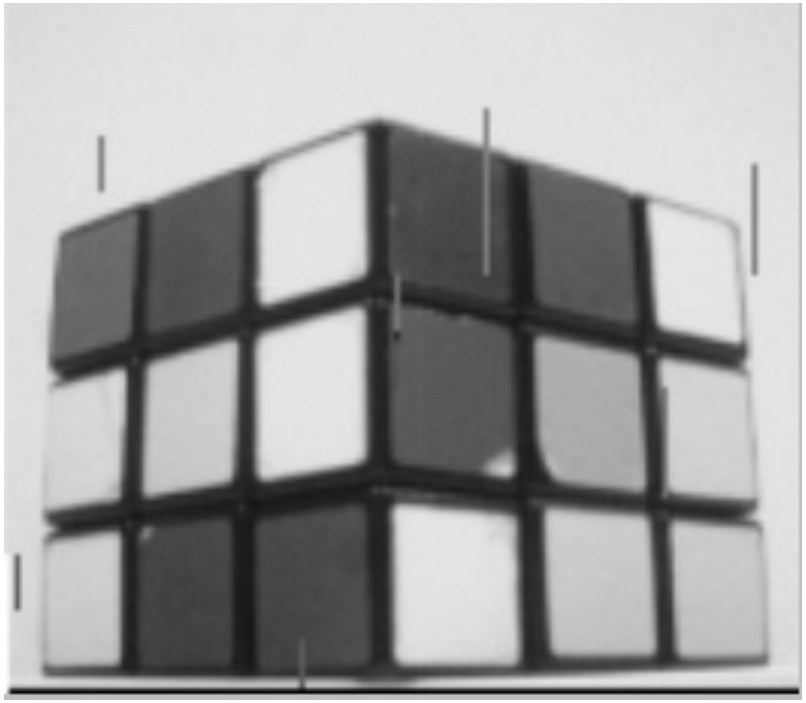
0
5
10
15
20
25

Distance (feet)

Wi-Fi Powered Camera

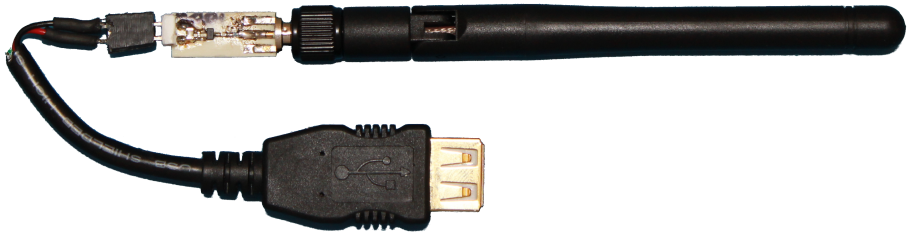


Applications of low rate cameras



- Deploy in hard to reach places, e.g., attics
- Integrate with ultra-low power motion detector to trigger camera

Wireless Charging Hotspot



USB charger for wearable devices

0 to 40% charge in 2.5 hours at a distance of 5 cm from a PoWi-Fi router

Conclusion

- First system to deliver power to low-power devices using existing Wi-Fi chipsets
- Real world deployment in six homes without significantly degrading network performance
- Built the first Wi-Fi powered temperature sensor, camera, battery and USB charger

Further Progress

- Extent Ambient Backscatter to a host of protocols:
  - Wi-Fi
  - **BLE**
  - ZigBee
  - **LoRa**
- Battery-free phones, microphones and cameras

Thank you

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