ETH zürich

Wi-Fi Backscatter: Battery-free Internet Connectivity to Empower the Internet of Things

Ubiquitous Computing Seminar FS2015

Bjarni Benediktsson

Internet of Things

- *"The Internet of Things (IoT) is a computing concept that describes a future where everyday physical objects will be connected to the Internet and be able to identify themselves to other devices."*

http://www.techopedia.com/definition/28247/internet-of-things-iot

Image: http://static1.squarespace.com

Internet of Things – Are we there yet?

- Today a lot of devices are connected to the internet:
  - Health monitors
  - Smart heating
  - Smart lighting
  - Cars
  - Polution sensors

Image: http://quartsoft.com/sites/default/files/internet-of-things-iot.jpg

Internet of Things – Where are we now?

- Even have internet connected refrigerators and baby monitors
- But why aren't these chairs connected?
- Lets look at power options for these devices

Images: http://www.billboard.com/files/styles/promo_650/public/stylus/1463459-Pandora-Fridge.png, http://ecx.images-amazon.com/images/I/317k-c6m2DL.jpg

Power options

- Power chords
  - Tie devices down
  - Prohibit movement
- Batteries
  - Add weight
  - Take up space
  - Need maintenance
  - Cost

Images: http://3.imimg.com/data3/WV/MR/MY-8533562/heavy-duty-power-cable-250x250.png, http://thumbs.dreamstime.com/x/big-batteries-18667224.jpg

Power options cont.

- Harvested energy
  - Mechanical
    - Need constant acceleration
  - Solar
    - Sunlight not always available
    - Need to cover large area of the device exterior

- None of these options suitable for tiny devices

Images: http://cnbestsolar.88582.net/admin/pic/200992165736605.jpg, http://33.media.tumblr.com/3008f381419b1855c4fa0ca90131cc2b/tumblr_mxknjebCa21qg3h2
1_500.gif

What about RF signals?

- RF signals are energy emitted in the RF spectrum
- Spectrum already full of signals
  - Unused energy
- Can harvest 10s of µW
- Can harvest power far away
  - TV – several kilometers
  - Cellular – several hunder meters

Image: http://www.charontech.com/img/signal_processing.jpg

Are 10s of microwatts enough?

- Energy efficiency of computers has improved exponentially
- Can now compute with microwatts

- RF singals can also be reused for communication
  - Creating communication signals is expensive

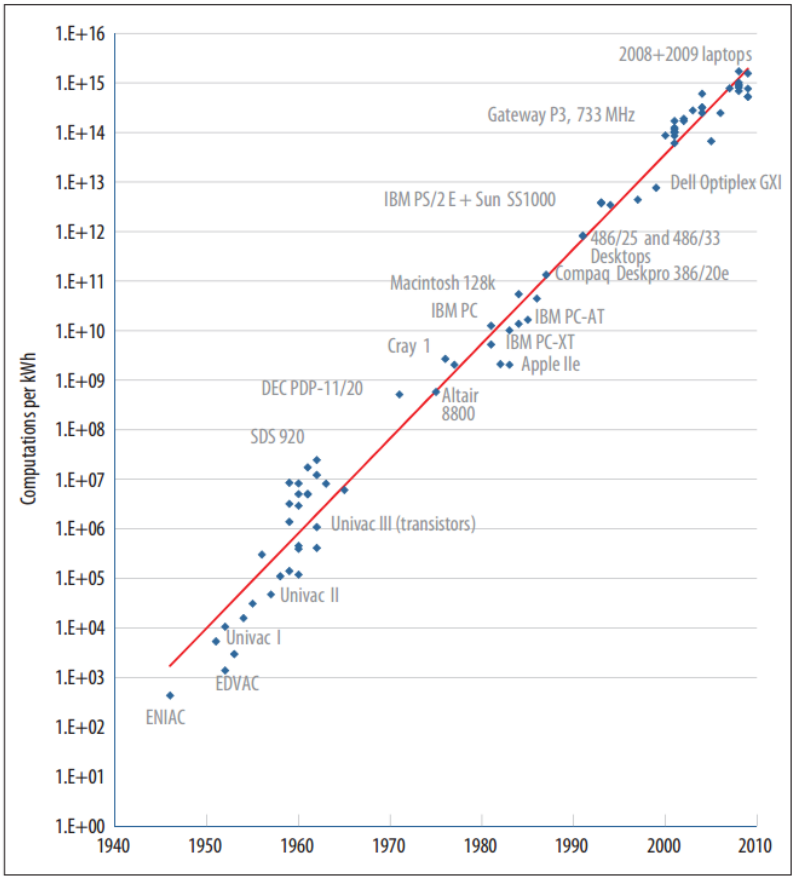
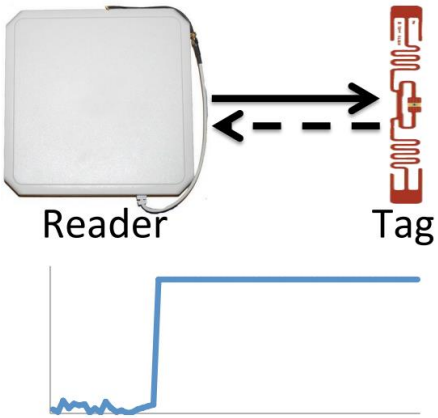


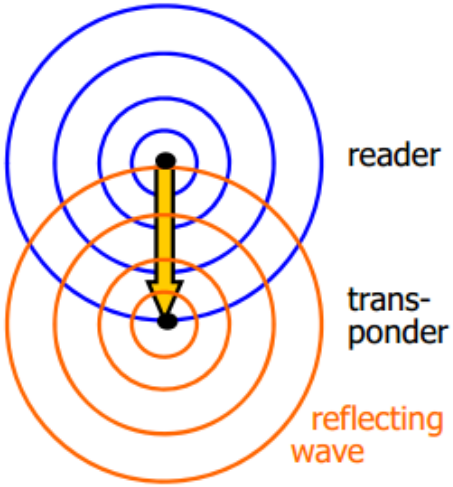
Image: 0-The Emergence of RF-Powered Computing

The Backscatter concept

- Reflect existing signals in a way to incode information

- Used by RFID technology
  - Reader sends constant signal
  - Signal reflected by RFID tag

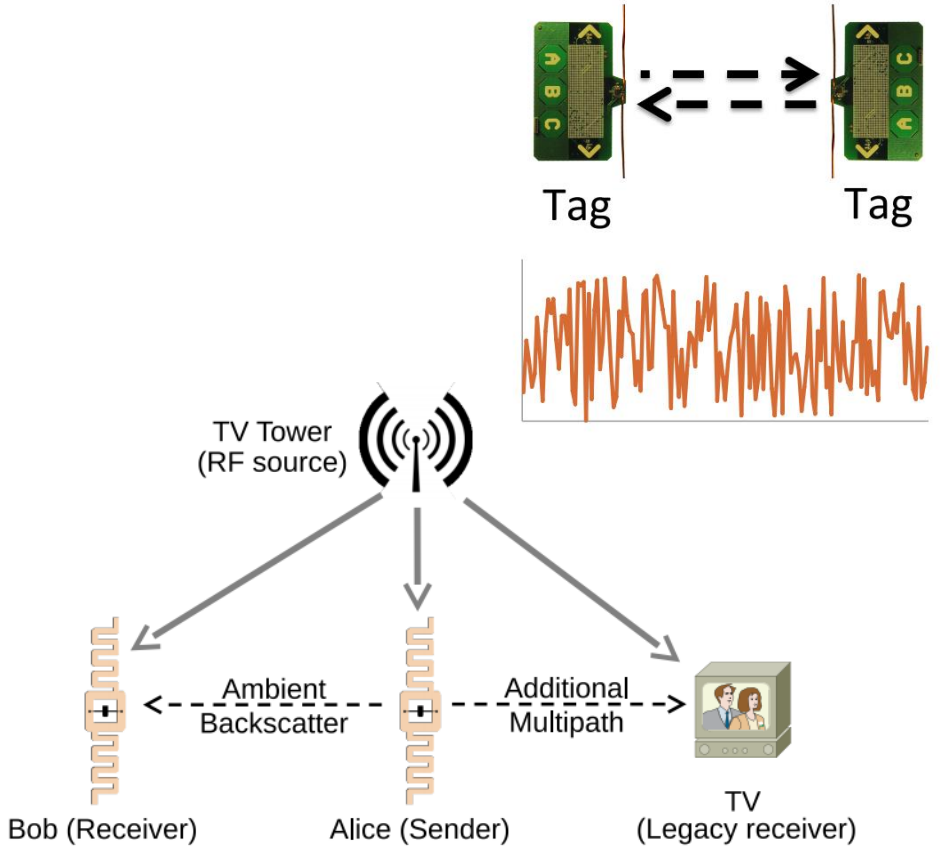




Images: Ubiquitous computing lecture 5, 2014 ETH,
Ambient Backscatter Wireless Communication Out of Thin Air

Ambient Backscatter communication

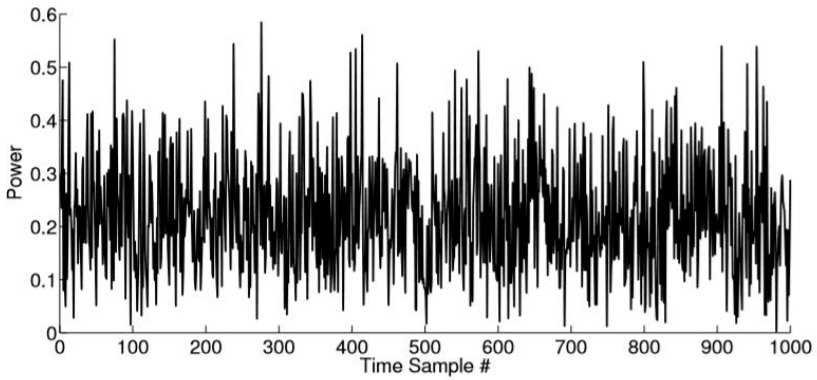
- Similar to RFID but
  - Does not require a reader
  - Works by modulating the reflection of an existing RF signal
- Does not cause interference with legacy devices
  - Just another multi-path



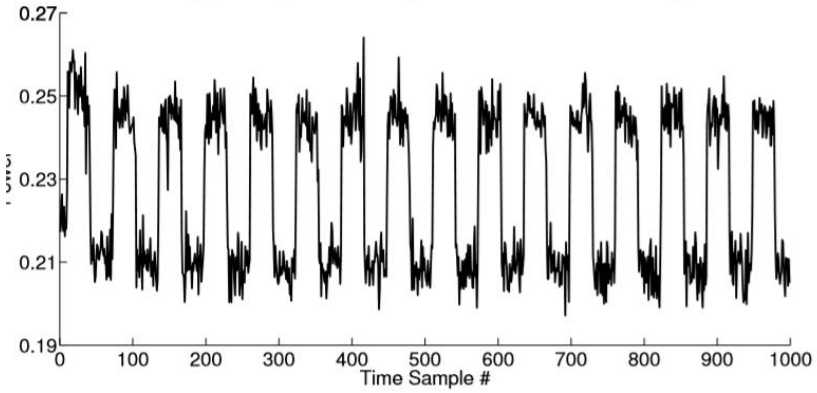
Images: Ambient Backscatter Wireless Communication Out of Thin Air

Ambient Backscatter – Challenge 1

- Can't control the ambient signals
  - These signals already encode information
  - Don't have constant amplitude
- But ambient signal changes faster than the backscattered one
  - Average the received signal across multiple samples
  - Removes the variation in the ambient signal



(a) Original TV plus Backscatter signal



Images: Ambient Backscatter Wireless Communication Out of Thin Air

Ambient Backscatter – Challenge 2

- Averaging digital samples requires conversion
  - Conversion takes a lot of energy
  - Need a more energy efficient solution
- Imitate in hardware
  - Use resistor-capacitor circuit

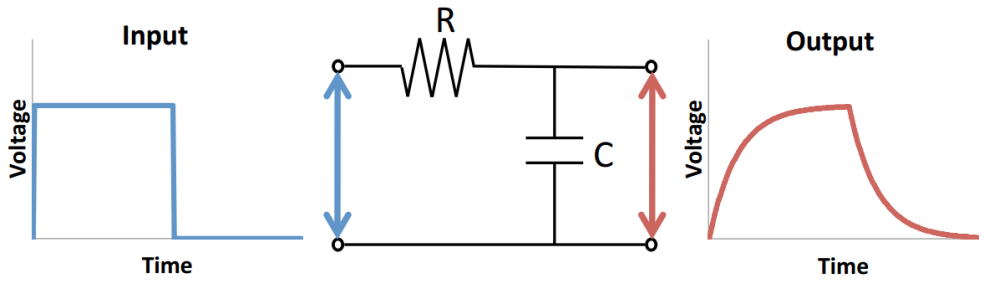
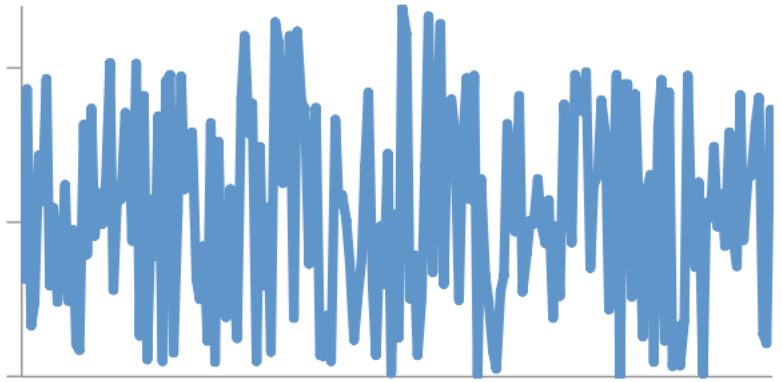


Image: Ambient Backscatter Wireless Communication Out of Thin Air

Ambient Backscatter – Challenge 3

- In case of many devices that need to share the channel
- Could use carrier sense (CSMA)
  - But devices have no access to energy levels

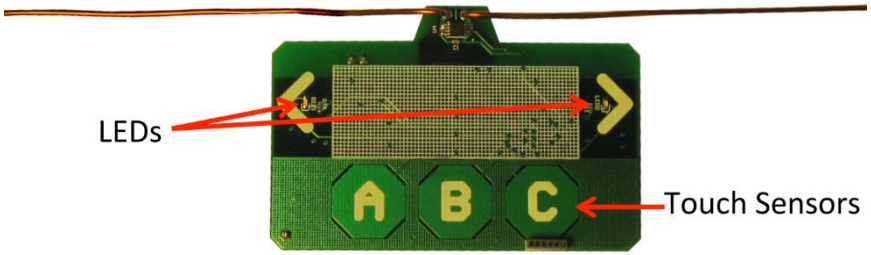


- No backscattering signal
  - The average received signal will be constant

Images: Ambient Backscatter Wireless Communication Out of Thin Air

Ambient Backscatter – Prototype

- Battery free
- Harvests an backscatters TV signals at 539 Hz
- Microcontroller performs computation
- 1 kbps at 76 cm (2.5 feet) outdoors

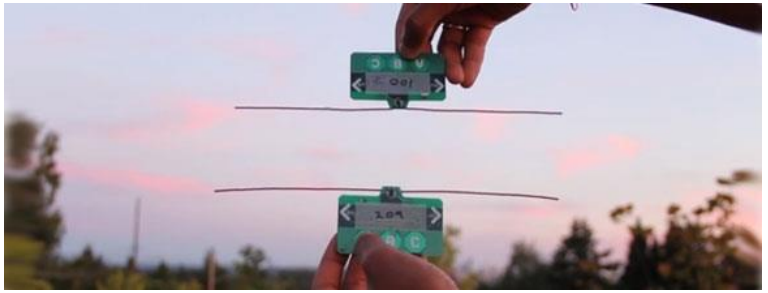


Images: Ambient Backscatter Wireless Communication Out of Thin Air

Some applications of Ambient Backscatter

- Grocery store application
  - Tags tell if item is missing or out of place on a shelf

- Smart card application
  - 2 cards can make a fund transfer between each other

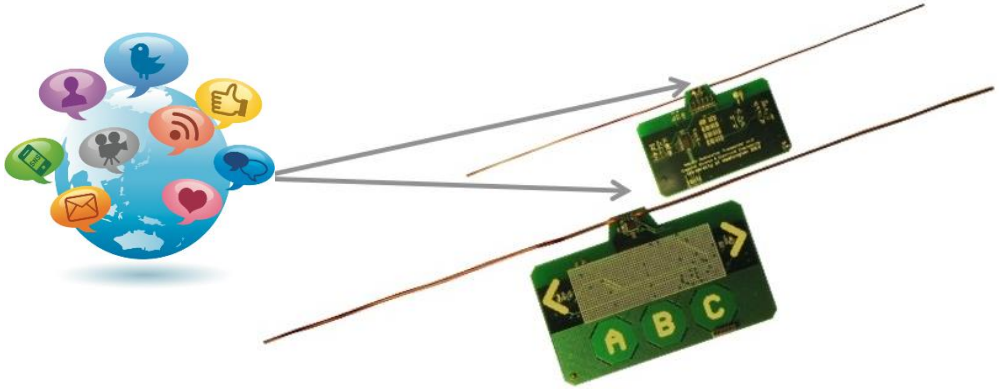


Images: Ambient Backscatter Wireless Communication Out of Thin Air, http://telecoms.com/wp-content/blogs.dir/1/files/2013/08/rf-ambient-backscatter.jpg

How to connect these devices to the internet?

- This would help realize the vision of IoT
- Need to enable RF-powered devices to talk to Wi-Fi devices

- Challenges:
  - Wi-Fi transceivers require much energy which we don't have
  - Wi-Fi devices can only receive Wi-Fi signals



Images: http://abc.cs.washington.edu/files/abc.jpg, http://www.adweek.com/socialtimes/files/2013/02/social-world.png

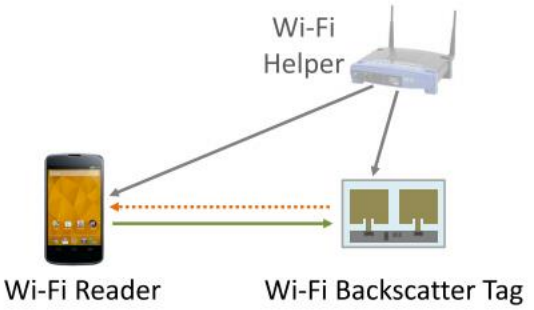
Possible solution

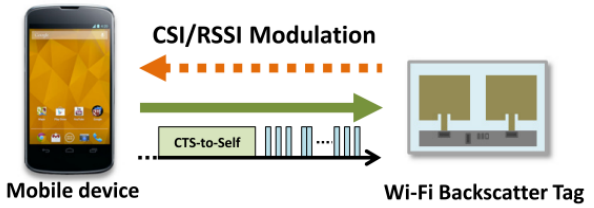
- Could deploy special powered infrastructure devices
  - Gateways to connect RF-powered devices and Wi-Fi devices
- But that would be costly
- Also key benefit of RF-powered systems
  - Require no extra infrastructure
- Can we use existing infrastructure?

Image: https://cdn4.iconfinder.com/data/icons/cia-operations/512/radio_transmitter-512.png

Introducing Wi-Fi Backscatter

- 3 actors:
  - Wi-Fi reader
  - Wi-Fi helper
  - Wi-Fi backscatter tag
- 2 main components
  - Uplink
    - Tag -> Reader
  - Downlink
    - Reader -> Tag





Images: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

Uplink - Overview

- Modulation
  - Transmit data by modulating the Wi-Fi Channel
- CSI decoding
  - How the reader extracts the modulated information using CSI
- RSSI decoding
  - Use only RSSI at reader to extract information

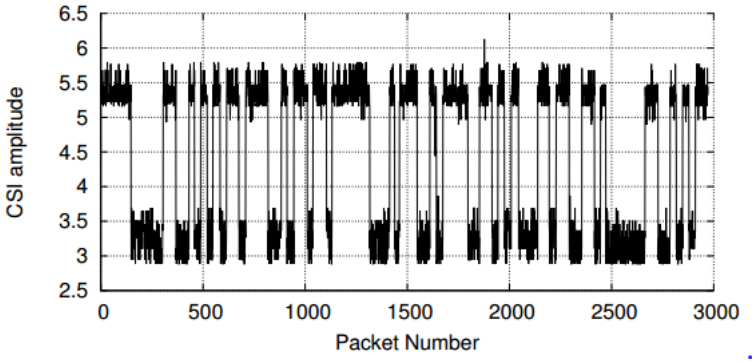
Image: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

Uplink – Modulation

- Antenna's impedance affects amount of reflected signal
- Minimal interference
  - Modulating doesn't change the channel within every Wi-Fi packet
  - Modulates only when queried by reader

Uplink – CSI extraction at reader

- Signal conditioning
  - Remove temporal variations by using moving average
- Exploiting frequency diversity
  - Identify good sub-channels
    - Use correlation with known preamble
  - Combine sub-channel information
    - Use weighted average



$$CSI_{weighted} = \sum_{i=1}^{G} \frac{CSI_i}{\sigma_i^2}$$

Images: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

Uplink – CSI extraction at reader

- Decoding bits from the CSI information
  - Reader can use simple thresholding on weighted CSI
    - Weighted CSI > 0, output ‘1’
    - Weighted CSI < 0, output ‘0’

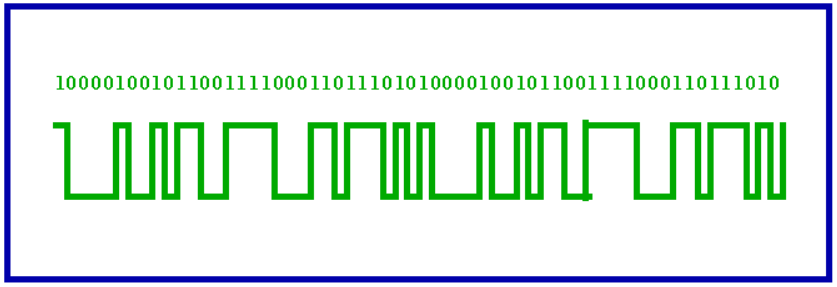


Image: http://www.colorado.edu/geography/gcraft/notes/gps/gif/bits.gif

Evaluation – Uplink

- Shows difference between randomly picking a sub-channel and using the frequency diversity method explained earlier
  - Using 30 packets per bit
- Much benefit in combining information across all sub-channels

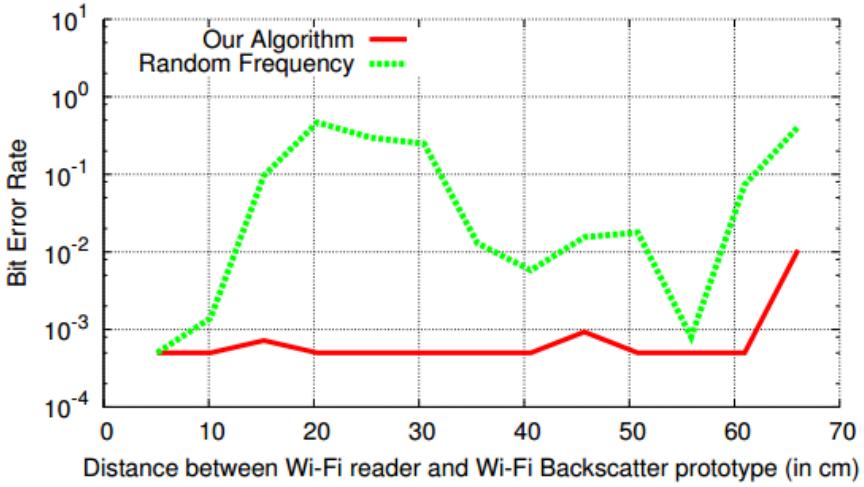


Image: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

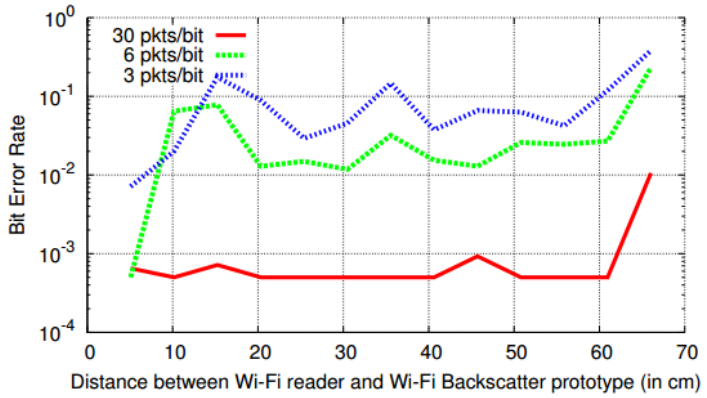
Uplink – Decoding using Recieved Signal Strength Indication (RSSI)

- Most existing chipsets only provide RSSI information
  - A metric for cumulative signal strength across all the sub-channels
- Can have multiple RSSI channels (multiple antennas)
  - Then choose channel with max correlation value

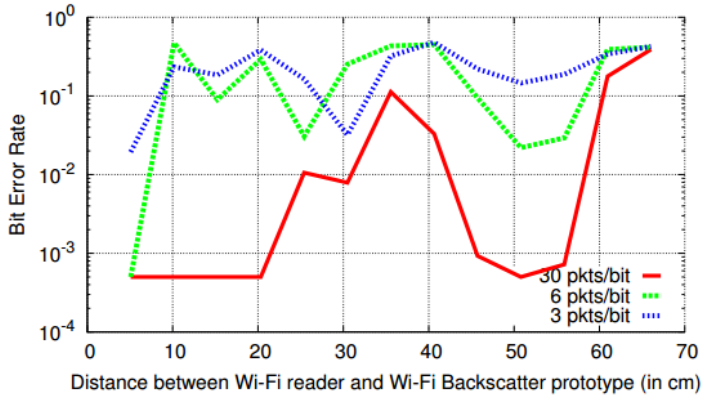
Image: http://www.unlocked-dongle.com/mobile/images/signal_strength_bars.png

Uplink – CSI vs. RSSI

- Higher packets per bit
  - BER and range improves
- CSI perfoms better than RSSI
- With BER less than 10^{-2} Reader can decode
  - Up to 65 cm with CSI
  - Up to 30 cm with RSSI



(a) CSI



(b) RSSI

Image: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

Downlink

- Challenges
  - Reader can only transmit Wi-Fi packets
  - Tag cannot decode Wi-Fi transmissions
- Solution
  - Encode information with the presence and absence of Wi-Fi packets
  - Circuit in tag can detect energy during a packet transmission

Image: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

Downlink – Encoding at reader

- Presence of a packet encodes a ‘1’ bit
- Silence encodes a ‘0’ bit
  - Duration of silence period equal to a packet
- First Reader transmits a CTS_to_SELF packet
  - To keep other devices from transmitting during silence periods

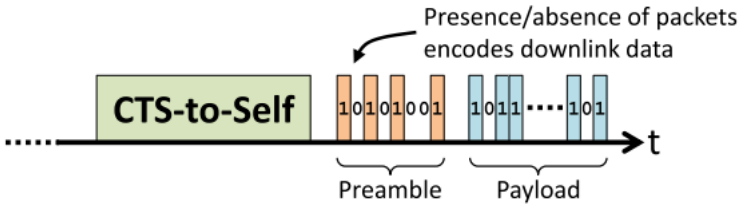


Image: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

Downlink – Tag receiver design

- Need to differentiate presence and absence of a packet
  - Energy detection circuit
- Microcontroller operates in 2 modes:
  - Preamble detection
  - Packet decoding
- Achieve 20 kbps at distances up to 3 meters

Handling multiple devices sharing the medium

- Downlink
  - Using the CTS_to_SELF packet
- Uplink
  - Number of packets transmitted from helper depends on traffic
  - Need equal number of helper packets for each transmitted bit
    - Reader needs to compute average number of packets the helper can send
    - Lets the tag know the bit rate

Image: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

Prototype Implementation

- Optimized for 2.4 GHz Wi-Fi channels
- Can modulate the channel and harvest RF signals
- MSP430 microcontroller running custom firmware
- Transmit circuit uses 0.65 µW
- Receiver circuit uses 9.0 µW

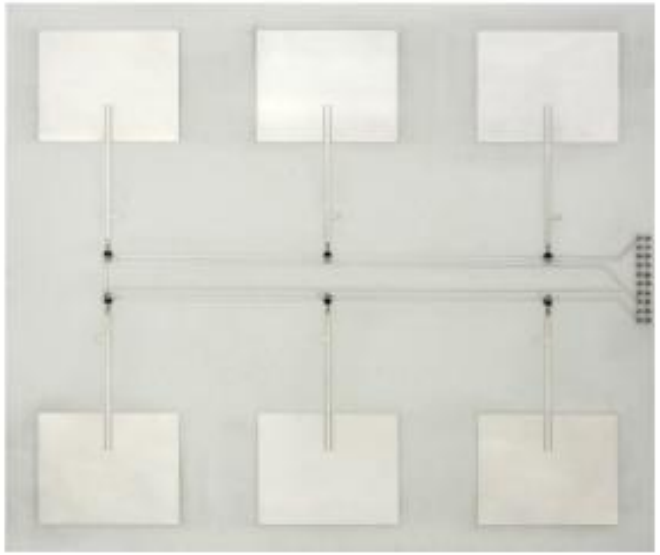


Image: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

Bit rate evaluation – Uplink

- Actual bit rate depends on Helper packet transmission rate
- Bit rate 100 bps with transmission rates of 500 pkts/s
- Bit rate 1 kbps with transmission rates 3070 pkts/s
- Bit rate more than sufficient for most IoT applications

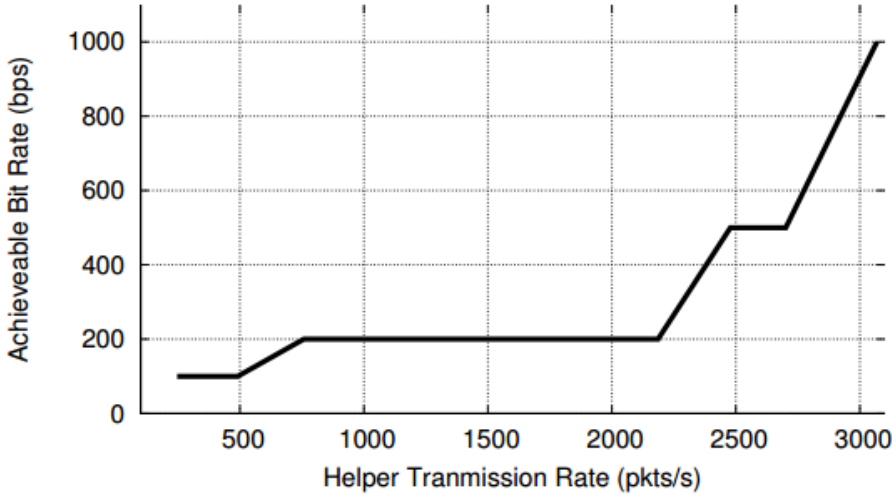


Image: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

Rangeevaluation – Downlink

- The bit rates correspond to packet lenghts of 50 µs, 100 µs and 200 µs
- BER increases with distance as expected
- Can achieve
  - 20 kbps at distances of 2.13 m
  - 10 kbps at distances of 2.90 m

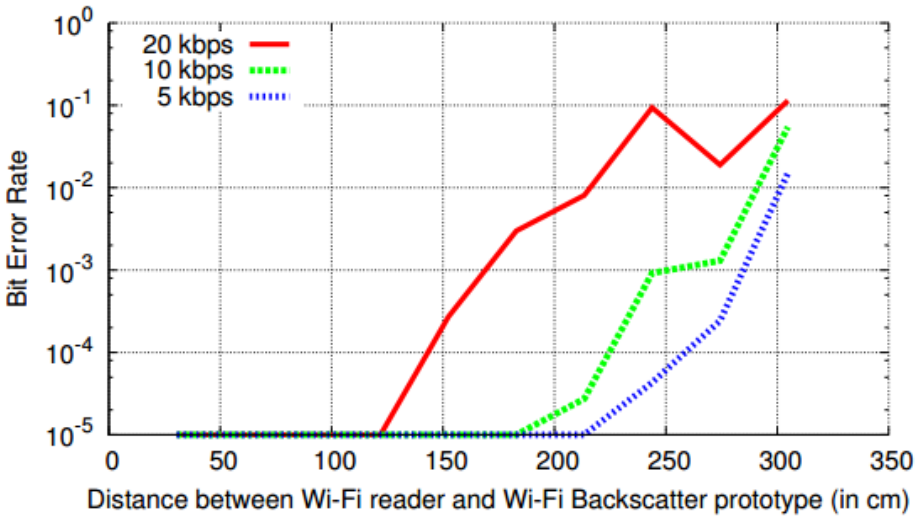


Image: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

Limitations and future research

- Limited by range and bit rate

- More range
  - Increase range using multiple antennas
- More bit rate
  - Decrease error rate using low-rate feedback channel

Image: Wi-Fi Backscatter Internet Connectivity for RF-Powered Devices

Summary

- Can harvest and reuse RF signals
- Wi-Fi Backscatter connects battery free devices to the internet
- Achieve 1 kbps and range up to 2.1 meters (Uplink)
- Achieve 20 kbps and range up to 3 meters (Downlink)
- Can reuse existing infrastructure
- Helps realize the pervasive vision of the Internet of Things

ETH zürich

Thanks for Listening

- Gollakota, Shyamnath, et al. "The emergence of RF-powered computing."*Computer* 47.1 (2014): 32-39.
- Kellogg, Bryce, et al. "Wi-Fi Backscatter: Internet connectivity for RF-powered devices." Proceedings of the 2014 ACM conference on SIGCOMM. ACM, 2014.
- Liu, Vincent, et al. "Ambient backscatter: wireless communication out of thin air." *ACM SIGCOMM Computer Communication Review*. Vol. 43. No. 4. ACM, 2013.