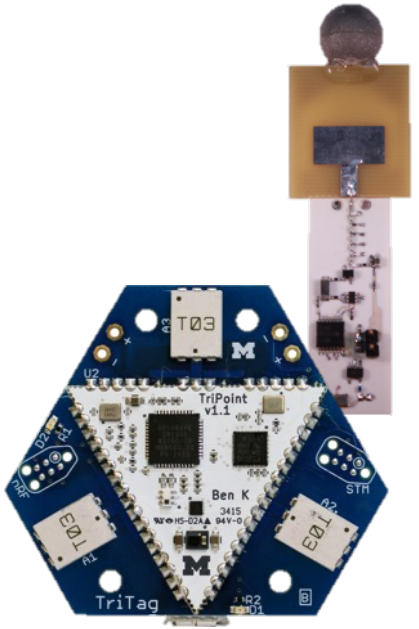
This presentation includes video, please use the powerpoint version where appropriate, available at http://patpannuto.com/talks.html

Ultra-Wideband and Indoor Localization

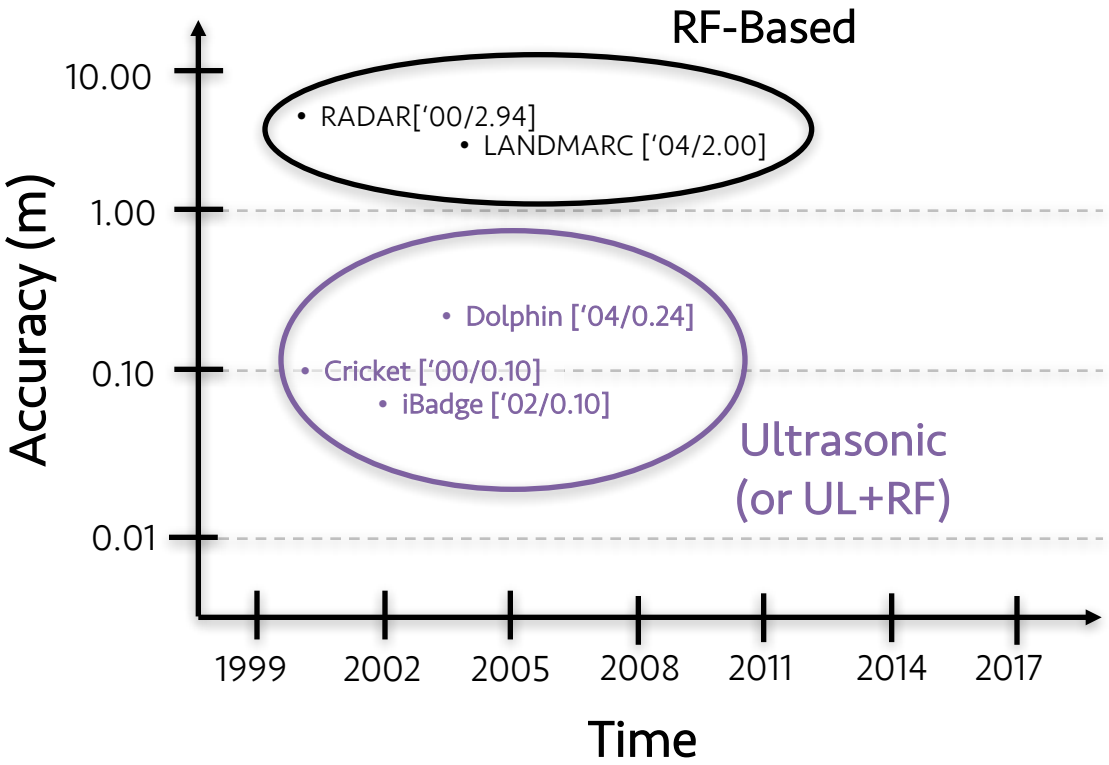
Pat Pannuto

In collaboration with Benjamin Kempke, Bradford Campbell, and Prabal Dutta

HotWireless'16
October 3, 2016, NYC, NY, USA

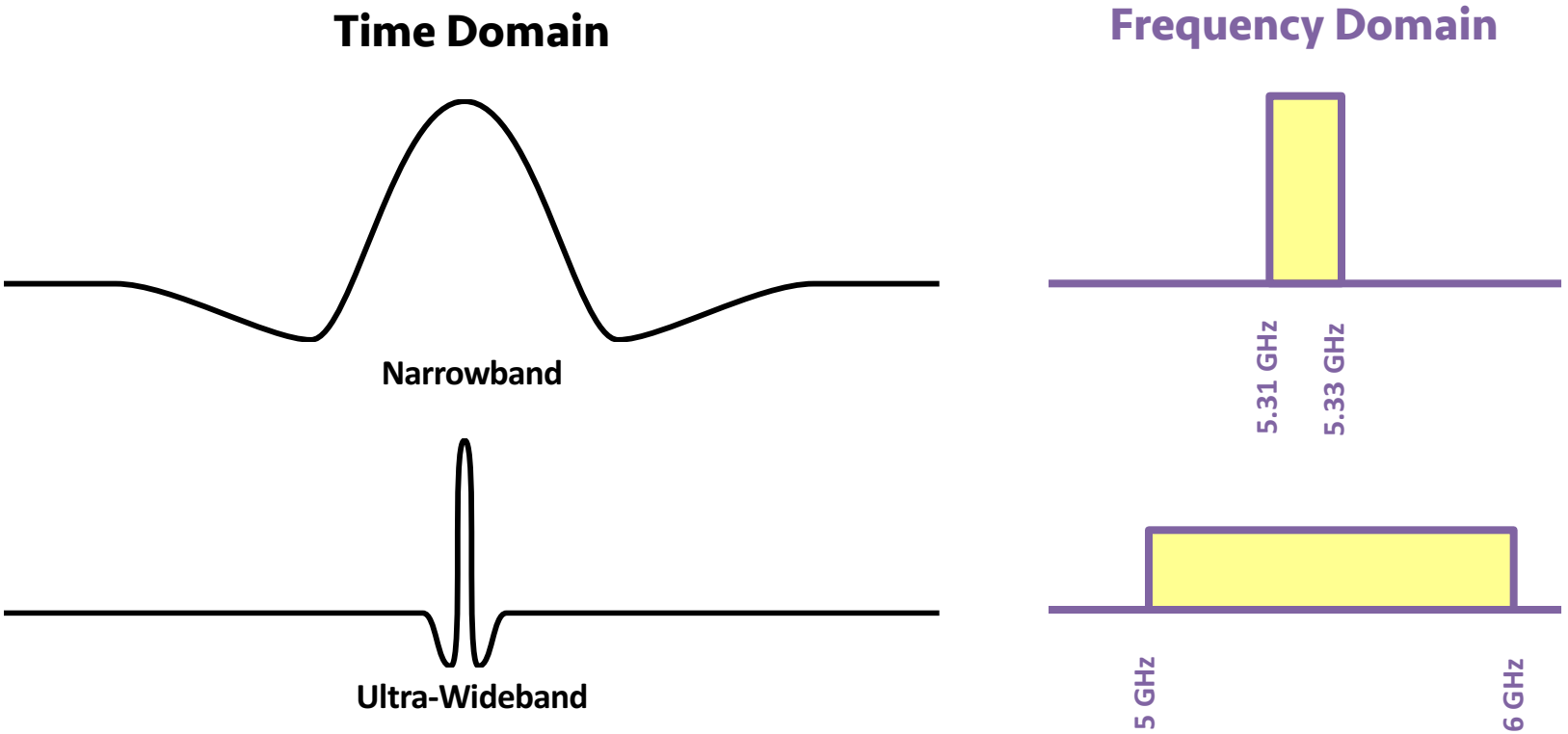


Early RF-only localization (largely RSSI) had comparatively poor accuracy

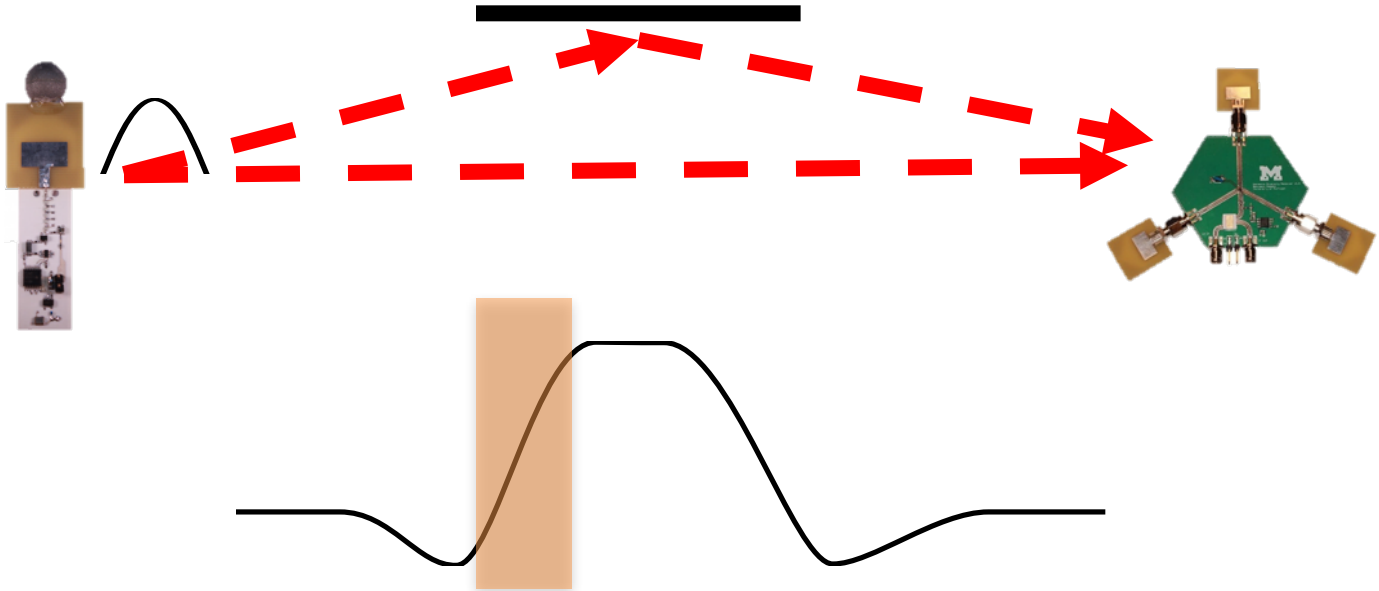


- 2002
  - FCC allows unlicensed use of UWB spectrum
- 2005
  - International UWB regulations
- 2007
  - IEEE 802.15.4a

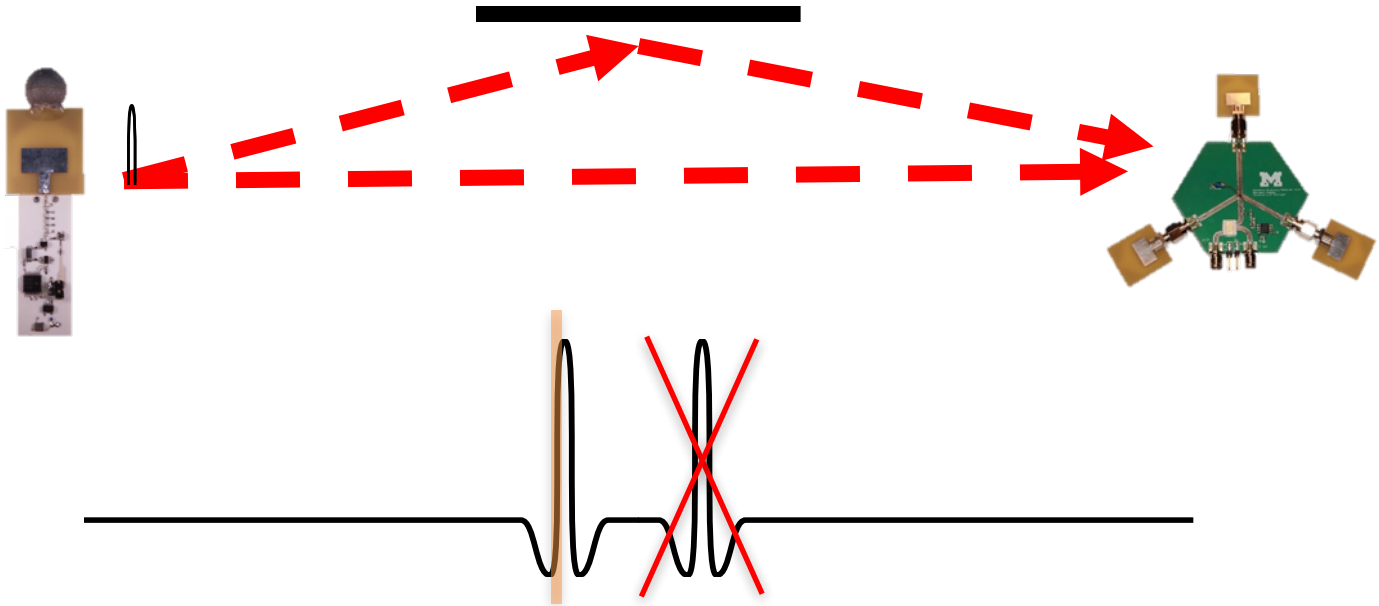
What is Ultra-Wideband?



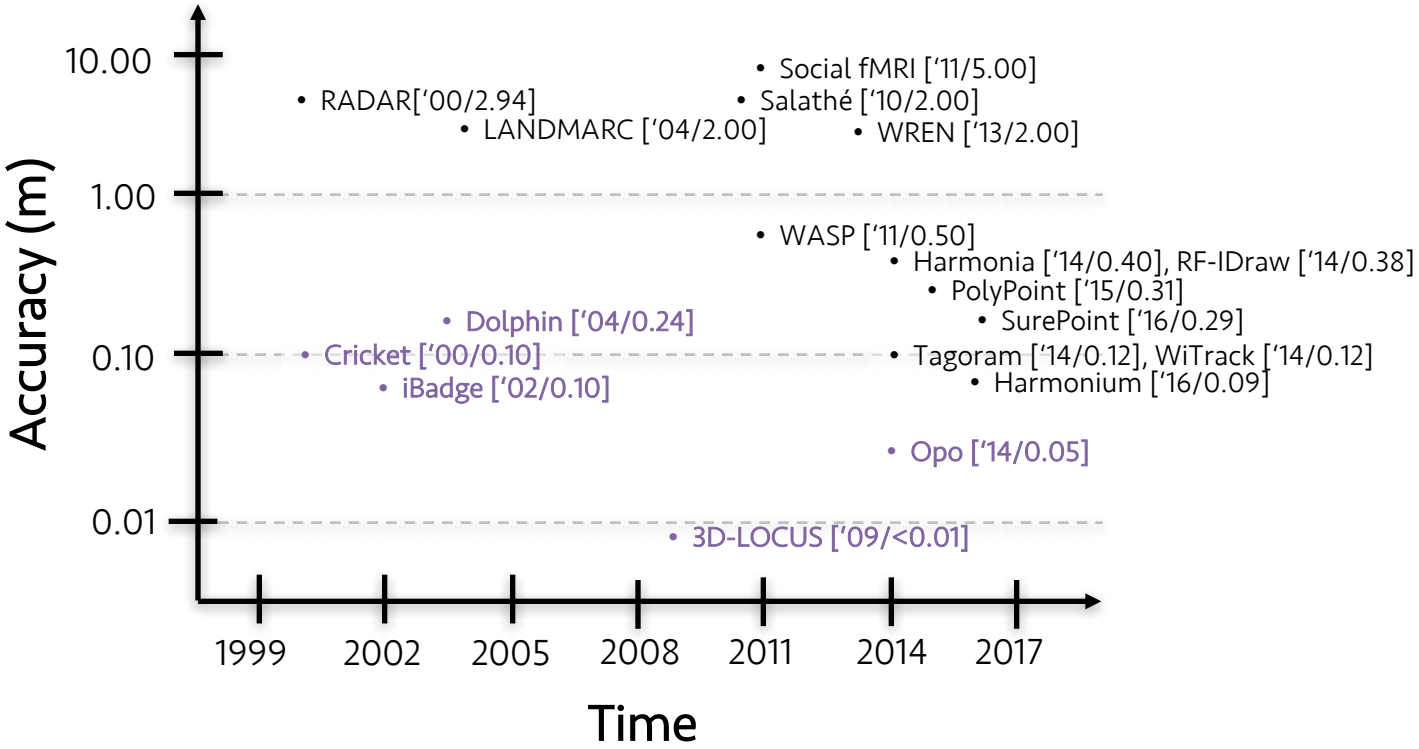
Indoors, reflections make time-of-flight estimation difficult and inaccurate



UWB can better disambiguate multipath and identify signal arrival time

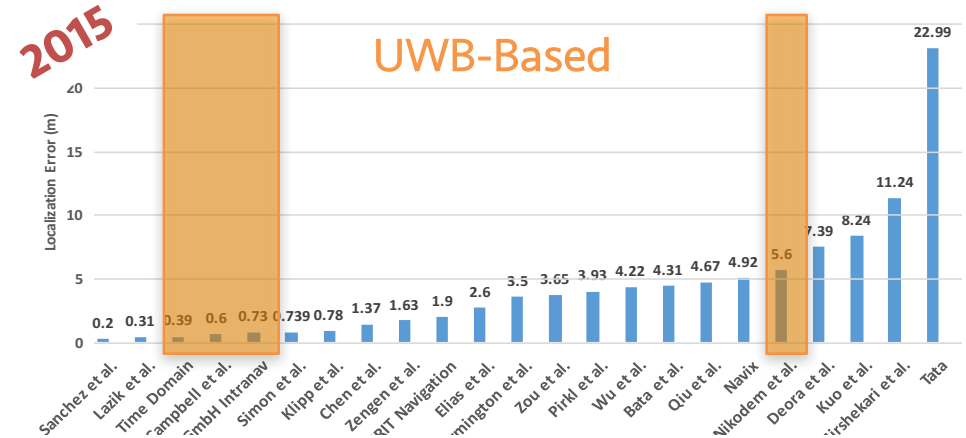


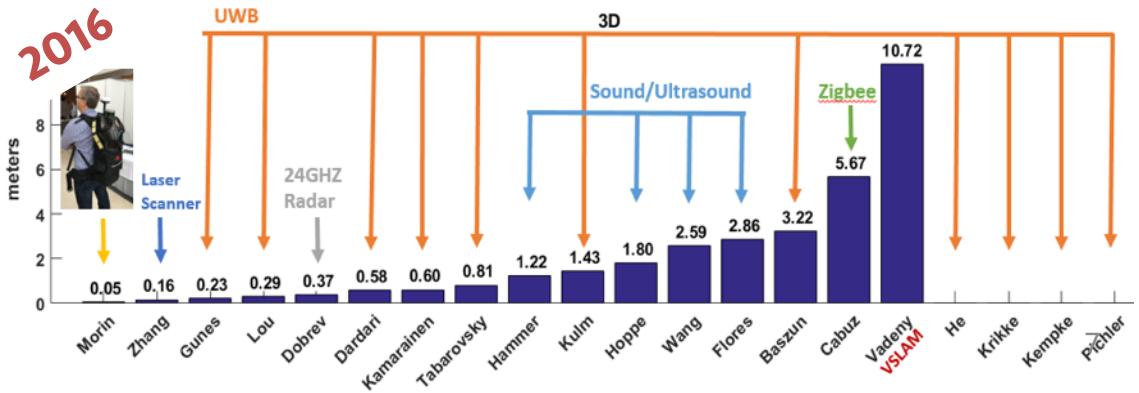
Highly accurate (RF-based) indoor localization technology has arrived



UWB technologies have driven success in high-fidelity RF-based localization

- UWB-based entries beginning to dominate IPSN localization competition
- Half of competing teams achieved sub-meter accuracy
- *Takeaway:* accuracy is a "solved" problem

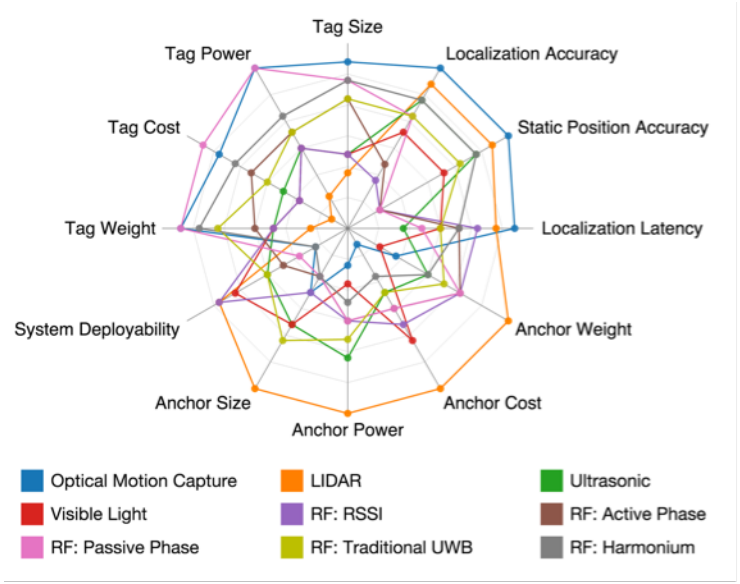




D. Lymberopoulos, J. Liu, X. Yang, A. Naguib, A. Rowe, N. Trigoni, and N. Moayeri. Microsoft Indoor Localization Competition – IPSN 2015.
D. Lymberopoulos, J. Liu, Y. Zhang, P. Dutta, X. Yang, A. Rowe, V. Dequeira. Microsoft Indoor Localization Competition – IPSN 2016.

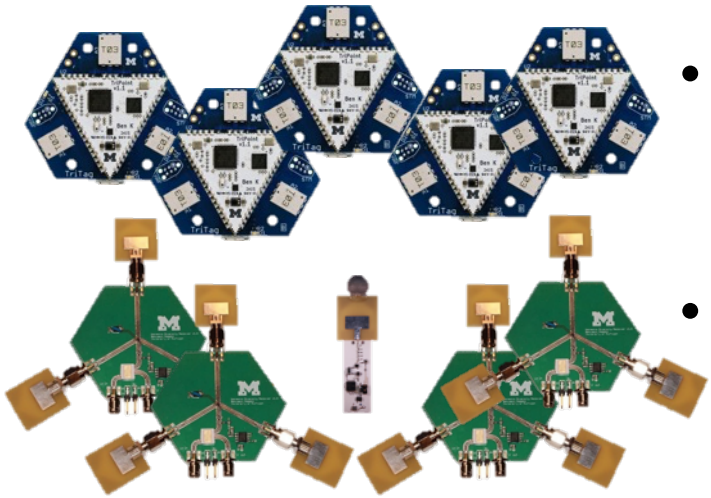
Accuracy is only one facet of localization, and has reached "good enough"

- Here are 12 dimensions
  - Covering 9 technologies
    - Each have several implementations
  - (bigger is better) →
- No one technology will fit all applications
  - What does it mean to localize a person to 1cm?
  - Motion? Walls? More??



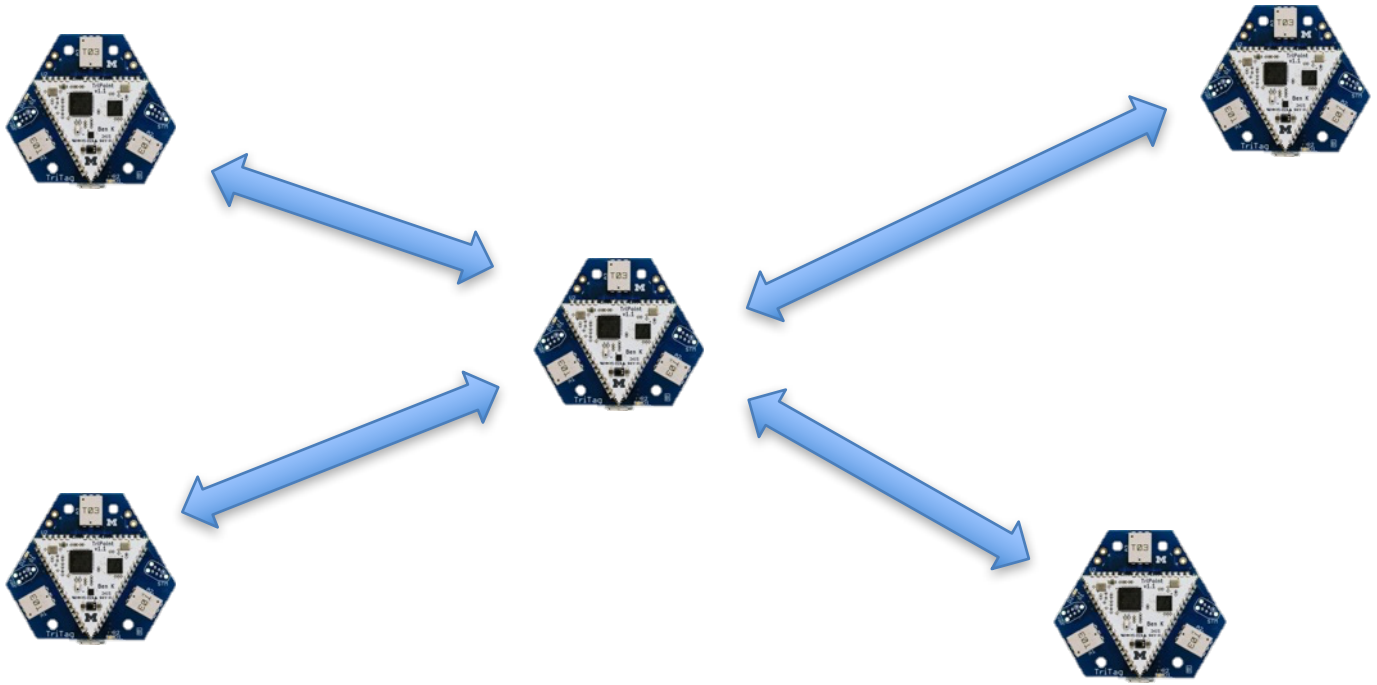
This talk: New UWB-based systems that go beyond accuracy

(Though, all are highly [10-30 cm] accurate)

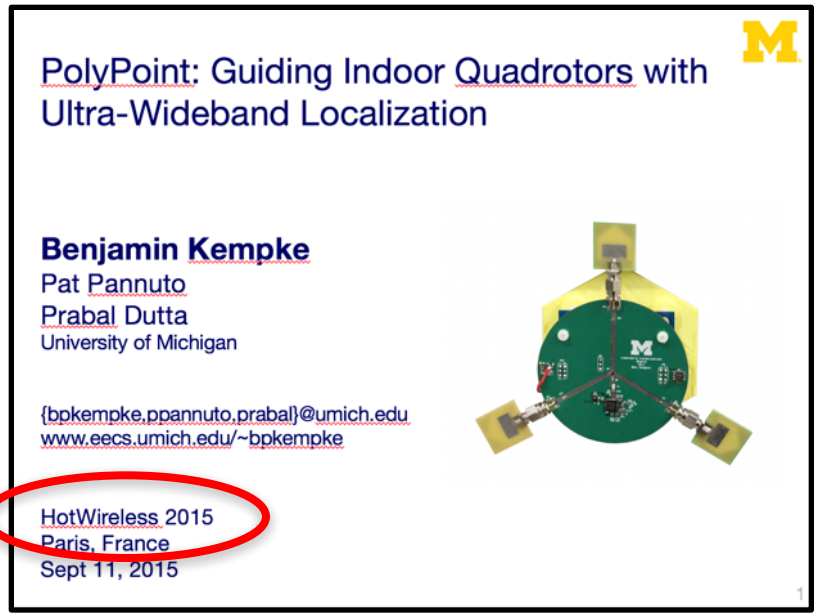


- SurePoint [SenSys'16]
  - Robust, scalable, and reliable
    - 53 cm 99th percentile error
- Harmonium [IPSN'16]
  - Inexpensive, low-power, lightweight
    - Localizes quadcopters with 5 g payload limit
- Slocalization [*in progress*]
  - Lowest power and massively scalable

SurePoint: Time-of-Flight between symmetric tag and anchor nodes



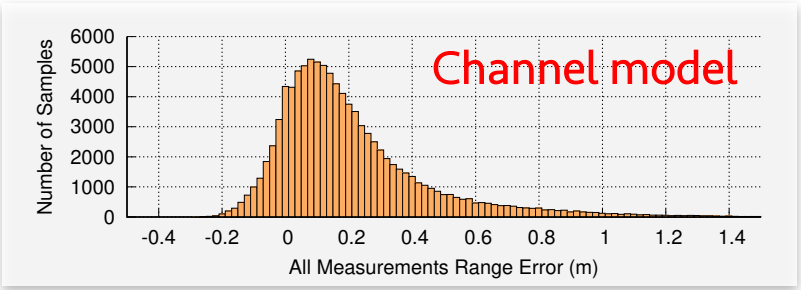
PolyPoint showed how to make commercial UWB accurate, SurePoint makes it usable

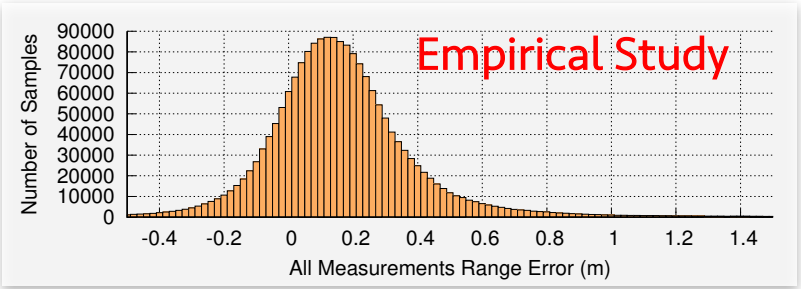


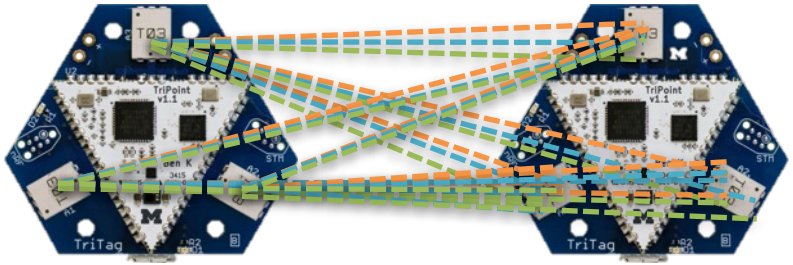
- PolyPoint/SurePoint key innovations:
  - Exploit UWB channel diversity
  - ^Efficiently with a broadcast-based ranging protocol
  - UWB *constructive interference* to schedule and scale

PolyPoint: Guiding Indoor Quadrotors with Ultra-Wideband Localization (HotWireless'15)
SurePoint: Exploiting Ultra Wideband Flooding and Diversity to Provide Robust, Scalable, High-Fidelity Indoor Localization (SenSys'16)
Benjamin Kempke, Pat Pannuto, Bradford Campbell, and Prabal Dutta

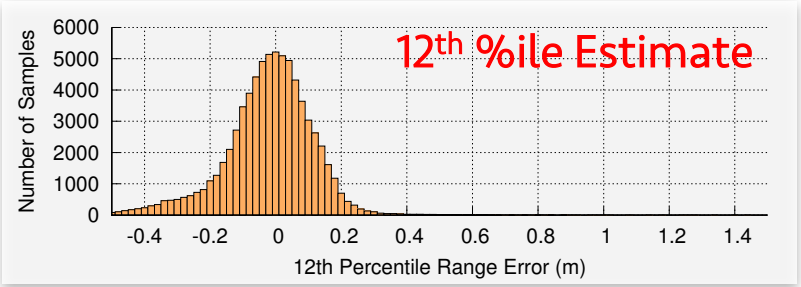
PolyPoint taught us that the UWB channel exhibits high variance







27 Samples → 1 Range



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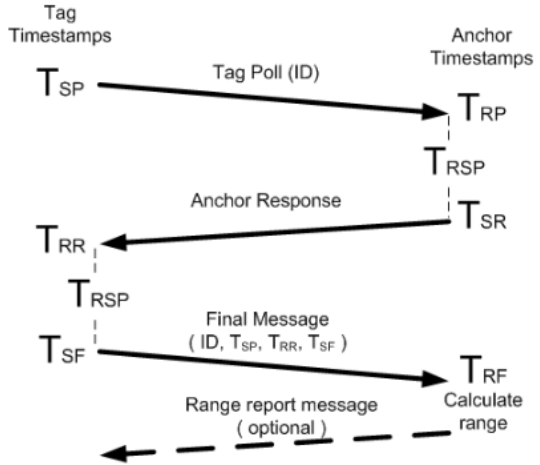
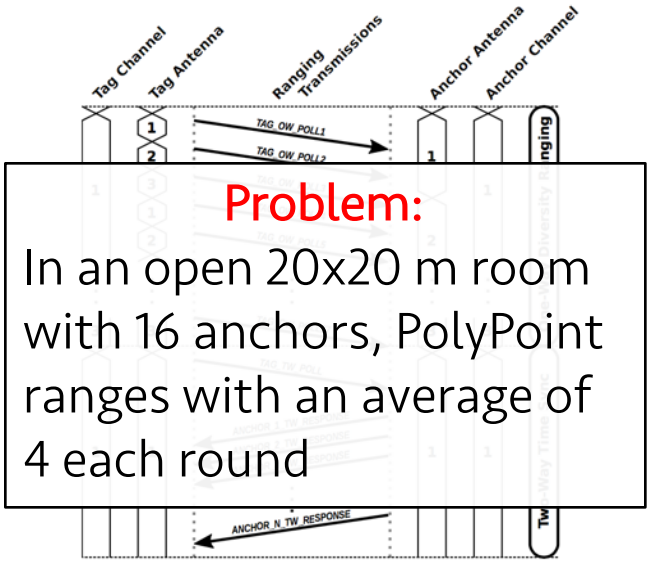
Broadcasts can make diversity acquisition efficient, but must also be robust



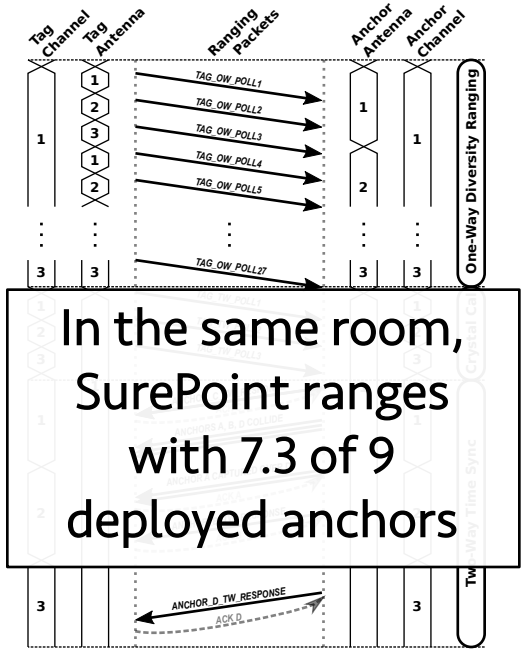
Naïve implementation: 27x3xN packets

3 anchors:
243 packets (~4 Hz)



PolyPoint: 27+1+N packets

3 anchors:
31 packets (~32 Hz)

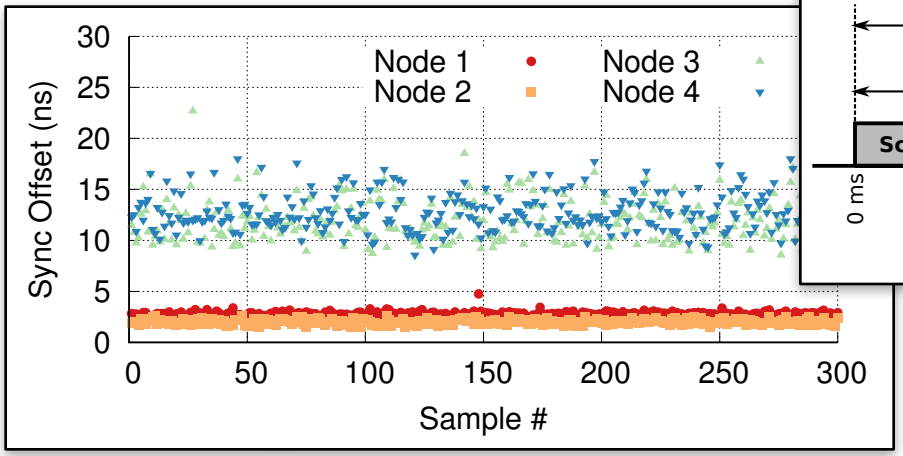


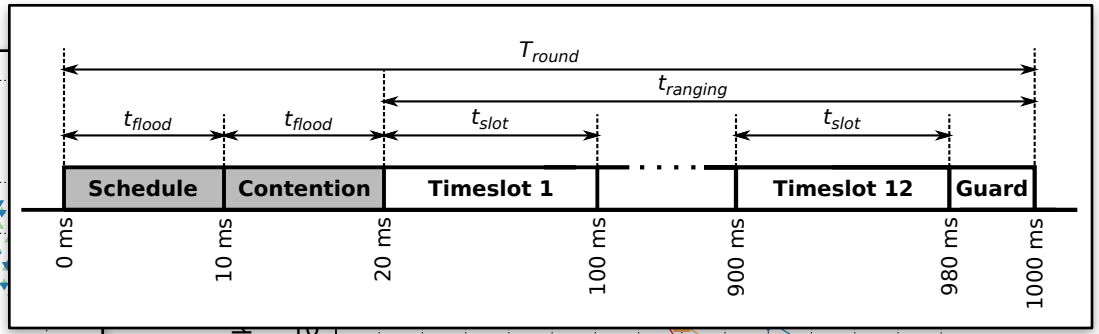
SurePoint: 27+3+N packets

3 anchors:
33 packets (~31 Hz)

Localizing multiple devices requires coordination to avoid interference

- Insight: Borrow scheduling from sensor networking
  - State of the art relies on *constructive interference* – UWB friendly?





New Tradeoffs:

- Number of tags vs. update rate
- Join latency vs. update rate

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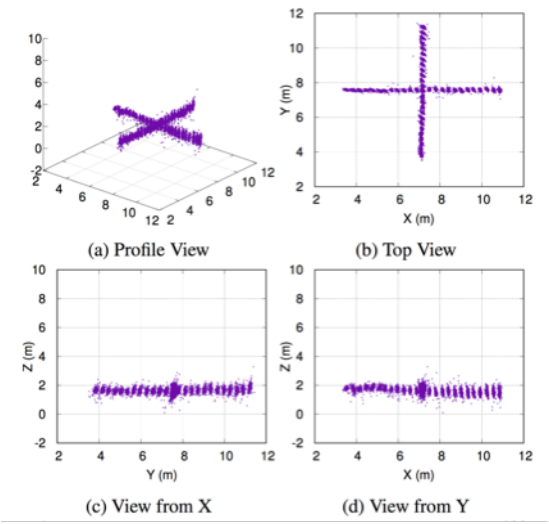
Robust, accurate localization and best-in-class long-tail performance



- Stationary Experiment
  - 7,500 samples
  - 0.29 m median error
  - 0.77 m 99th percentile error
  - 1.53 m worst case error
    - 0.76 m with 3-point median filter
  - Recovered range in **every** eligible round

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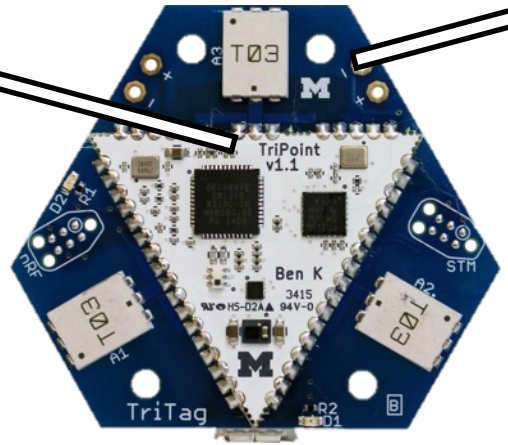
SurePoint Today: Providing localization as a drop-in, modular primitive

TriPoint

- Drop-in localization module
- Towards "where-am-I" as an I^2C command



TriTag

- Carrier board
- Adds BLE for offloading position information

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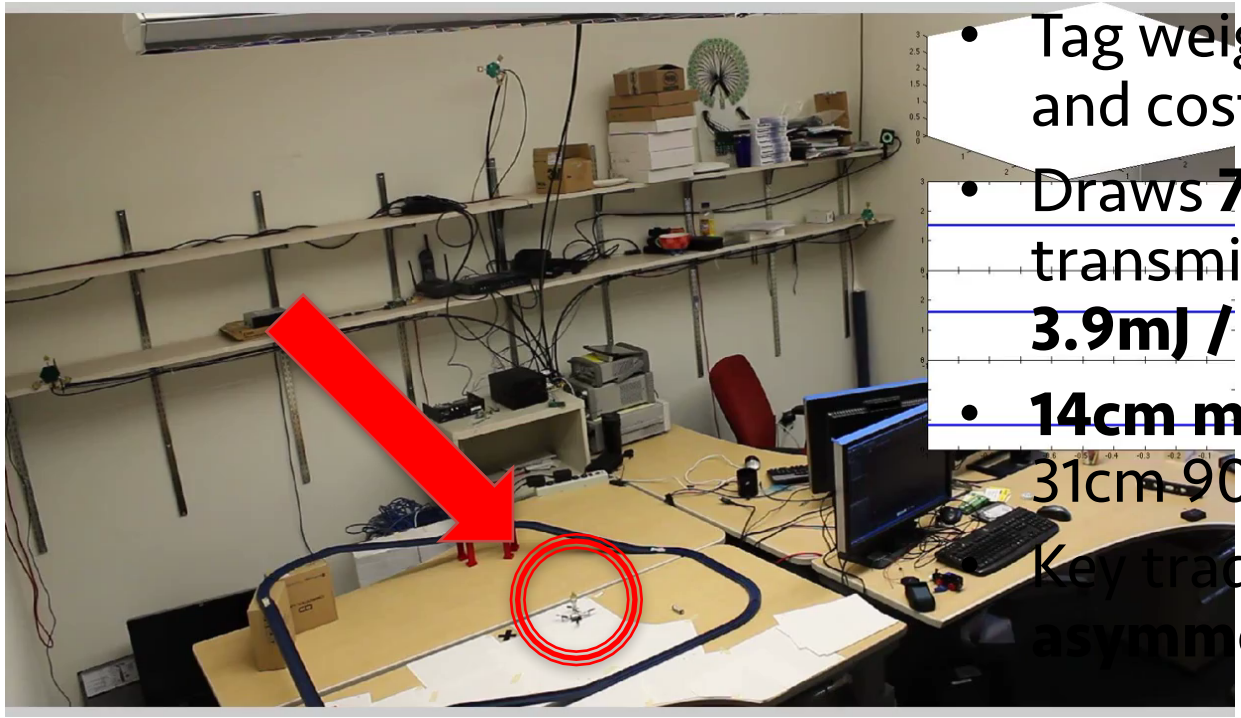
SurePoint design is limited by the use of a commercial UWB transceiver

- Economic cost
  - ~$10 at quantity 1,000
- Energy cost
  - 280 mW
- Flexibility
  - 802.15.4a conflates time-of-flight ranging and data transmission

Harmonium: Decouple ranging and data to realize low-power, high-speed, high-fidelity tracking

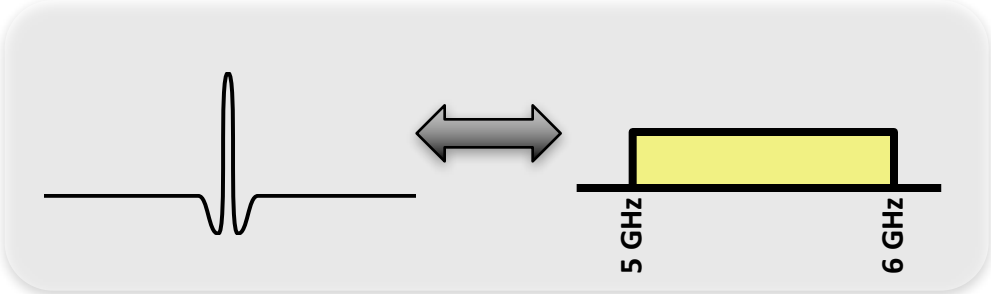


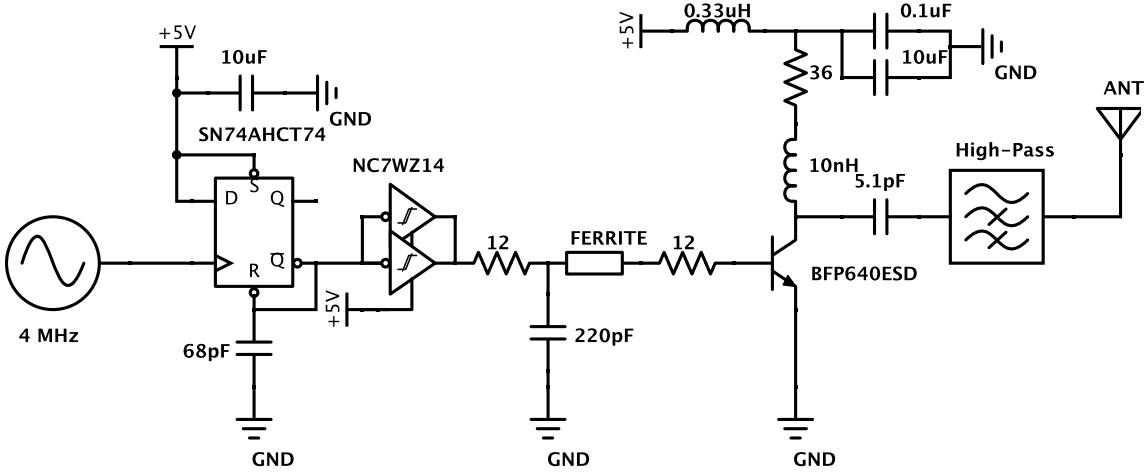
- Tag weighs **3g** and costs **~$4.50**
- Draws **75mW** transmitting, **3.9mJ / fix**
- **14cm median** 31cm 90%ile
- Key tradeoff is **asymmetry**

Harmonia: Wideband Spreading for Accurate Indoor RF Localization (HotWireless'14)
Harmonium: Asymmetric, Bandstitched UWB for Fast, Accurate, and Robust Indoor Localization (IPSN'16)
Benjamin Kempke, Pat Pannuto, and Prabal Dutta

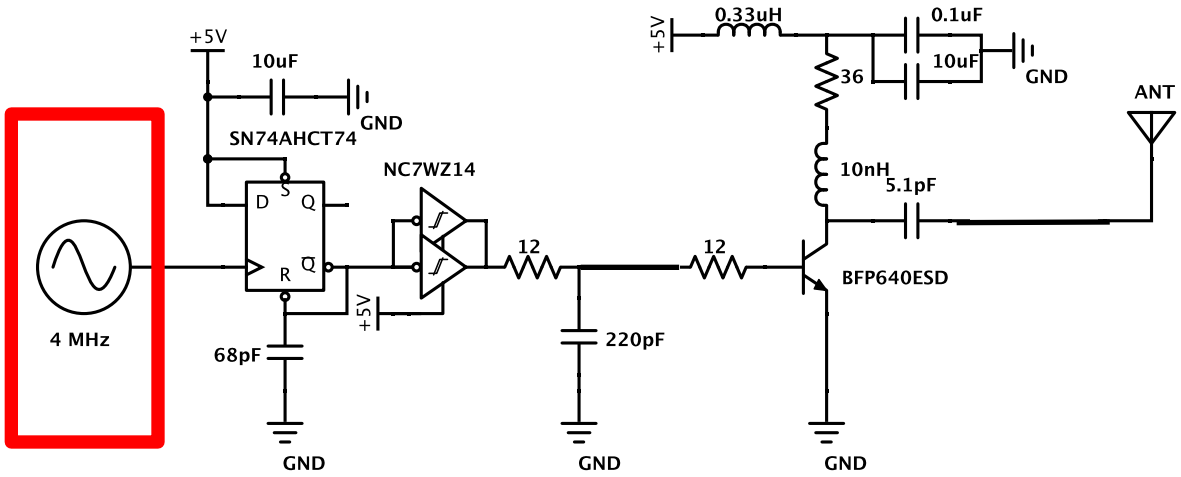
Insight: The harmonics of a sharp pulse *are* a UWB signal (thus, “Harmonium”)

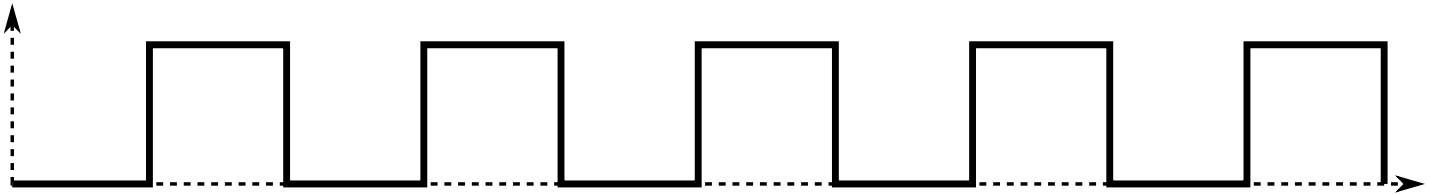
- Concept of operation:
  - BJT NPN Pulse generator
  - Monoflop generator
  - Pulse Repetition Frequency (PRF) generator
  - Trigger filter
  - Pulse-shaping filter



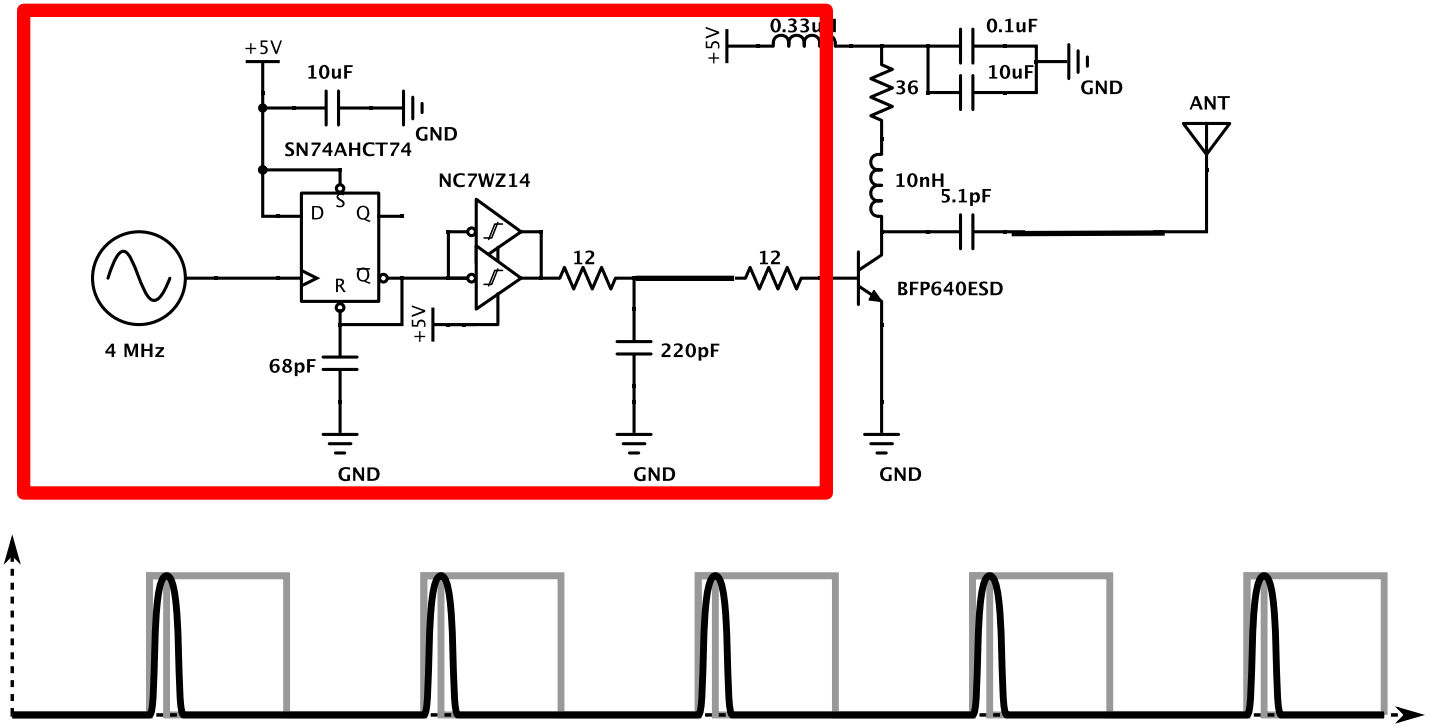


Pulse train generation

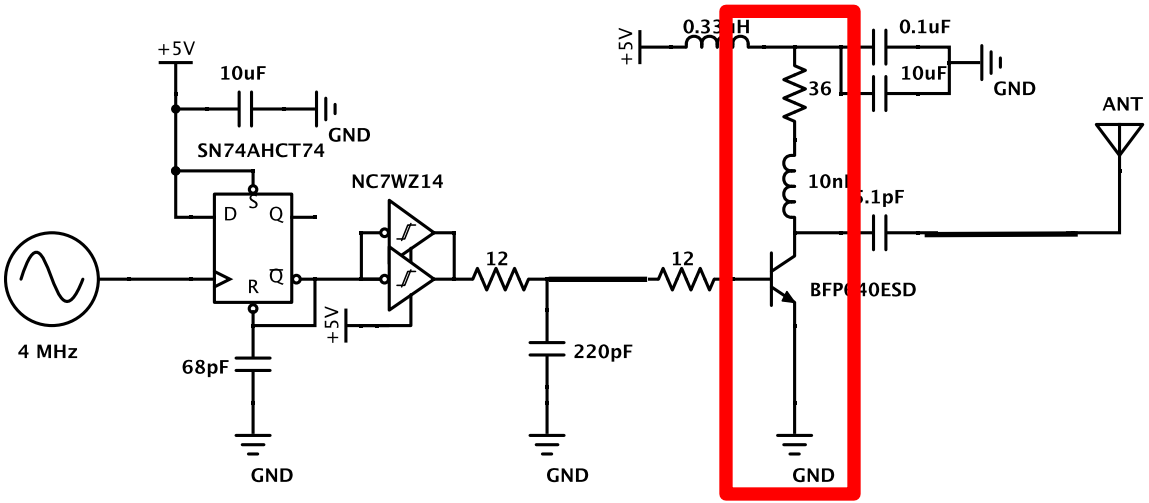


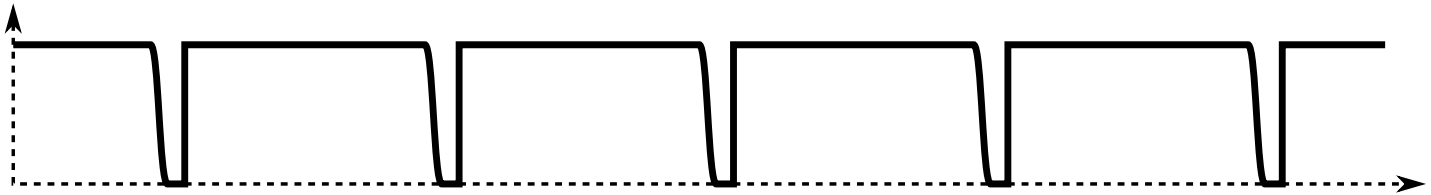


Pulse train generation

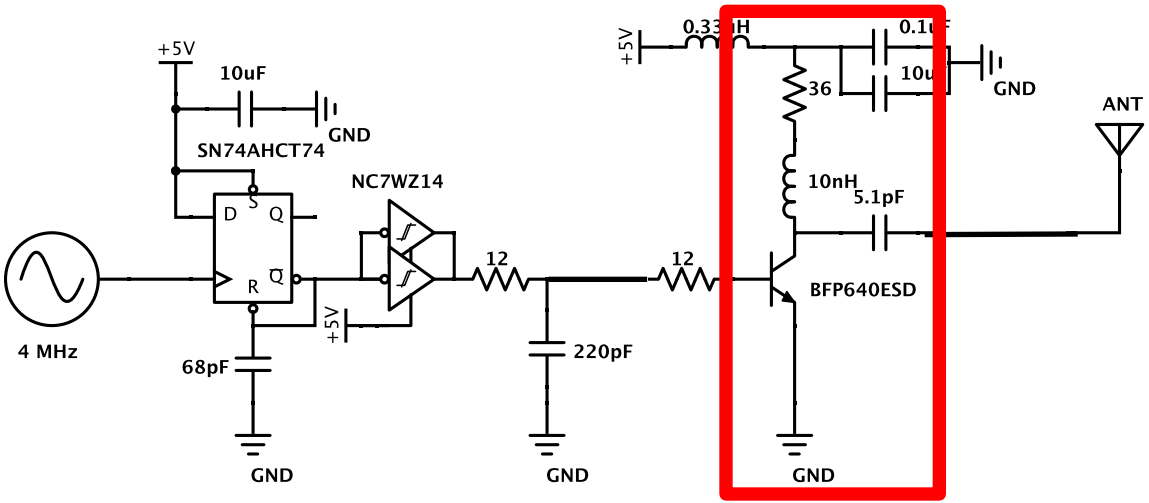


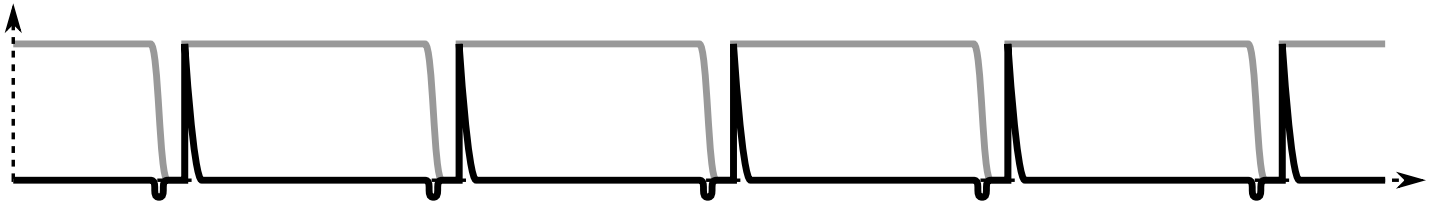
Pulse train generation





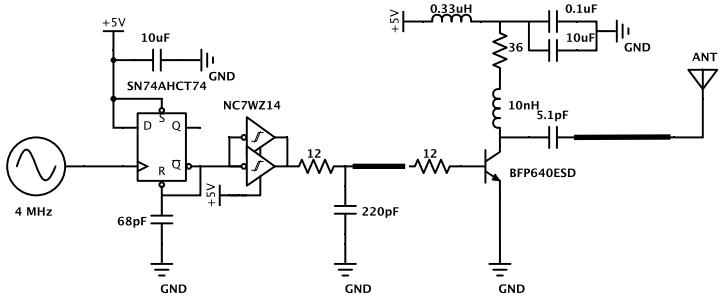
Pulse train generation

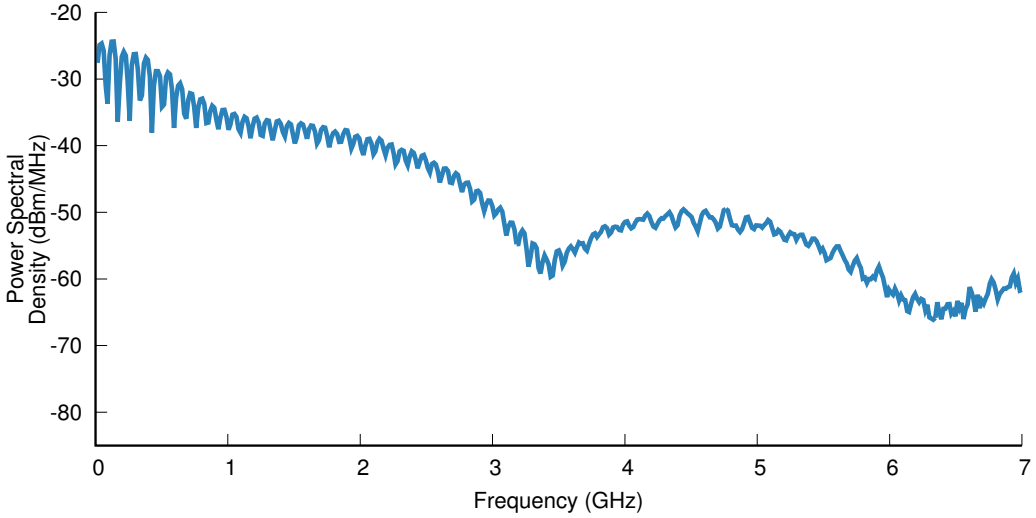




Pulse train generates a UWB signal

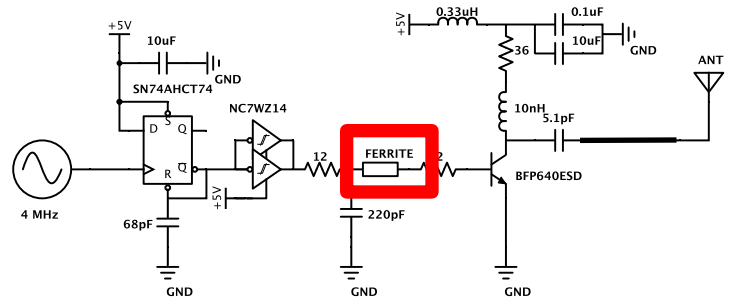
Pulse w/o filtering

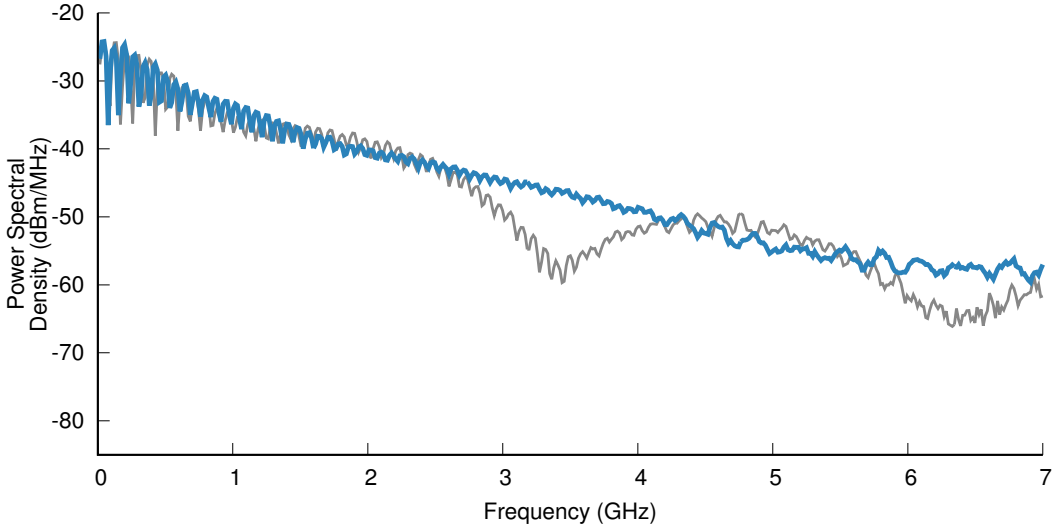




Nit: filter input trigger

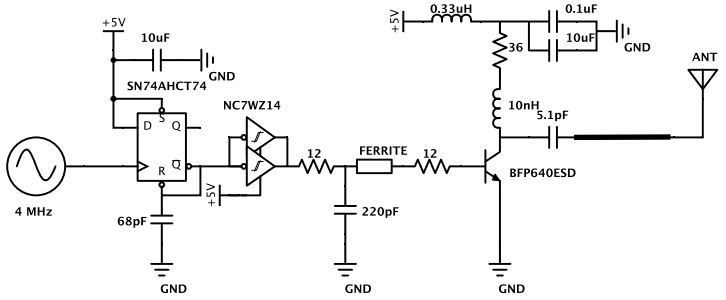
Pulse w/o filtering
→ Pulse w/ trigger filtering

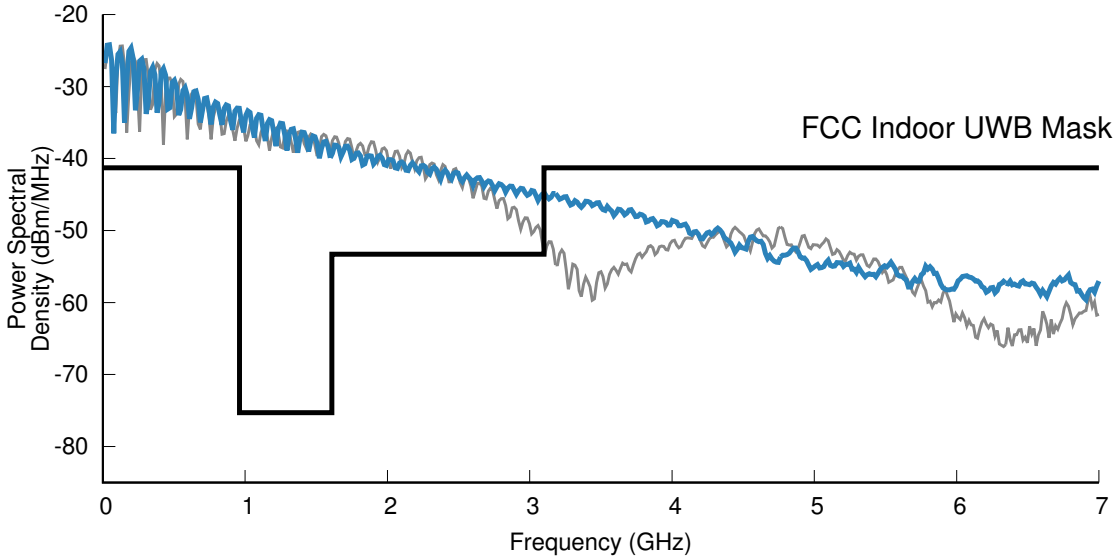




UWB spectral mask starts at 3.1 GHz

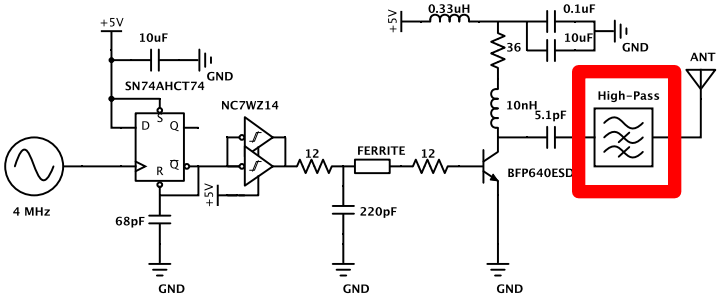
Pulse w/o filtering
→ Pulse w/ trigger filtering

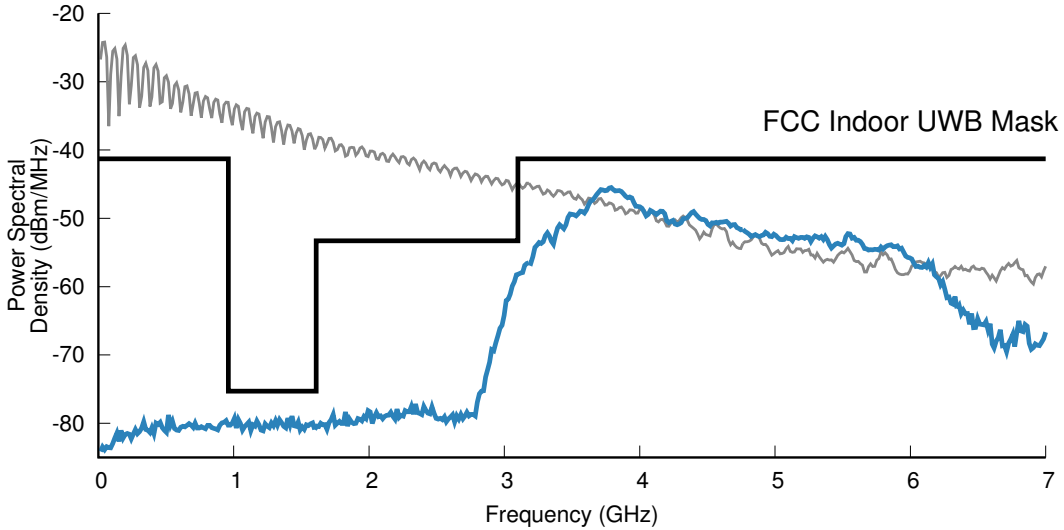


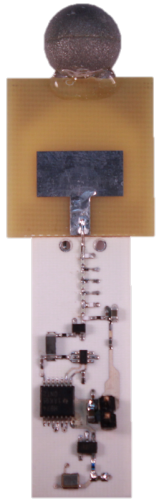


The Harmonium signal for $4.50 and 75 mW

Pulse w/o filtering
→ Pulse w/ trigger filtering
→ Pulse w/ shaping filter

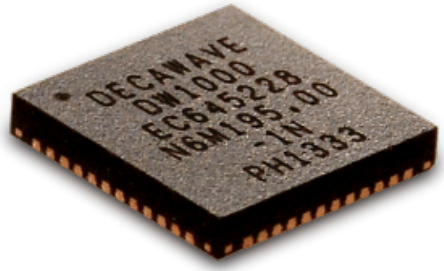


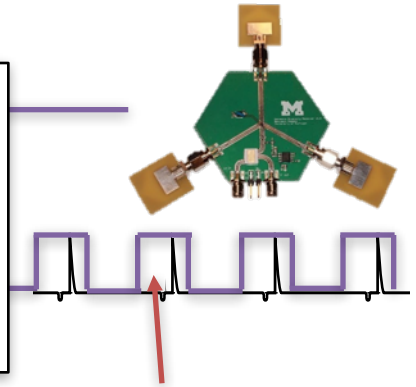


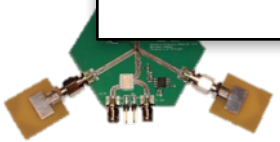


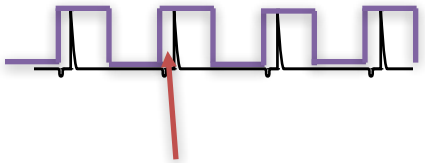
Measure the time-difference-of-arrival to estimate the location of the tag

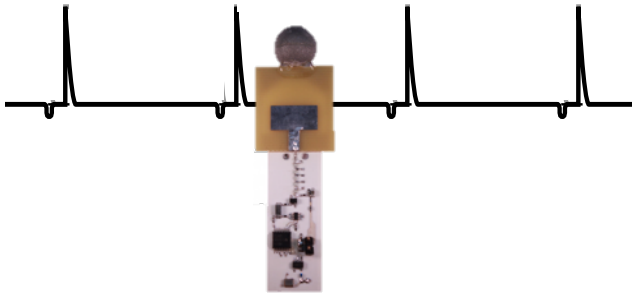
Commercial UWB receivers expect standard packets and modulation





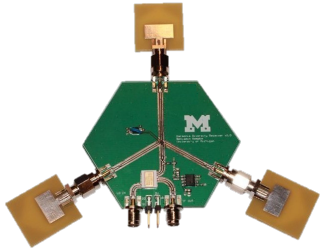


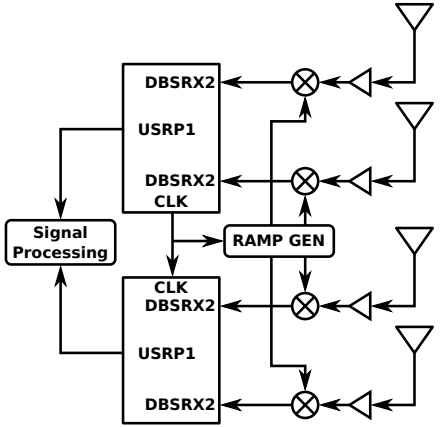


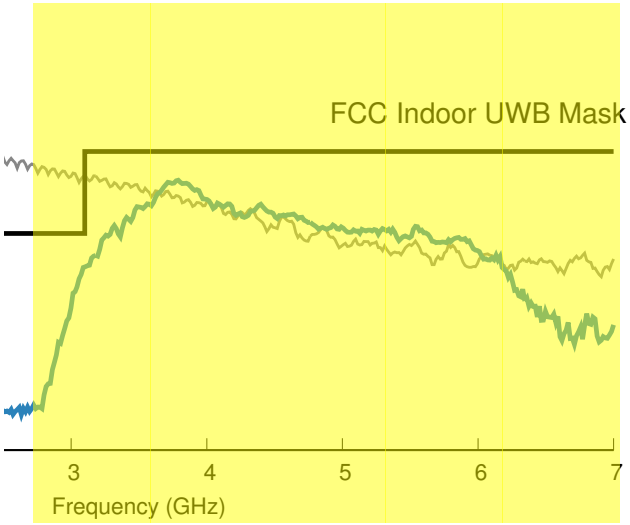


Harmonium: UWB Reception with Narrowband Radios

- Concept of operation:
  - Generic narrowband receiver
  - Frequency-swept local oscillator
  - Antenna diversity

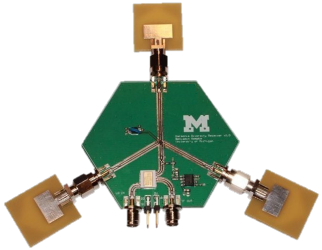


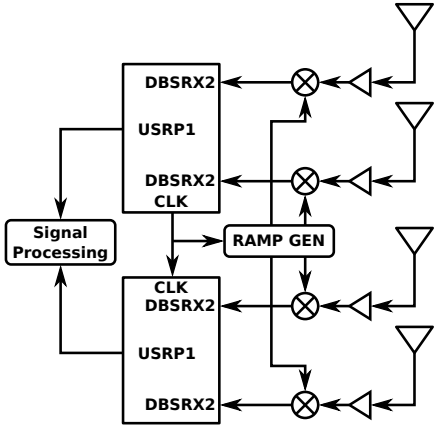


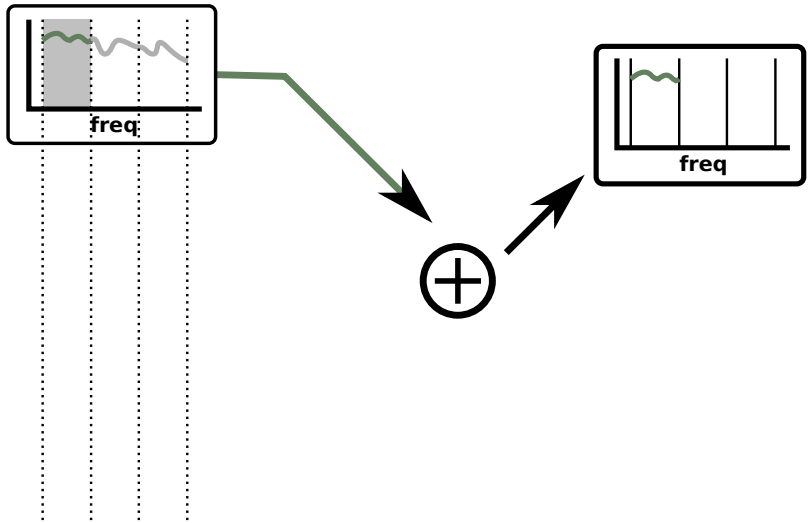


Harmonium: UWB Reception with Narrowband Radios

- Concept of operation:
  - Generic narrowband receiver
  - Frequency-swept local oscillator
  - Antenna diversity







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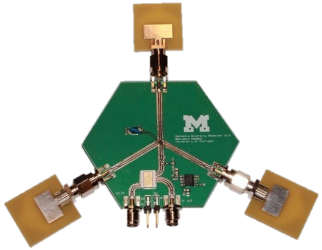

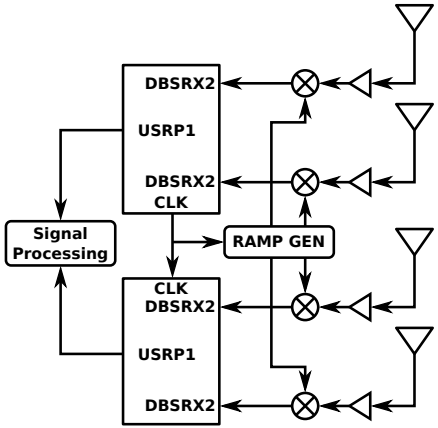

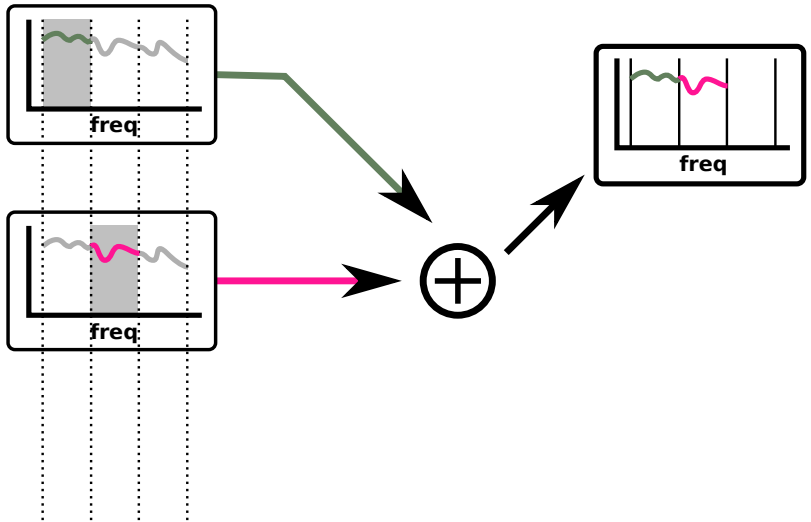

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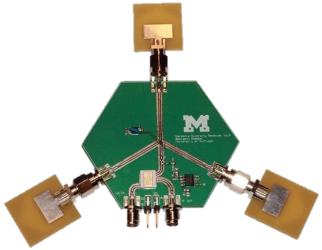

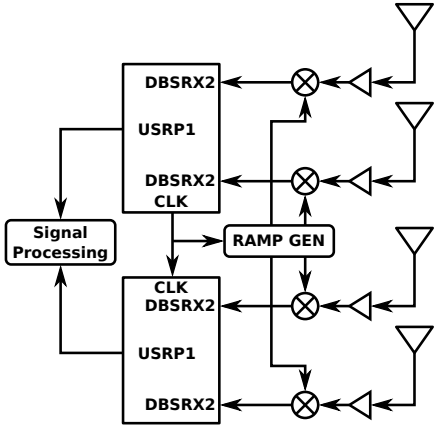

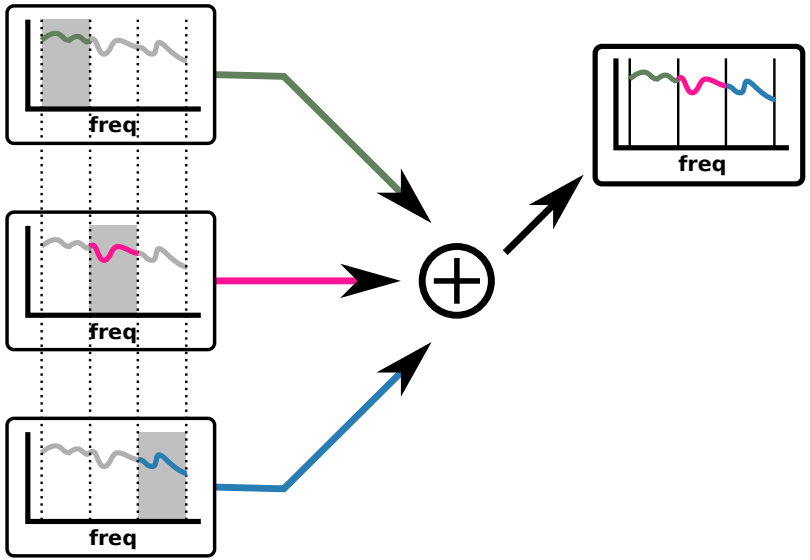

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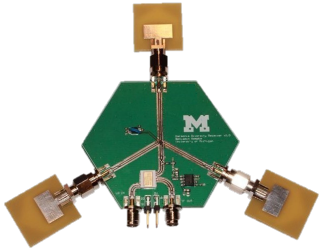
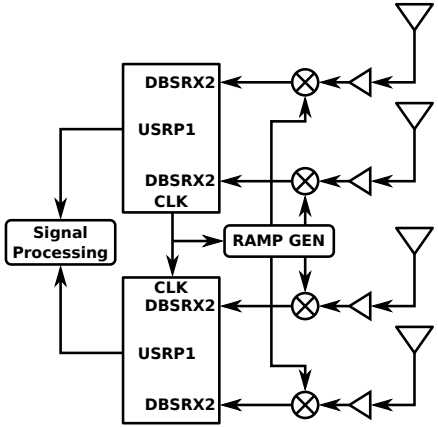
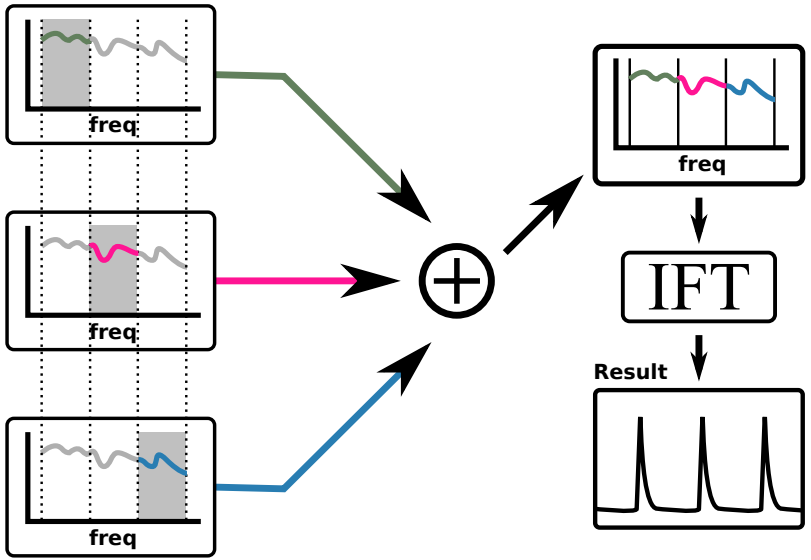
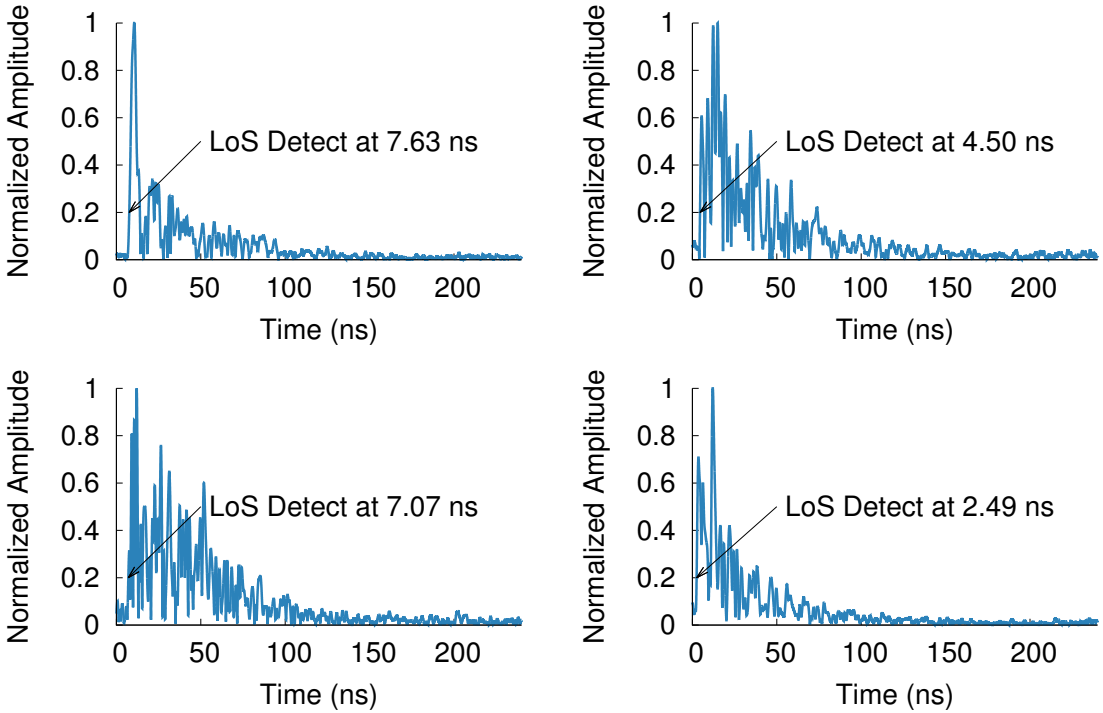




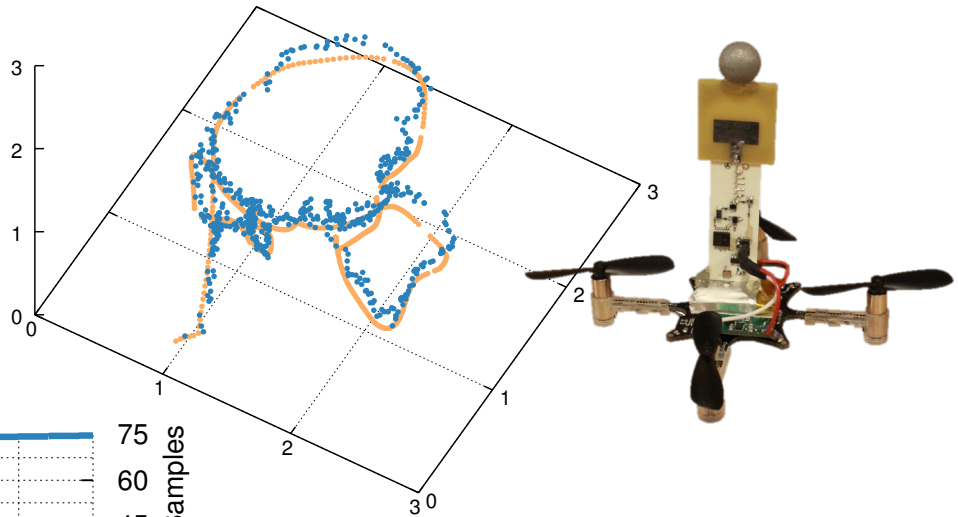


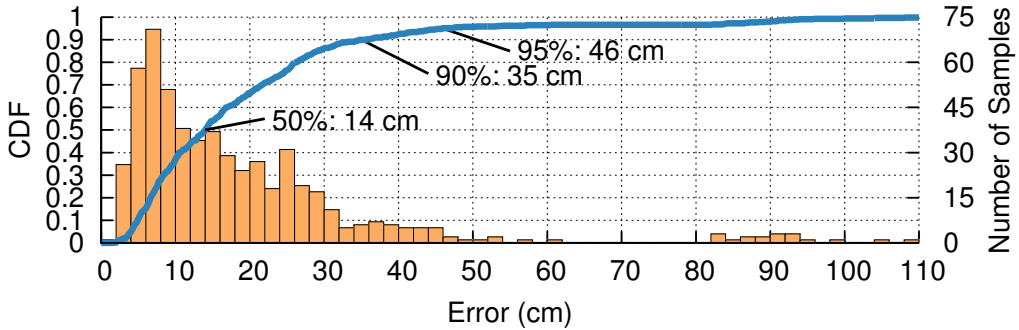
Time-of-arrival estimation from a real-world trace



Harmonium successfully tracks micro quad-rotors accurately and with minimal impact

- 14 cm median error
- 46 cm 95%ile error
- Up to 1.4 m/s
- 19 Hz sampling



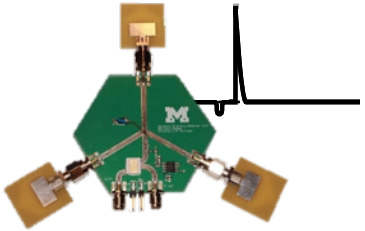


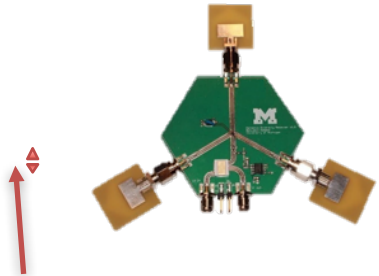
SurePoint lasts at best a few hours, Harmonium a few days – can we do better?

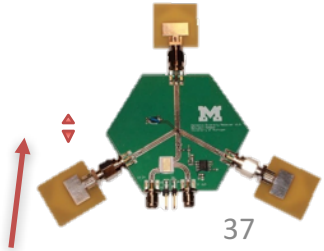
- How might an energy-harvesting localization system work?

Slocalization: Backscatter-based UWB localization

- Energy-harvesting tag drives PN code through a shift register loading/unloading an antenna
- Well below noise floor, but integration in a static environment can reveal the tag signal
- Longer PN code → more tags & slower localization

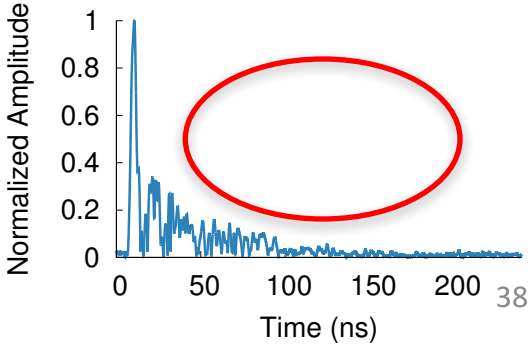






We are only beginning to scratch the surface of the UWB localization space

- SurePoint
  - Robust, reliable, with excellent long-tail performance
- Harmonium
  - Lower tag energy, area, and cost but anchor sync hinders deployment
- Slocalization
  - Vastly lowest energy, but update rates in the minutes / fix
- Other opportunities…
  - Solve for anchor positions, no measuring?
  - SurePoint tags range in parallel, eavesdropping?
  - UWB CIR underutilized?



For More Information…

- http://github.com/lab11
  - lab11/fast-square [harmonium]
  - lab11/polypoint [SurePoint]
- http://patpannuto.com