

This presentation includes some useful animations (and a pretty cool video!)  
The powerpoint version is available at  
<https://patpannuto.com/talks/kempke16harmonium.pptx>

# Harmonium:

## Asymmetric, Bandstitched UWB for Fast, Accurate, and Robust Indoor Localization

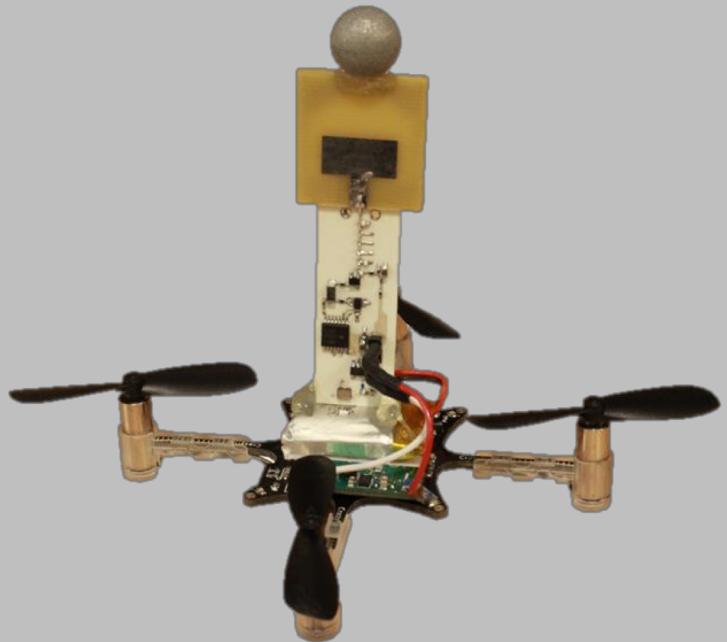
Benjamin Kempke  
Pat Pannuto  
Prabal Dutta

University of Michigan

IPSN 2016

# What is Harmonium?

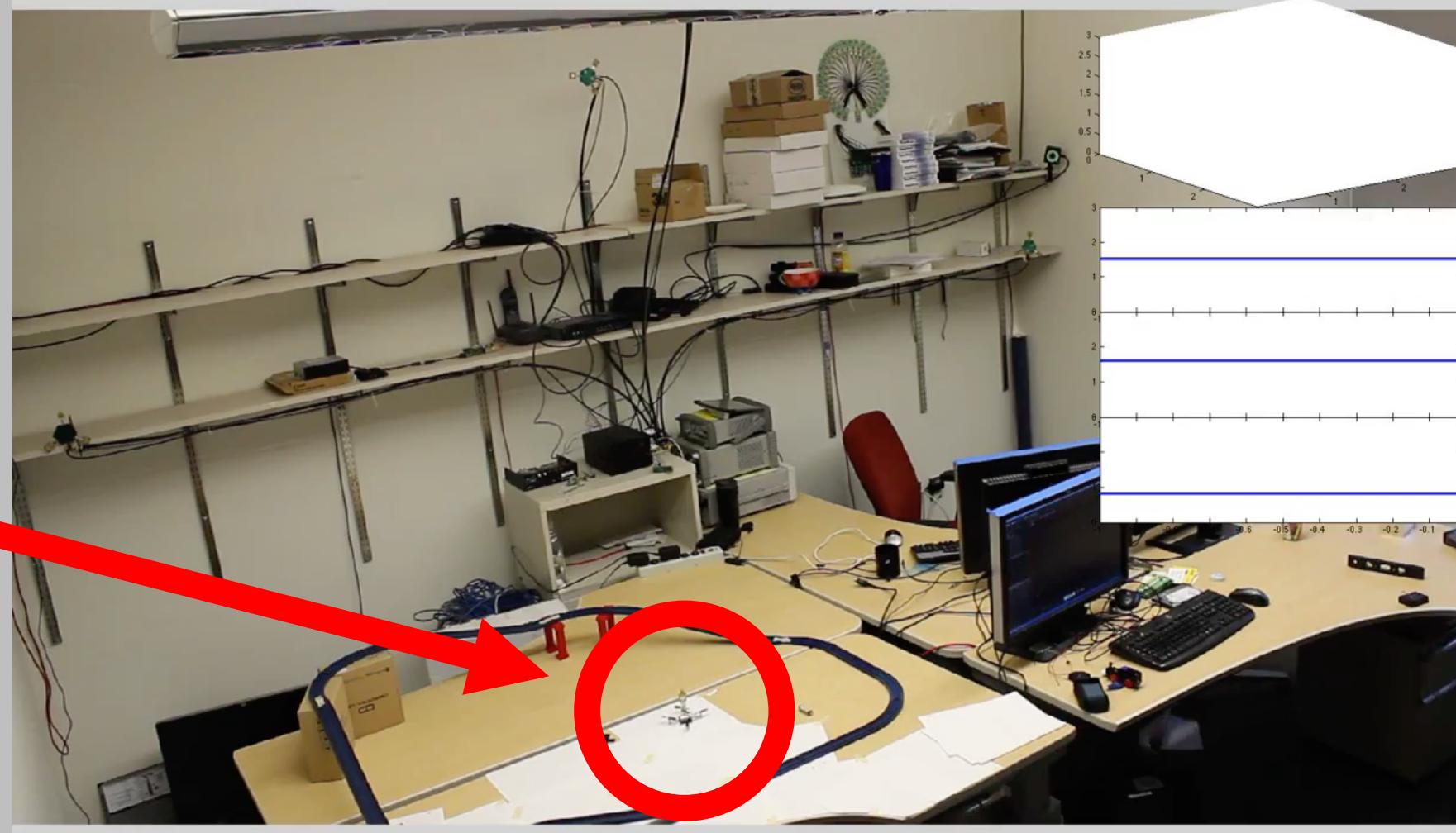
- High-quality indoor localization



The CrazyFlie Nano

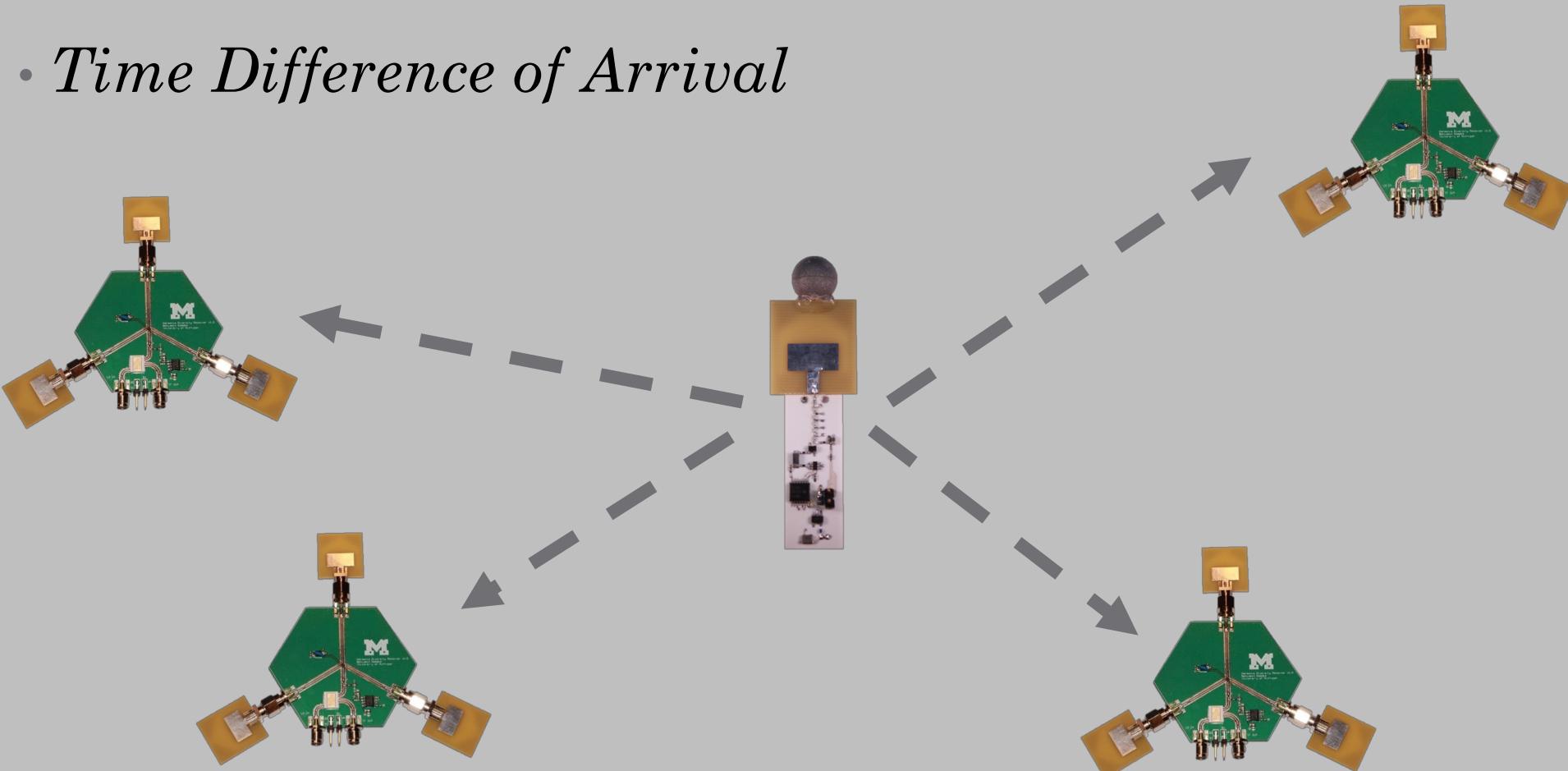
Fast ( $> 1$  m/s), small (5 g payload), flying machine

# Harmonium tracks microquadrotors in real time with 14 cm accuracy



# How does Harmonium do it?

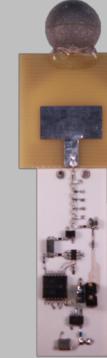
- *Time Difference of Arrival*



# What makes Harmonium different?

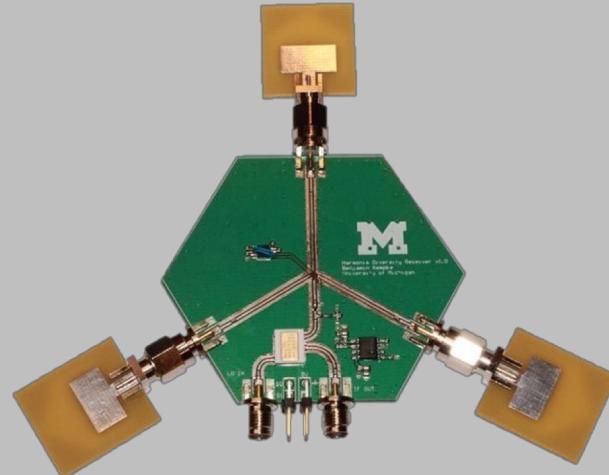
- Pushes most complexity from the node to localize to fixed infrastructure

- Tags are:
  - *Inexpensive*
  - *Low-power*
  - *Lightweight*



- Harmonium solves the shortcomings of current RF localization technologies

- Achieves *high accuracy* in *multipath-rich* environments
- Receiver uses *well-studied* traditional narrowband architecture
- Composed of only *common, off-the-shelf* components



# Why Bother with Indoor Localization Anyway?

- Autonomous Robotics



<http://www.irobotweb.com/~/media/Images/iRobot/Robots/HRD/Roomba/600%20Series/Anatomy/irobot-roomba-600-sideview.jpg?h=397&la=en&w=663>



[http://i.cbc.ca/1.2447541.1385989501!/fileImage/httpImage/image.jpg\\_gen/derivatives/16x9\\_620/amazon-drone.jpg](http://i.cbc.ca/1.2447541.1385989501!/fileImage/httpImage/image.jpg_gen/derivatives/16x9_620/amazon-drone.jpg)

- Asset Tracking



[https://farm2.staticflickr.com/1313/556806349\\_e38a6a2668\\_b\\_d.jpg](https://farm2.staticflickr.com/1313/556806349_e38a6a2668_b_d.jpg)



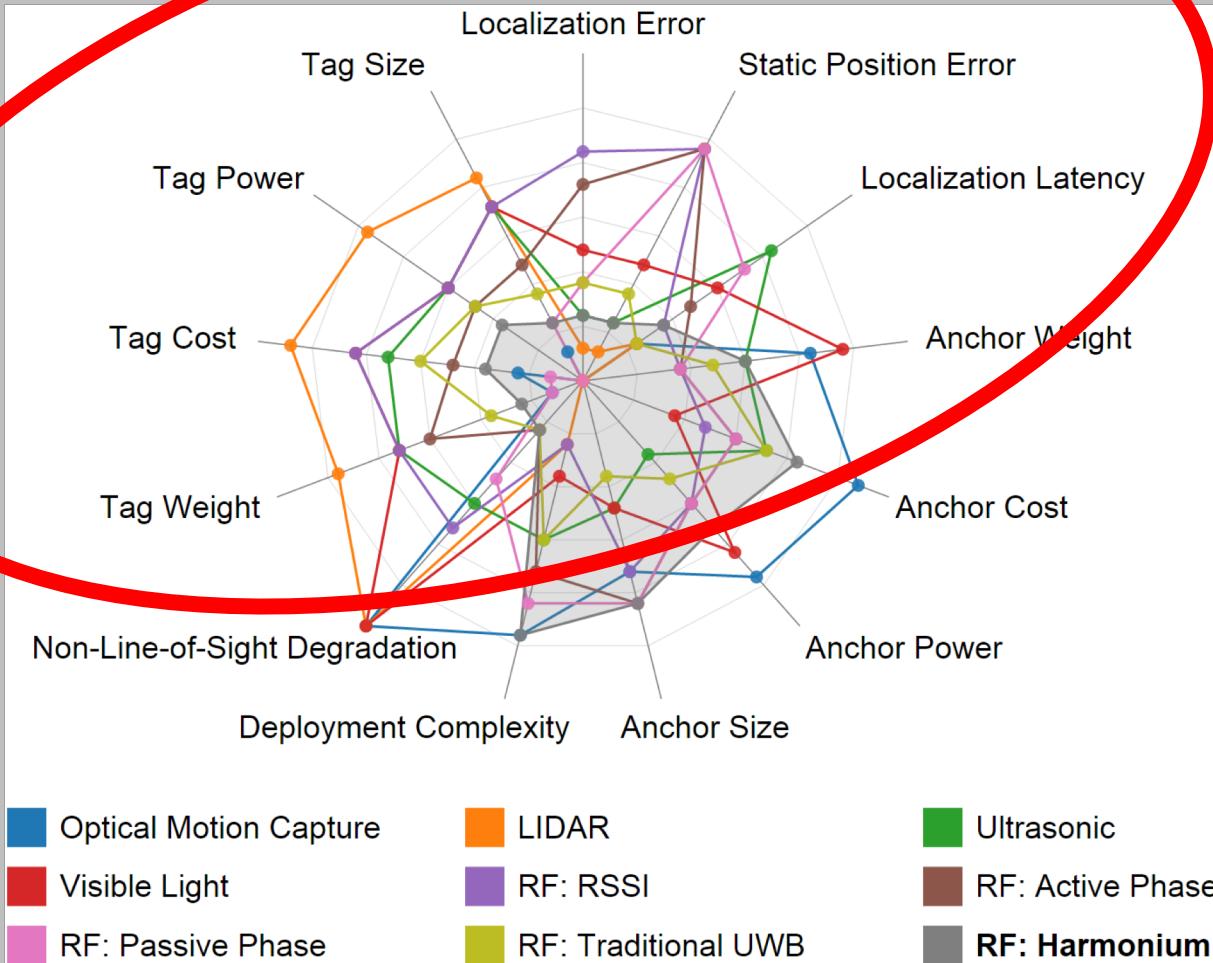
<http://cdn.wonderfulengineering.com/wp-content/uploads/2013/06/Amazon-warehouse.jpg>

- Location Attestation



[http://i.dailymail.co.uk/i/pix/2012/07/16/article-2174271-14150BDF000005DC-987\\_634x372.jpg](http://i.dailymail.co.uk/i/pix/2012/07/16/article-2174271-14150BDF000005DC-987_634x372.jpg)

# Hasn't indoor localization been done before? Why Harmonium?

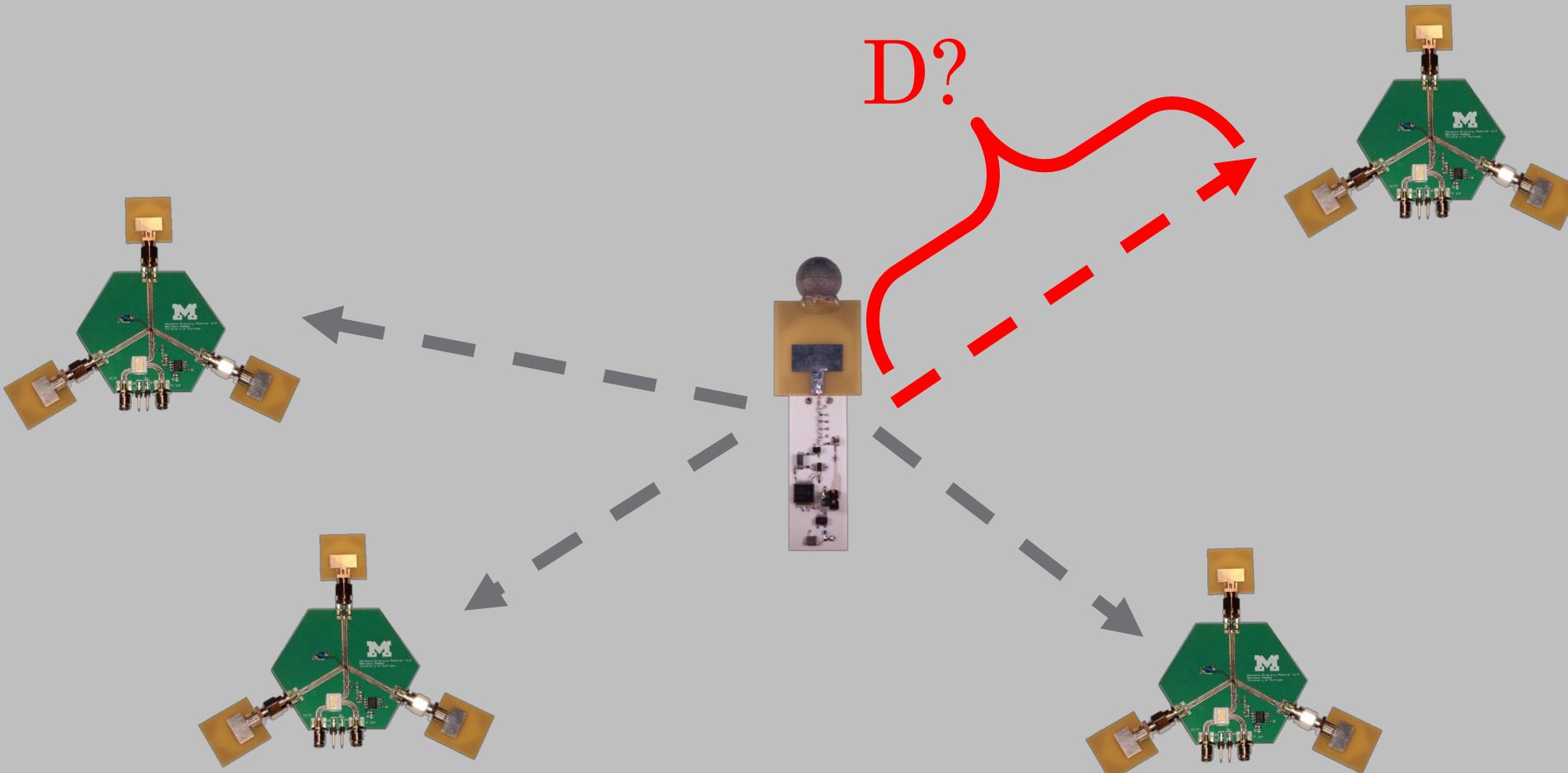


Harmonium prioritizes

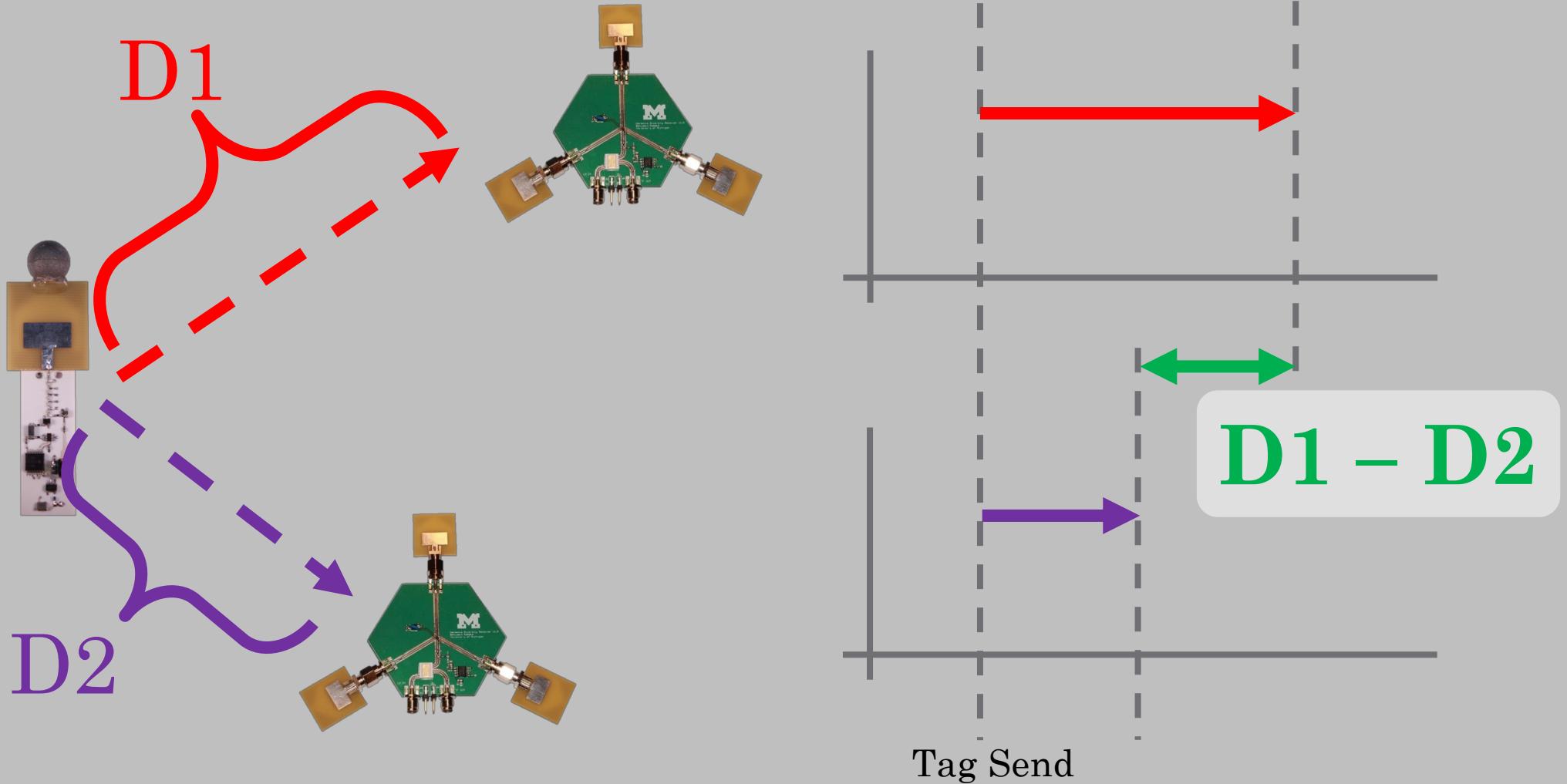
- Location quality
- Tag Simplicity

At the cost of anchor complexity

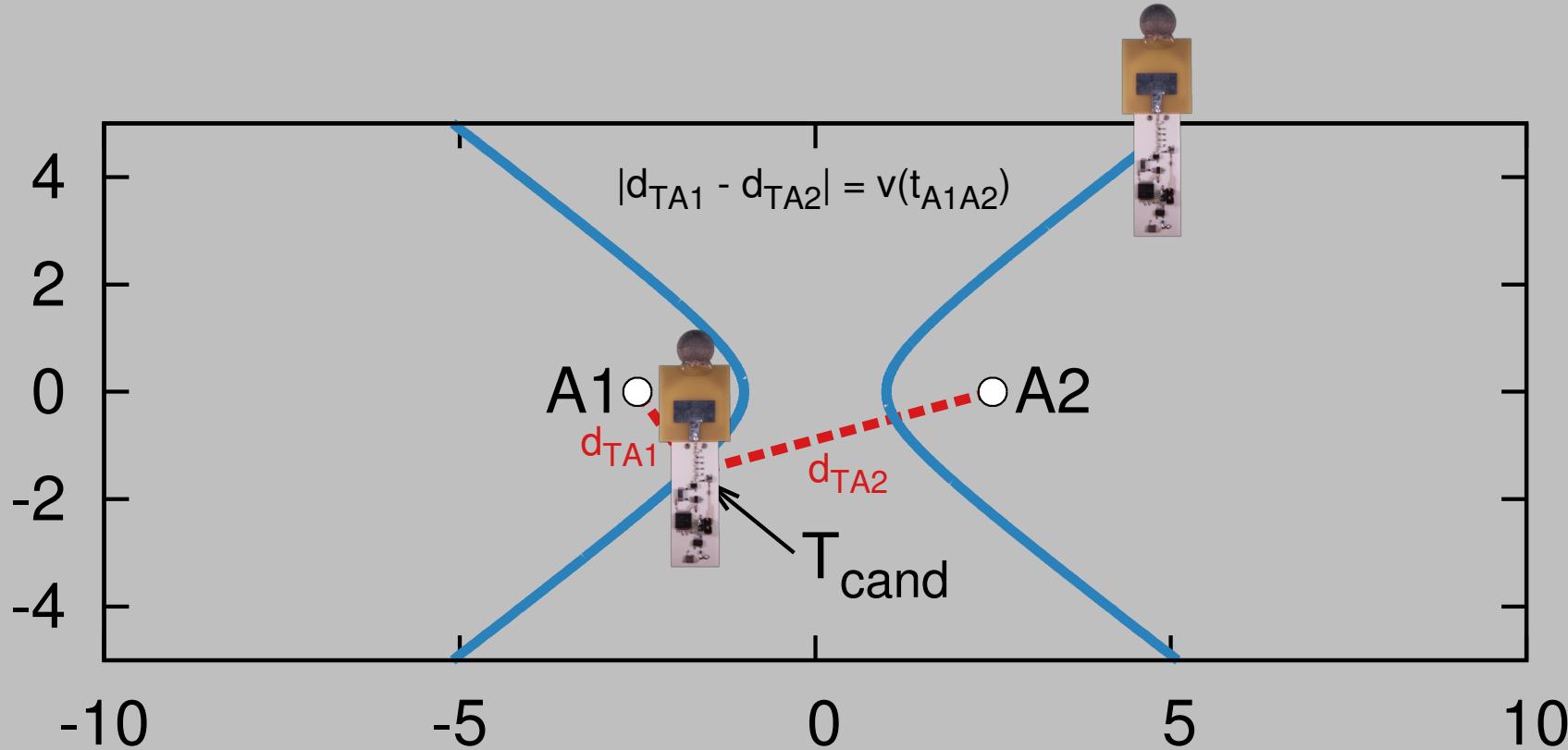
# So, how does Harmonium do it?



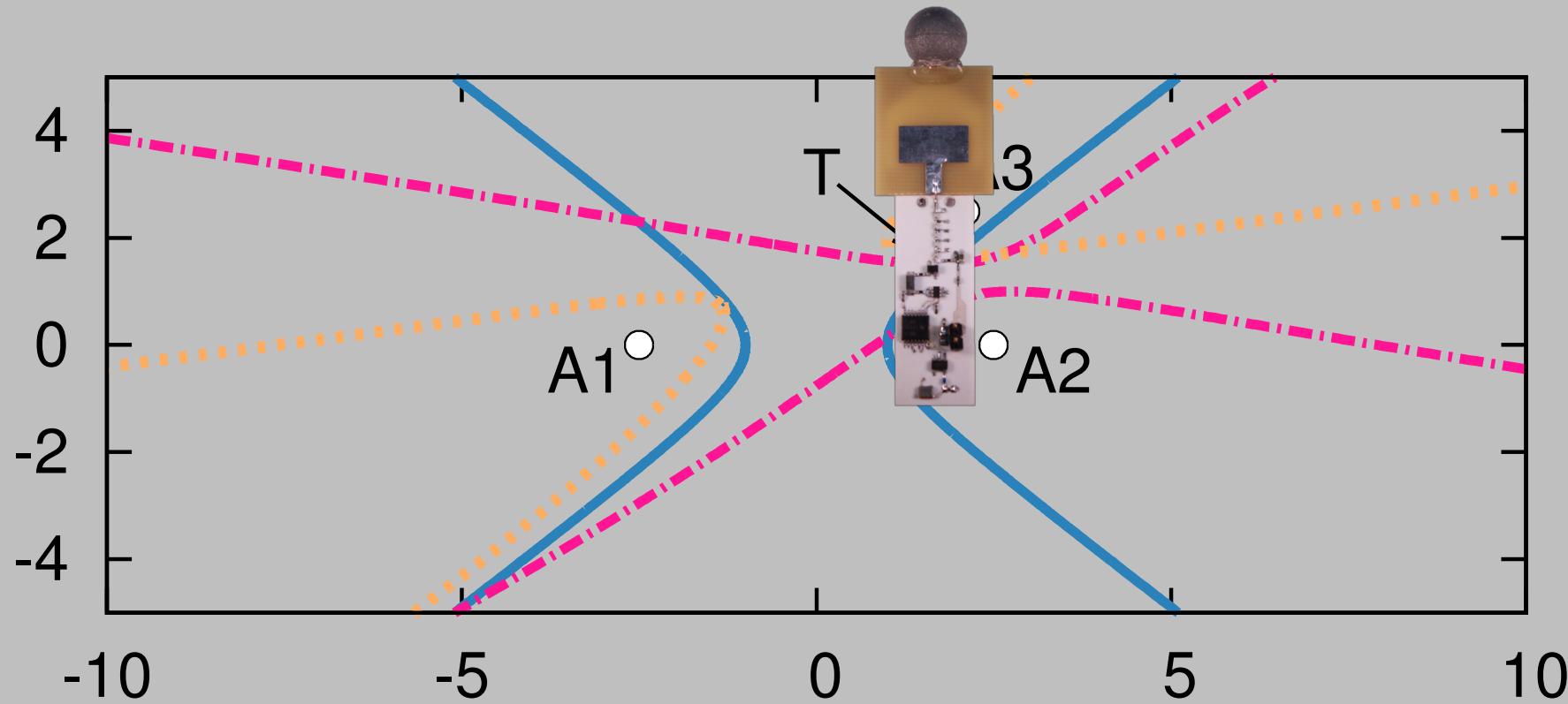
# Harmonium measures the Time Difference of Arrival



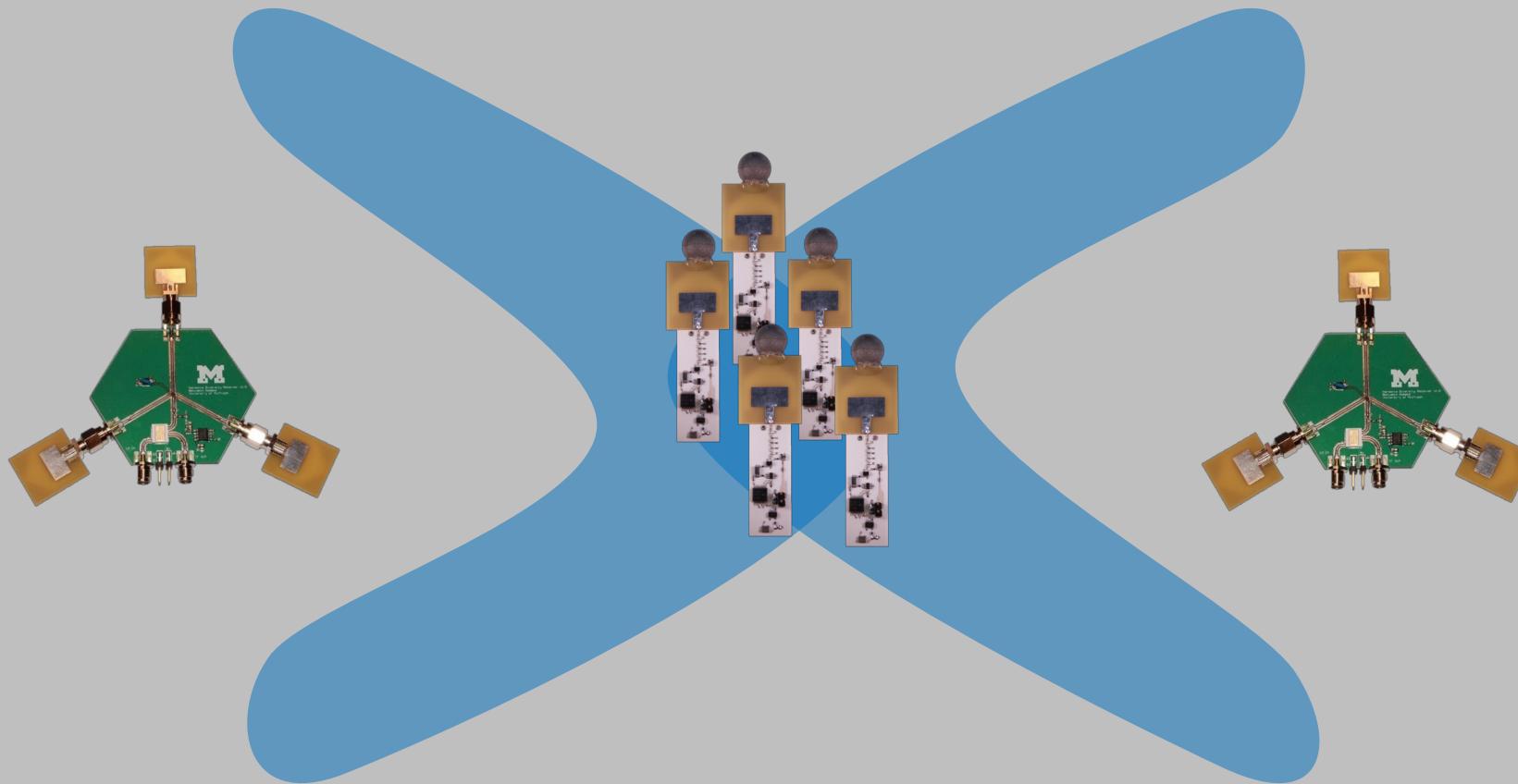
# Multilateration: Time-Difference-of-Arrival to Location



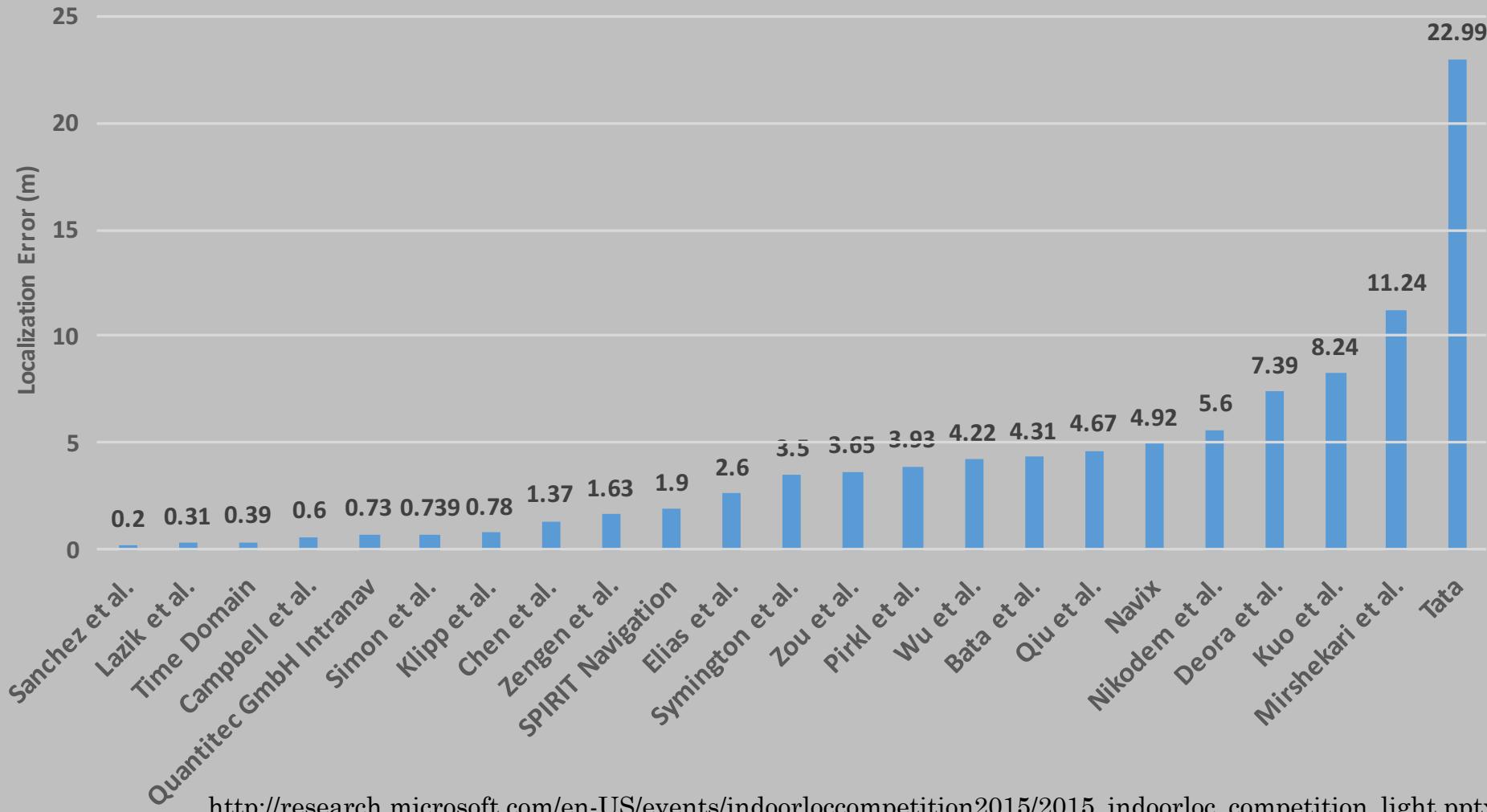
# Multilateration: Time-of-Arrival to Location



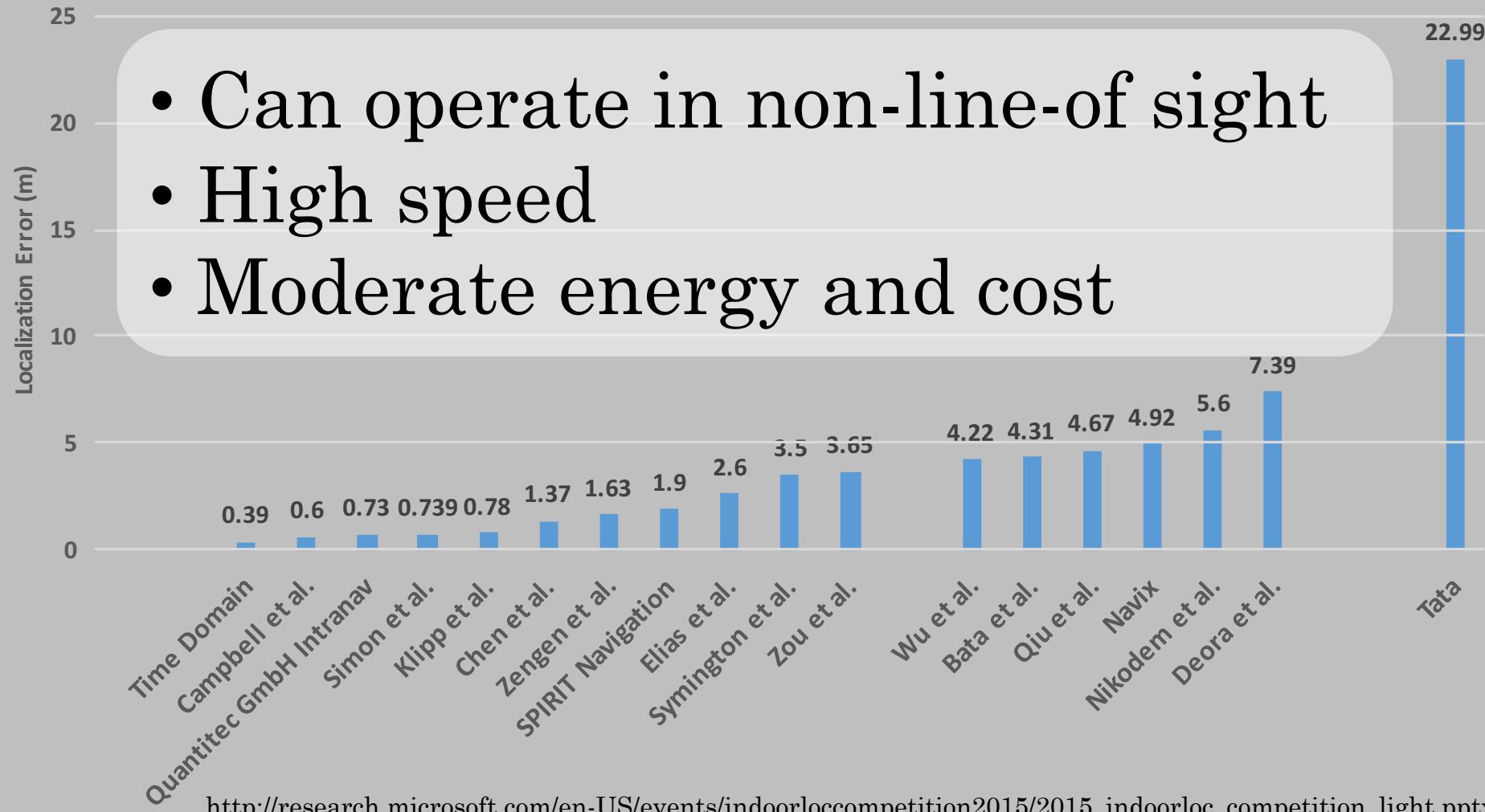
In the real world, it is hard to accurately measure these distances



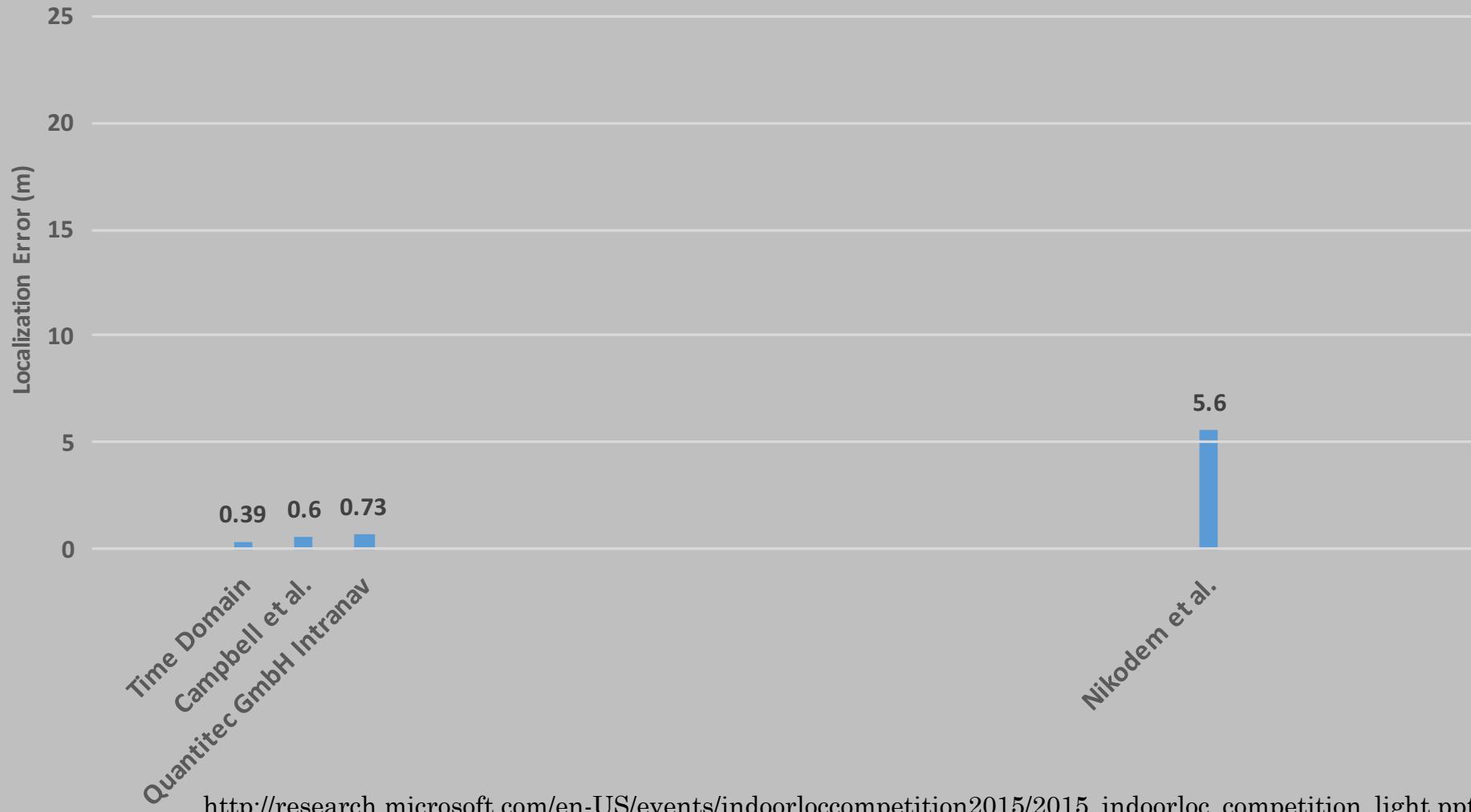
# IPSN'15 Microsoft Indoor Localization Competition: A strong indicator of localization performance



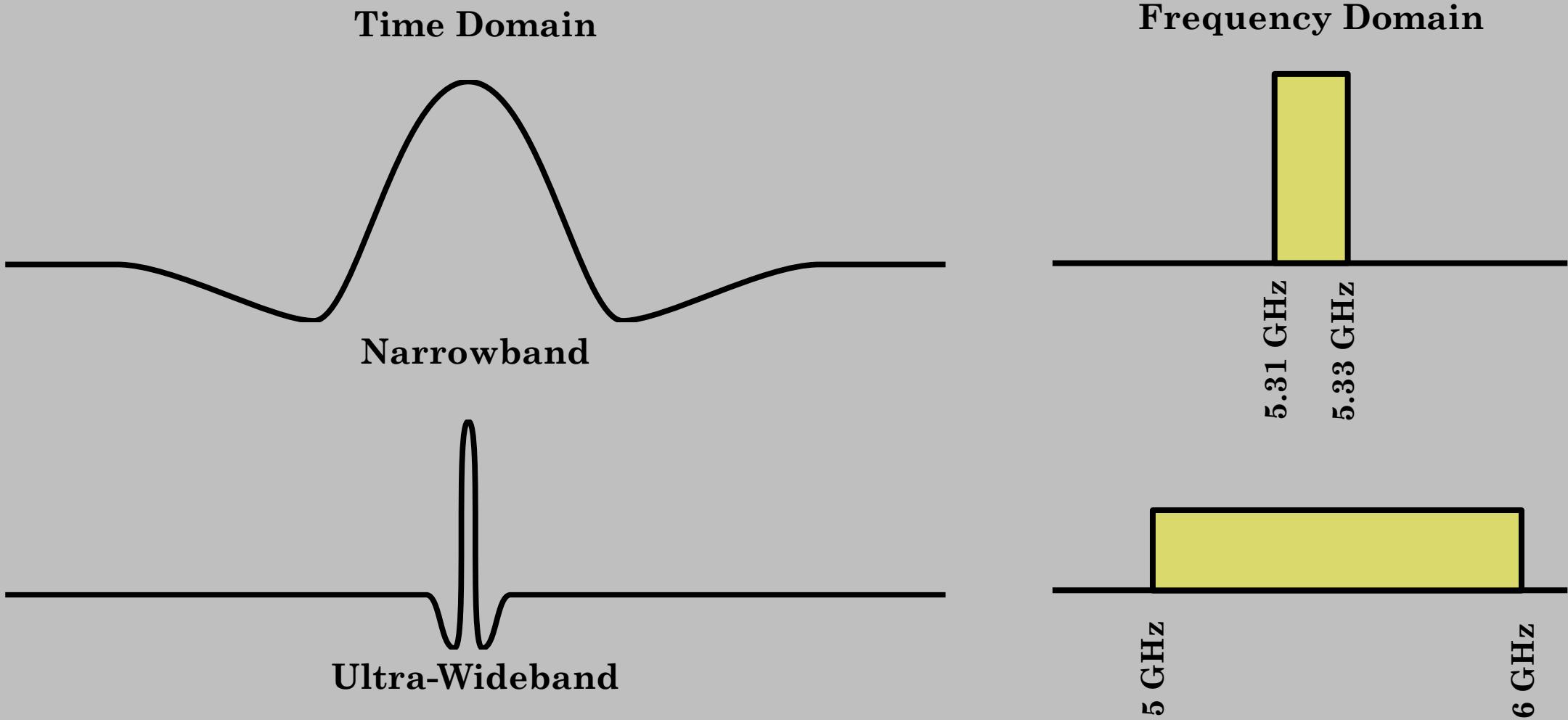
# The majority of indoor localization systems use RF



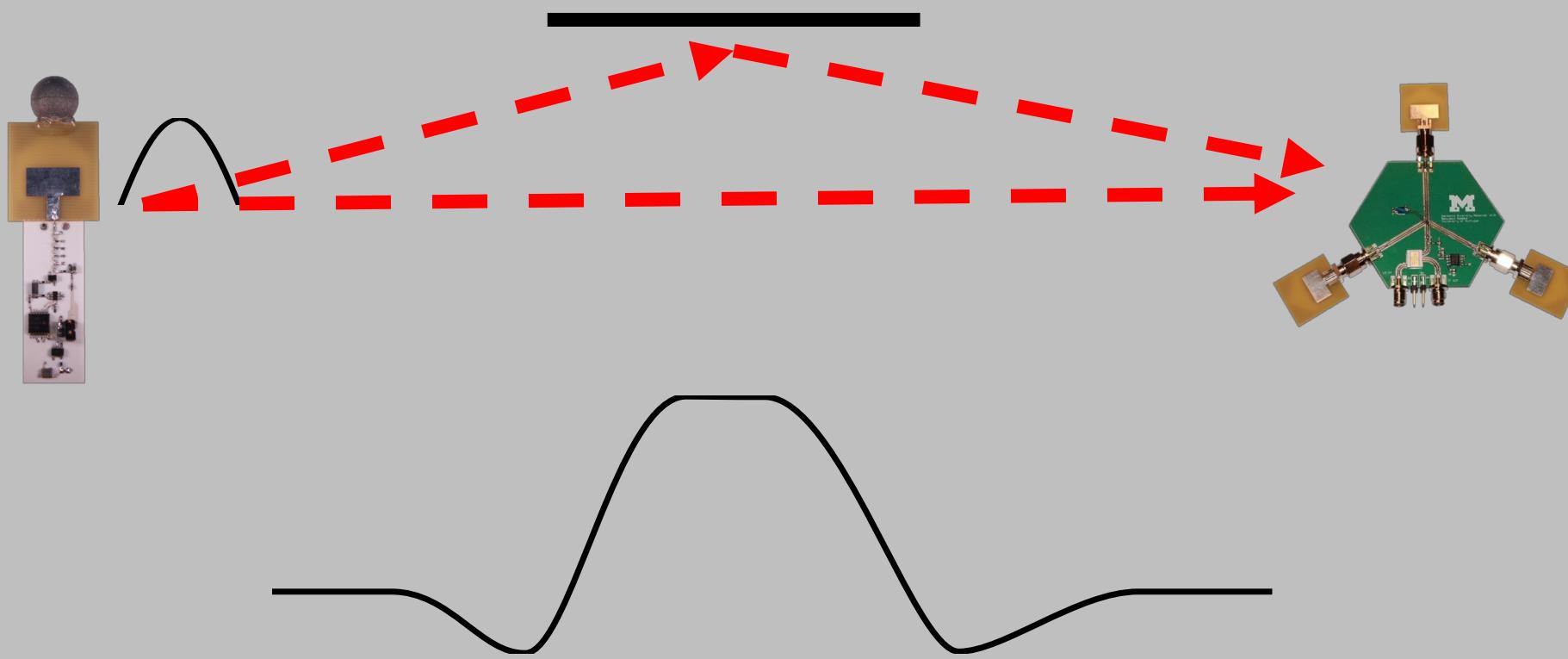
# And the best RF-based systems use Ultra-Wideband (UWB)



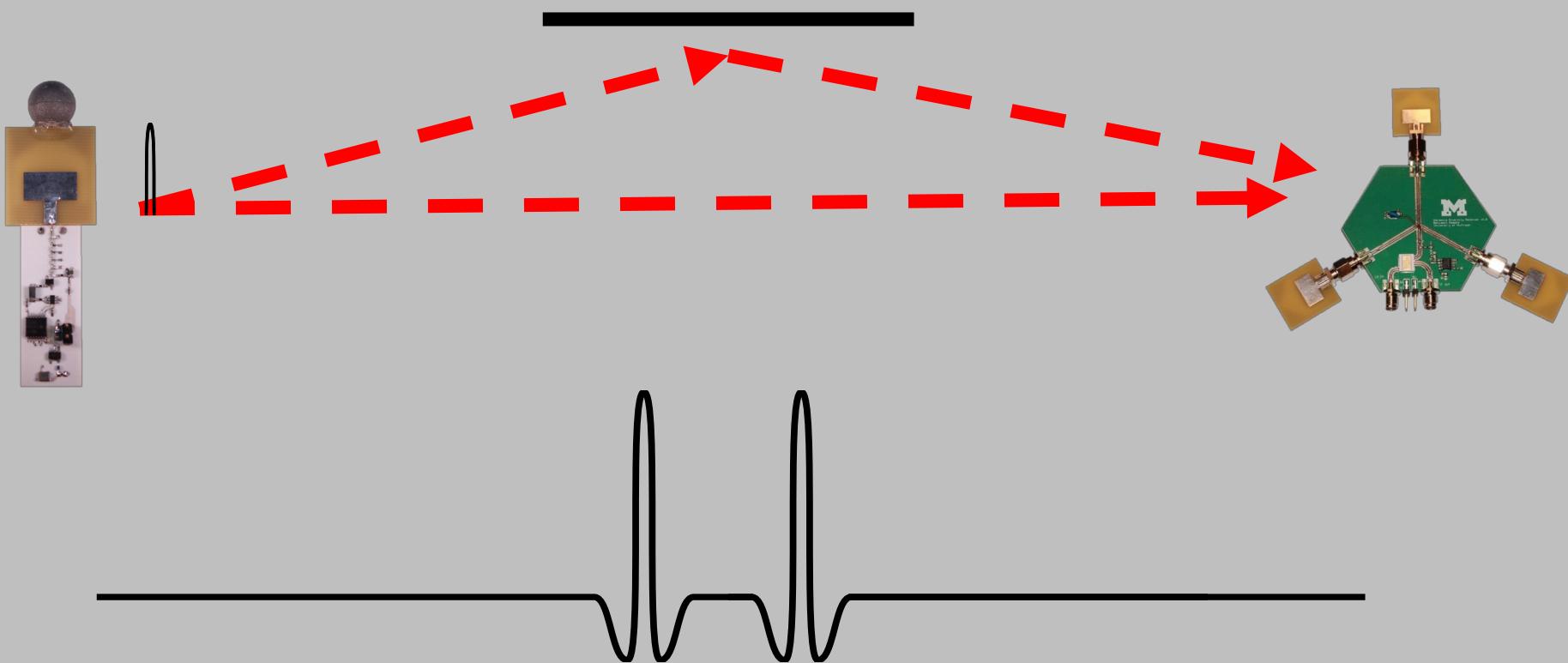
# What is Ultra-Wideband?



# Why does ultra-wideband give better range estimates?



# Why does ultra-wideband give better range estimates?



# If we want to use UWB today, what's available?

- Commercial RTLS
- 802.15.4a Transceiver (DecaWave)



TimeDomain P440



Ubisense Research Package



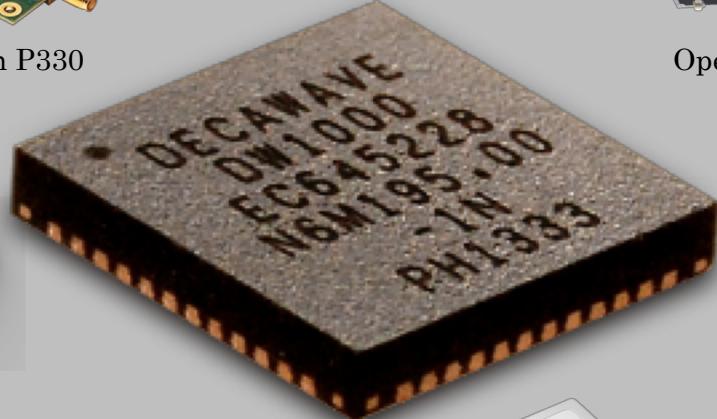
TimeDomain P330



Sewio



OpenRTLS



Pixie



Pozyx



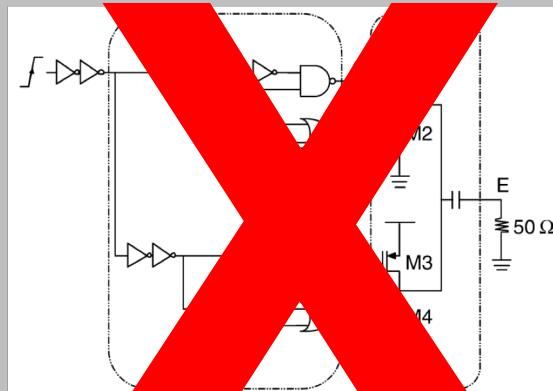
Ciholas DWUSB



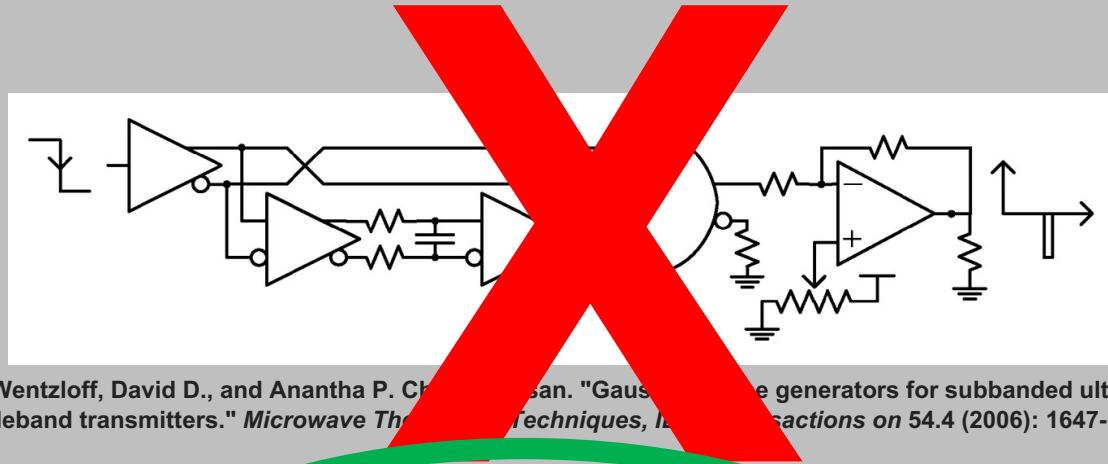
Redpoint Positioning

# What if we want to build our own UWB transmitter?

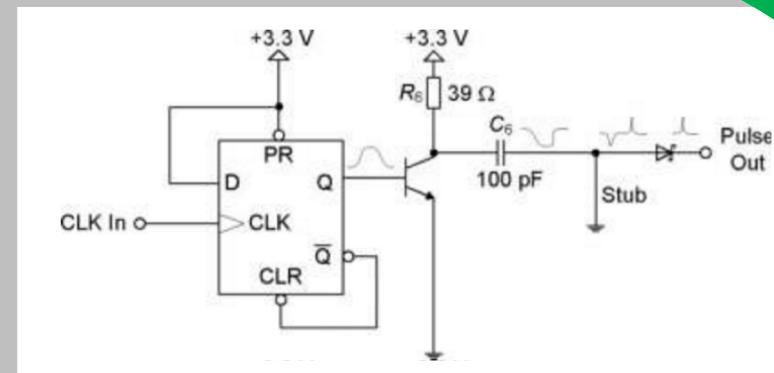
- Major types
  - High-Speed Comparators
  - SRD-Based
  - CMOS
  - BJT-Based



Kim, Hyunseok, D. Kim, and Y. Joo. "All-digital low-power CMOS pulse generator for UWB system." *Electronics Letters* 40.24 (2004): 1.



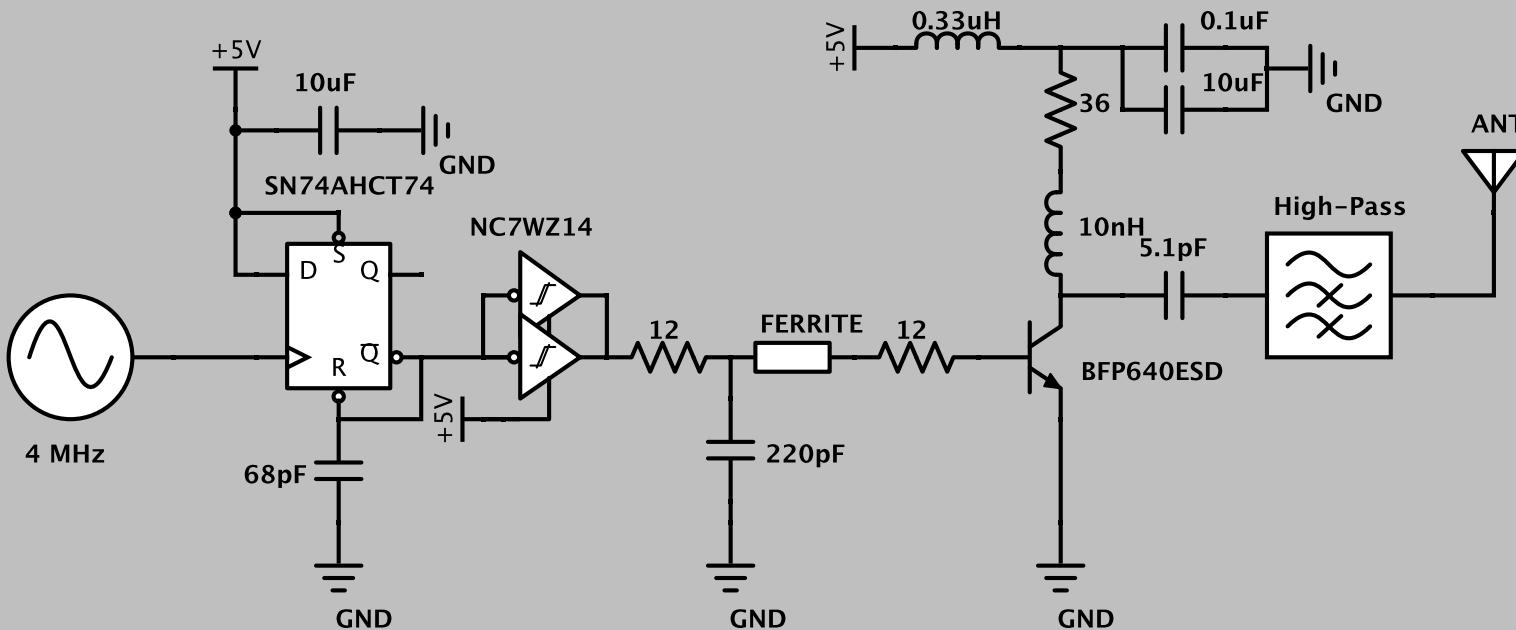
Wentzloff, David D., and Anantha P. Chandrakasan. "Gaussian pulse generators for subbanded ultra-wideband transmitters." *Microwave Theory and Techniques, IEEE Transactions on* 54.4 (2006): 1647-1655.



Hantscher, Sebastian, et al. "Hardware concepts for the sequential sampling of repetitive pulse radar echoes in cost-efficient ultra-wideband transceivers." *Microwave and Optical Technology Letters* 52.3 (2010): 585-591.

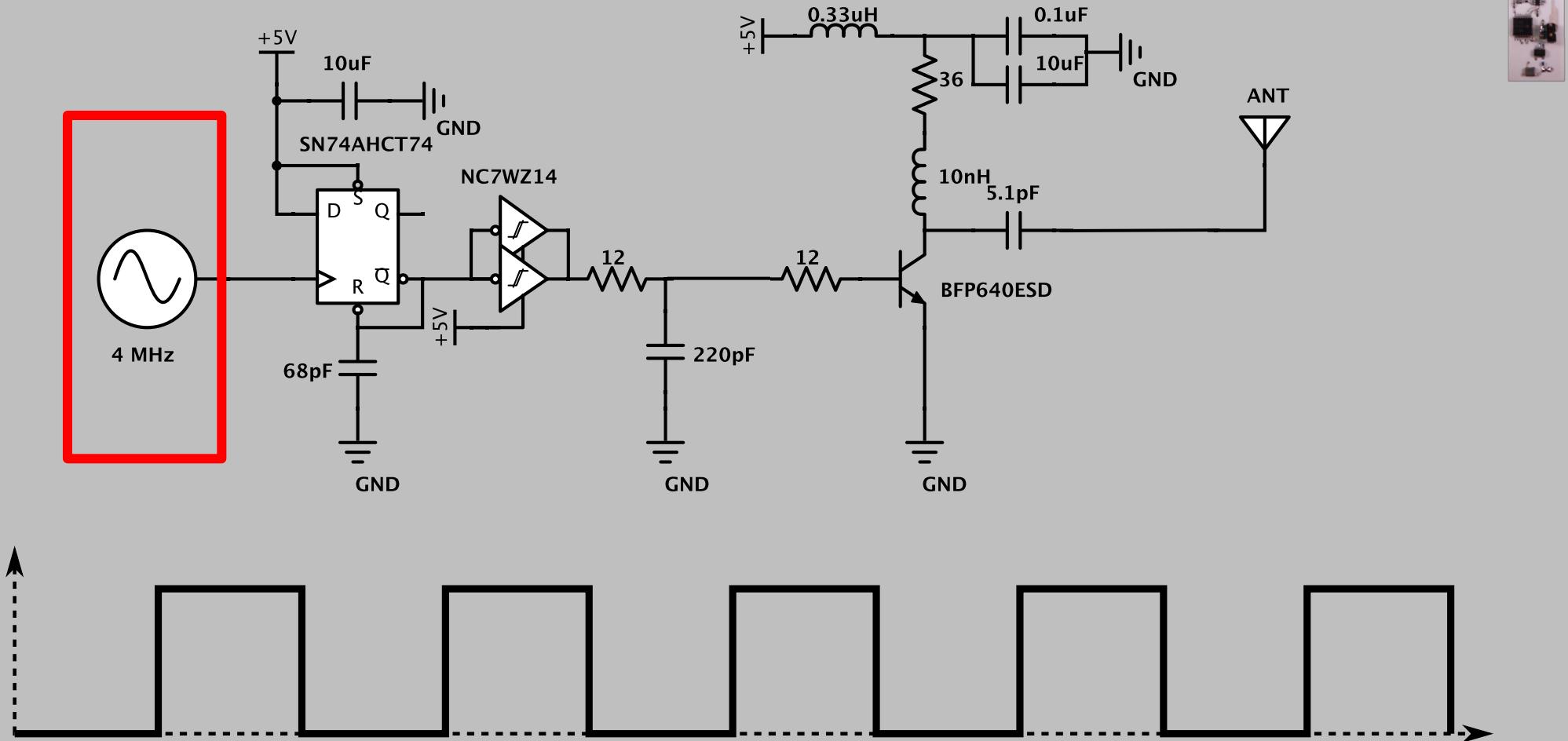
# Harmonium: The Tag

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

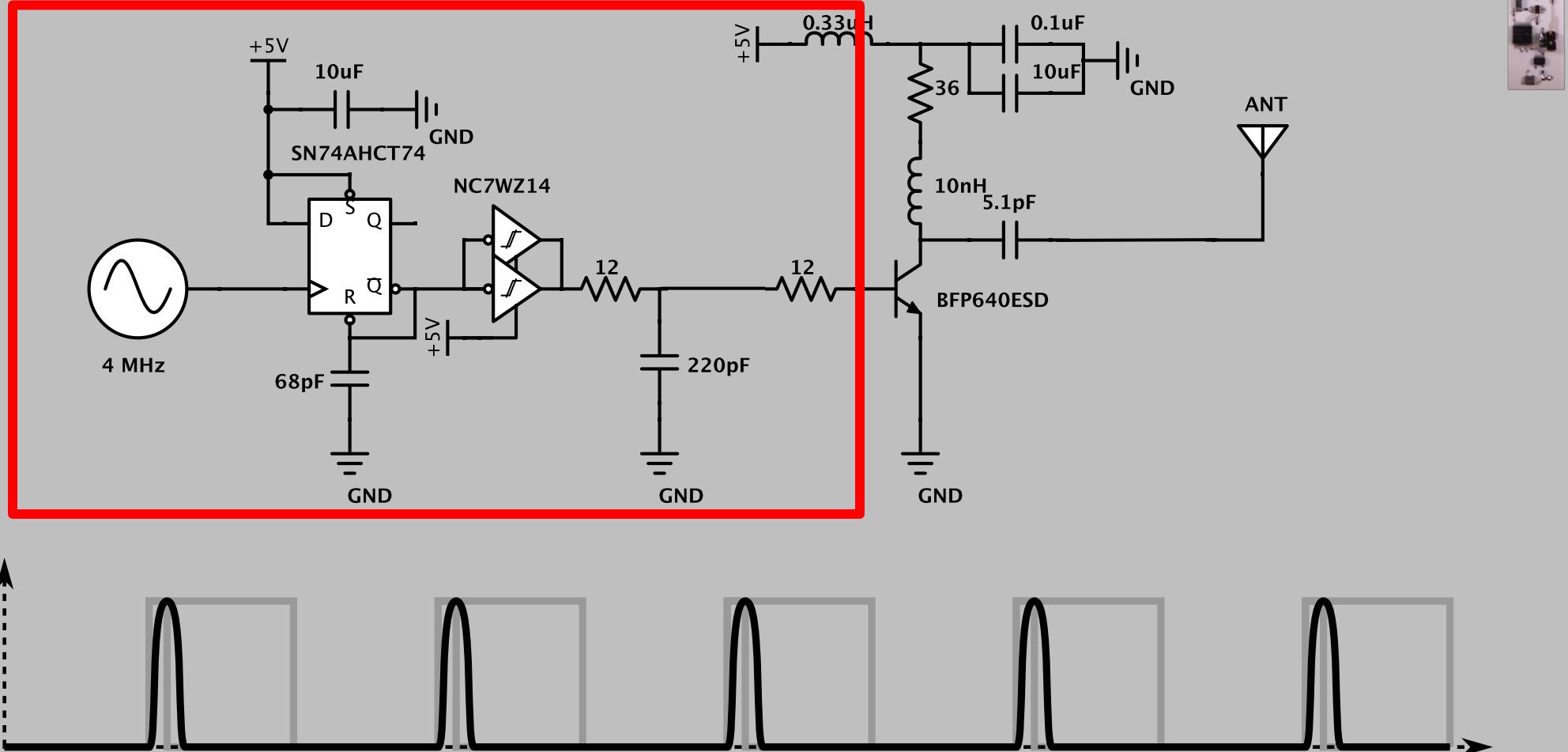


- Tag specs:
  - Pure COTS design
  - \$4.50 in modest quantity
  - 75 mW active power

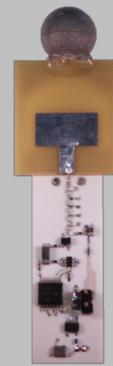
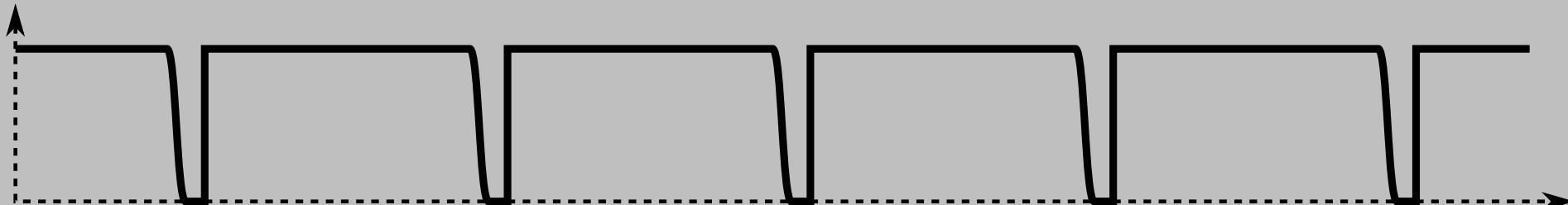
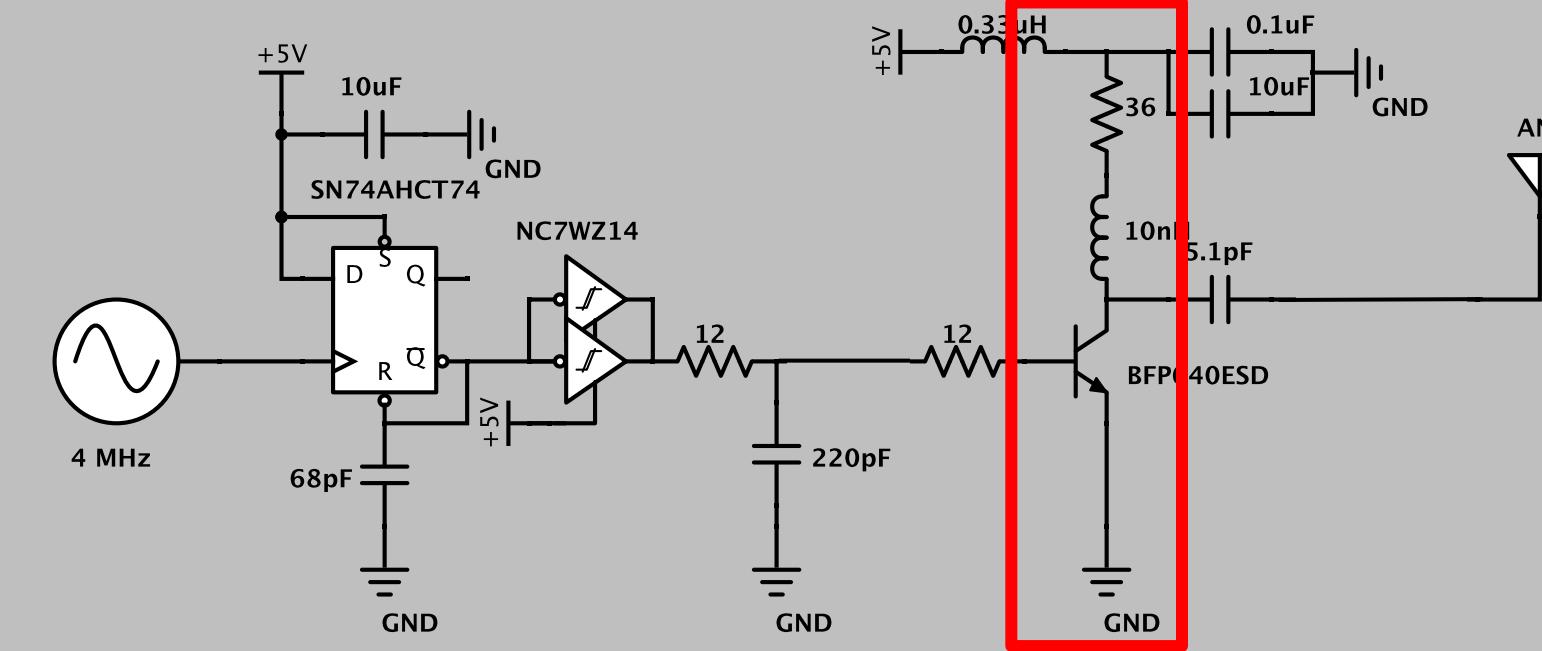
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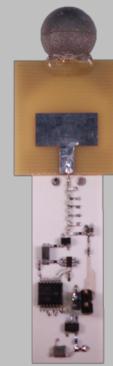
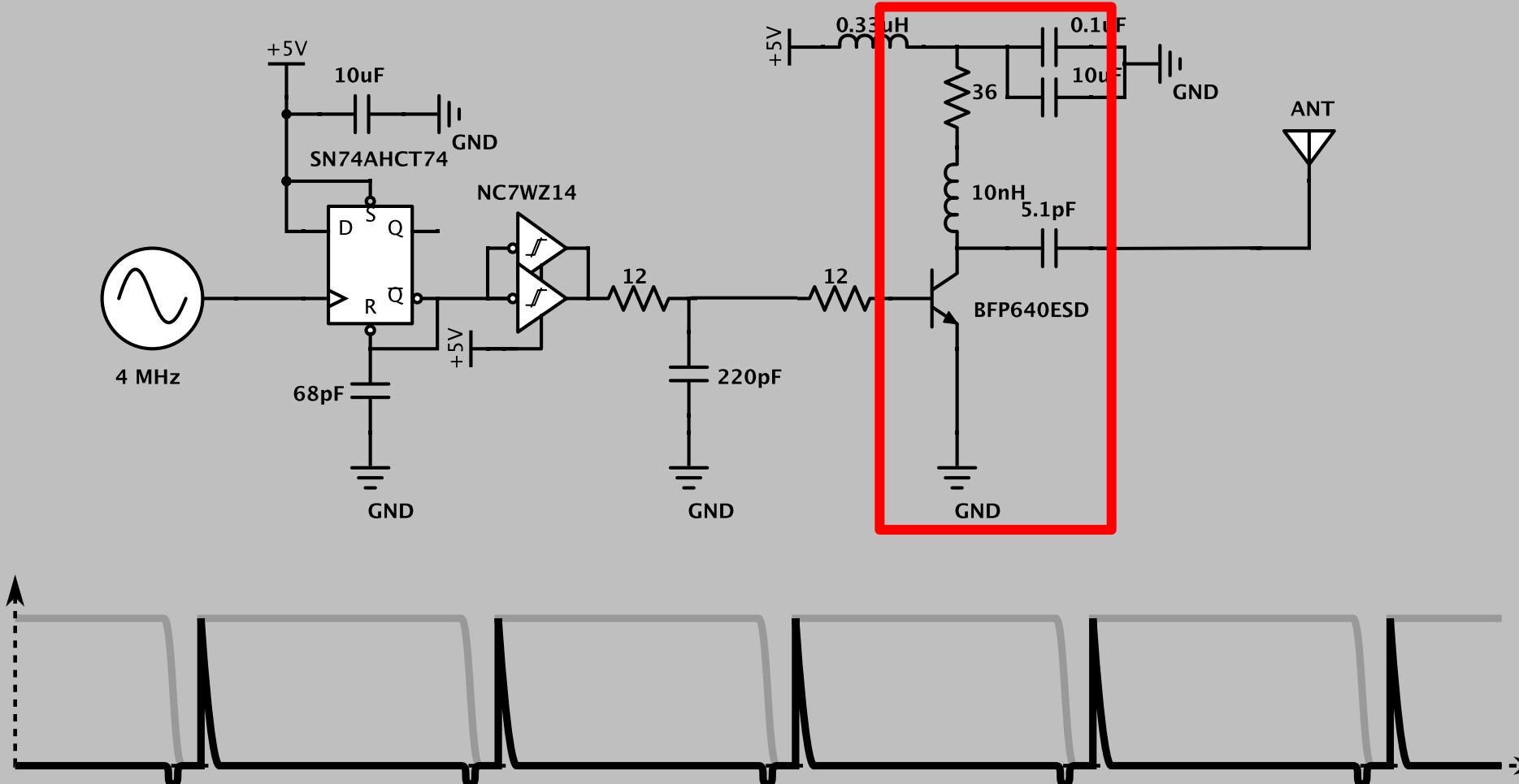
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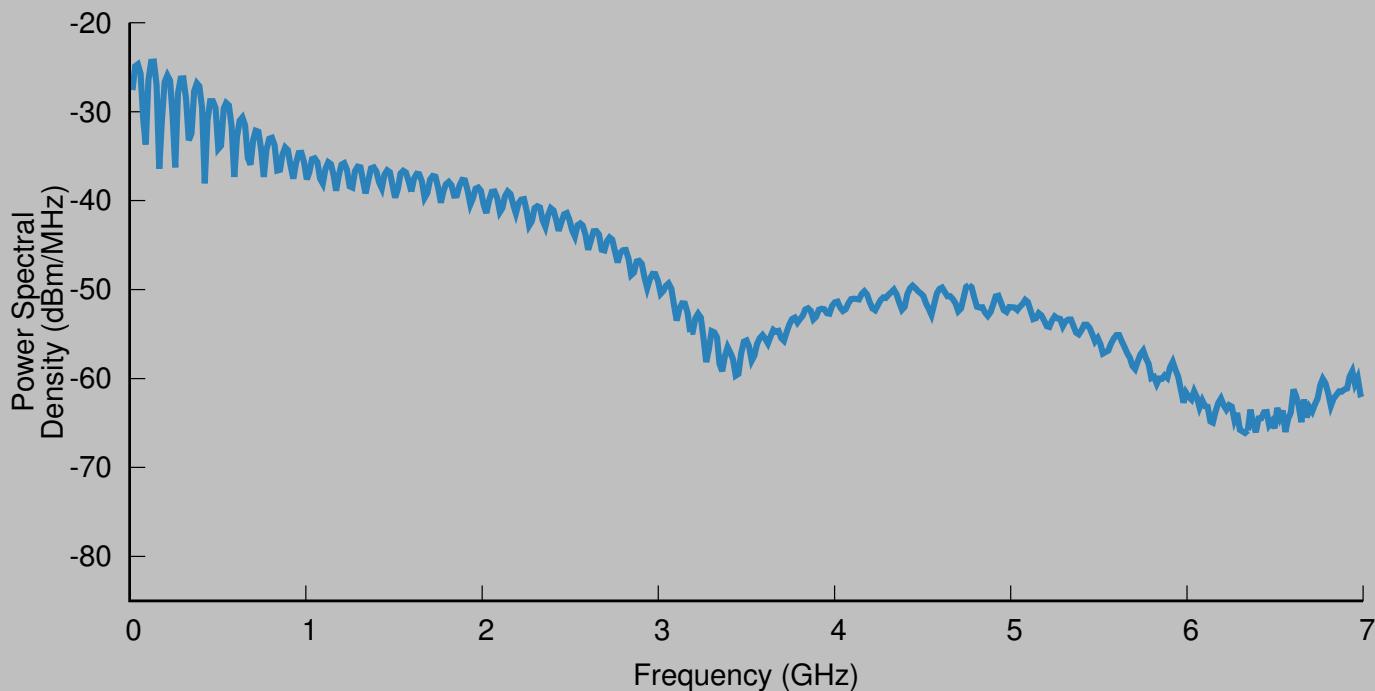
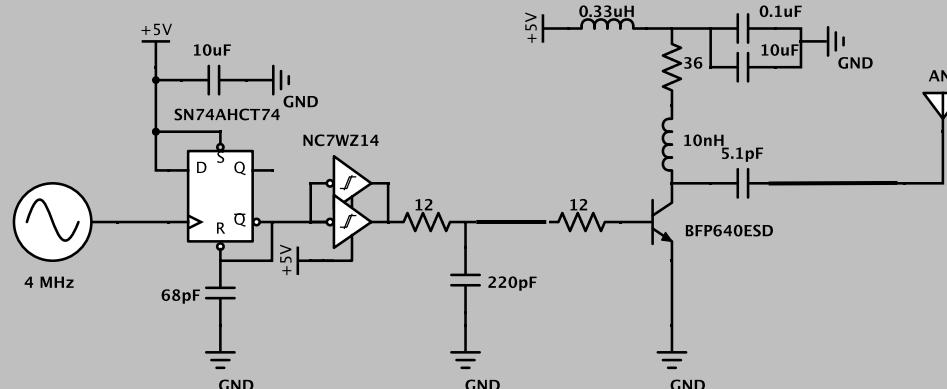


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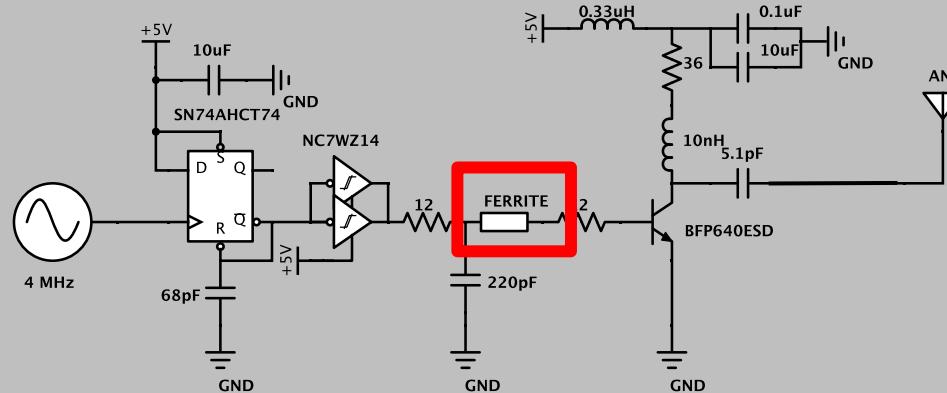
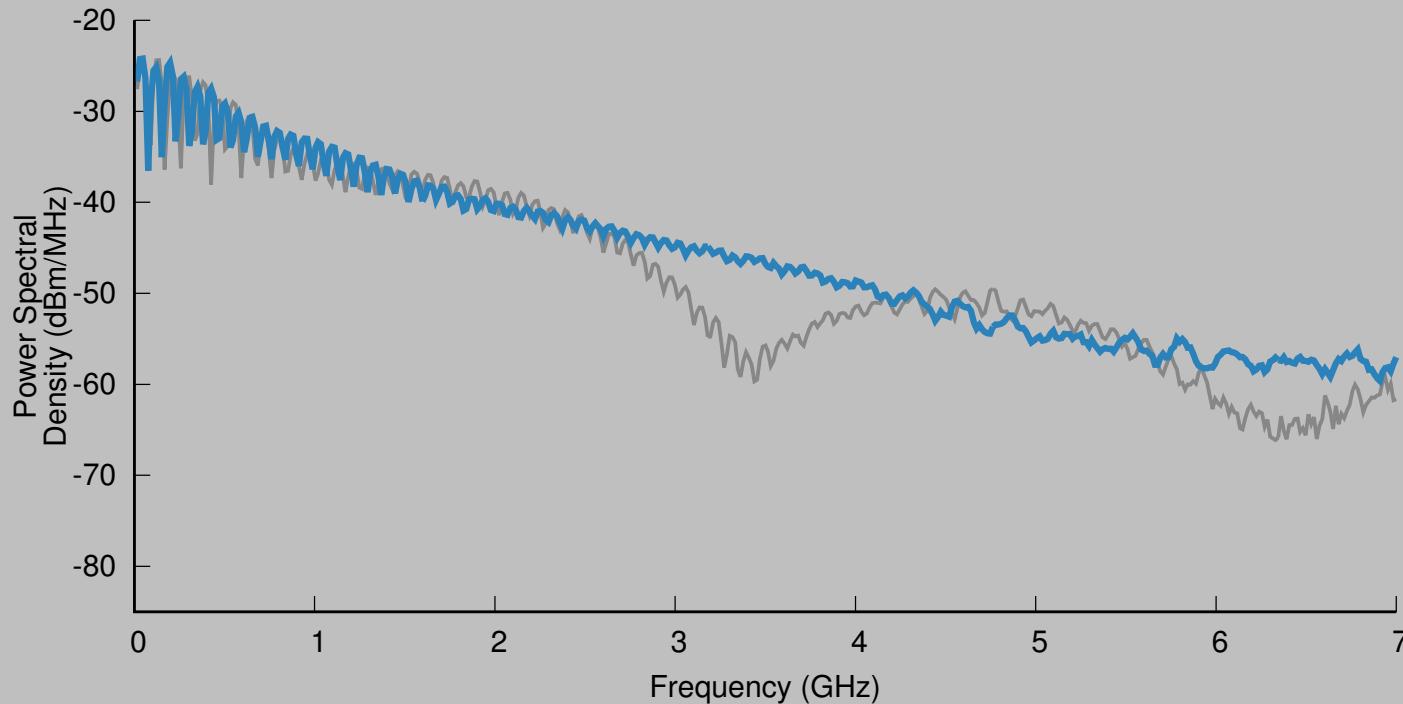
# Harmonium Tag: The Need for Filtering

Pulse w/o filtering



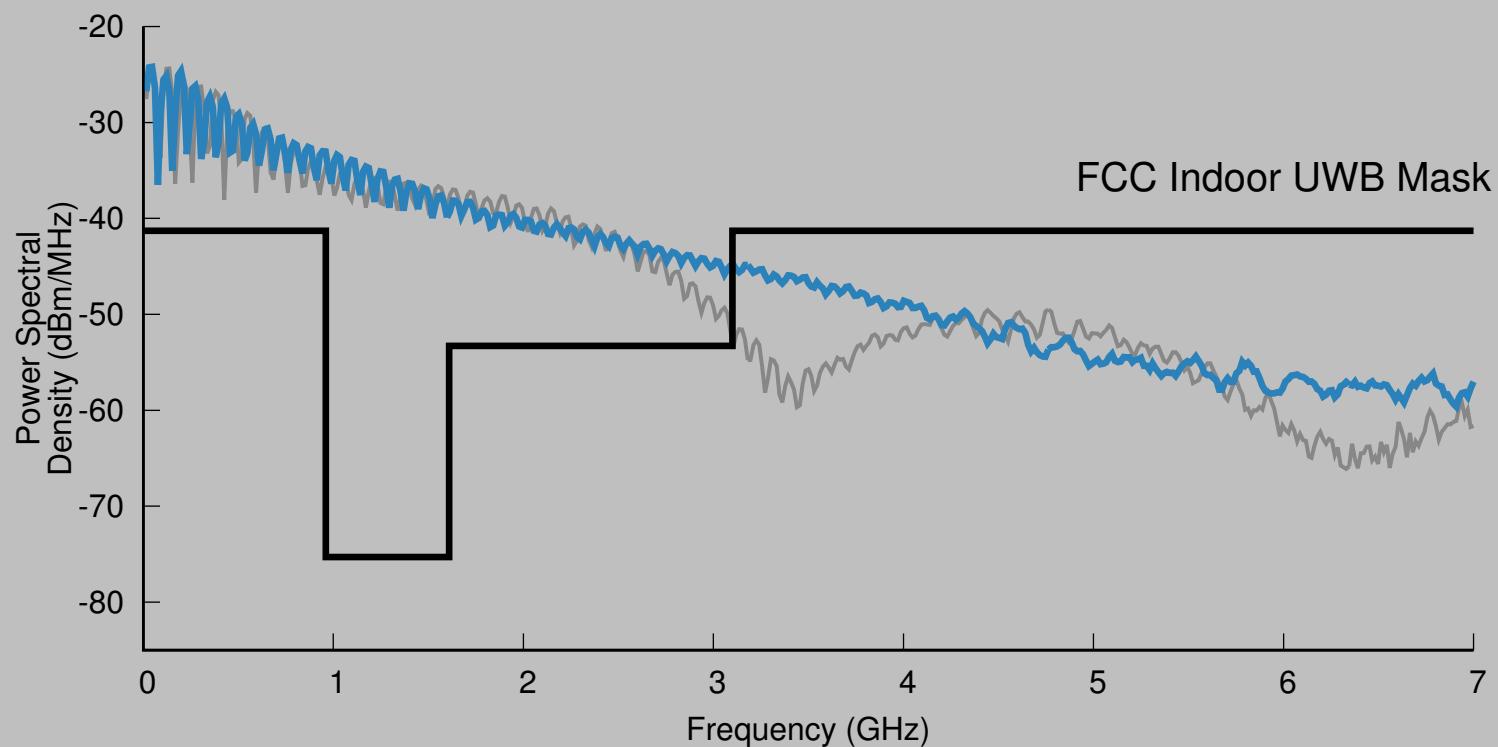
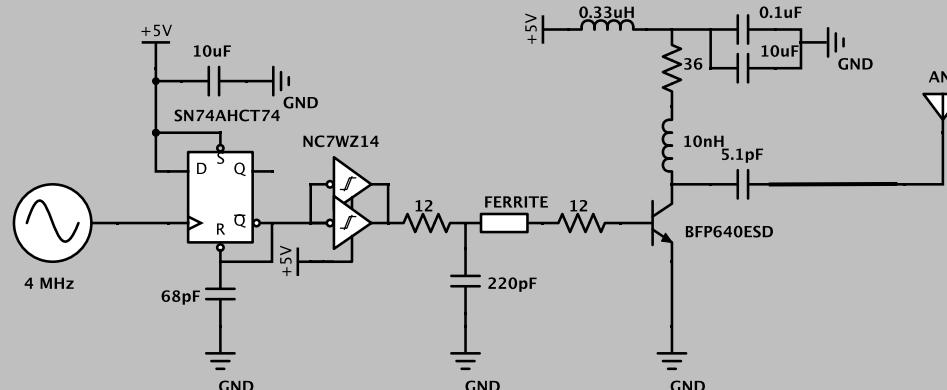
# Harmonium Tag: The Need for Filtering

Pulse w/o filtering  
→ Pulse w/ trigger filtering



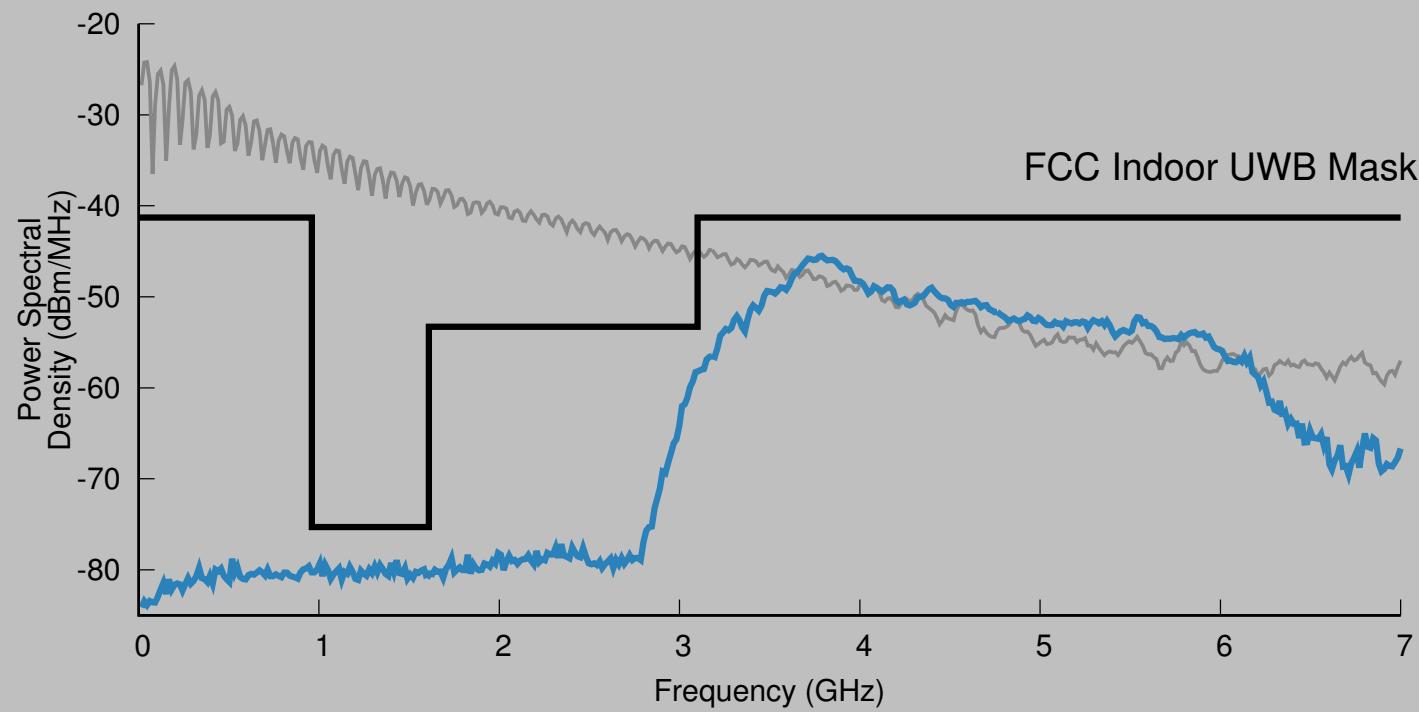
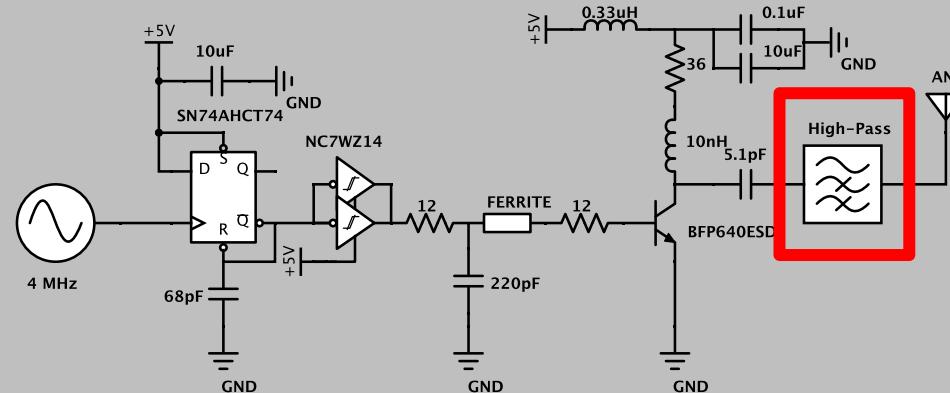
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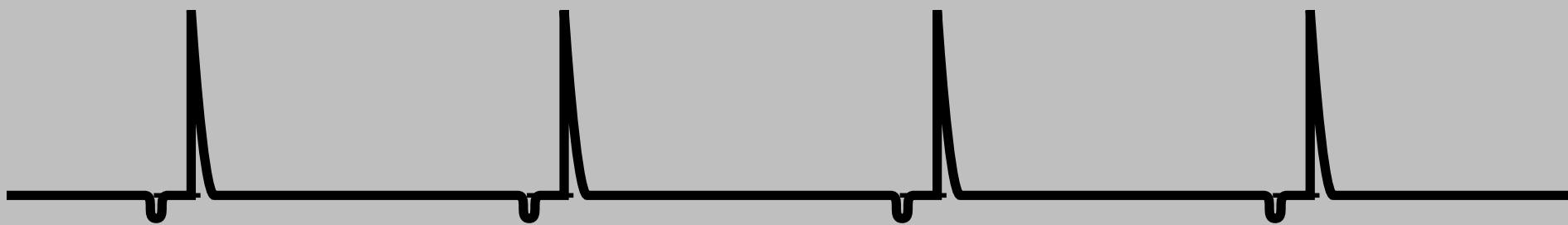


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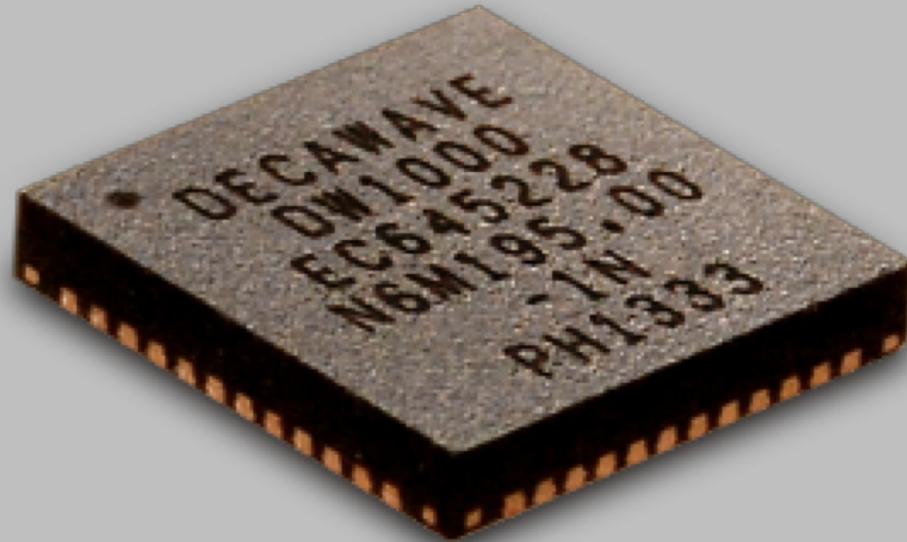
- Pulse w/o filtering
- Pulse w/ trigger filtering
- Pulse w/ shaping filter



How to measure the time of arrival of pulses from the tag?

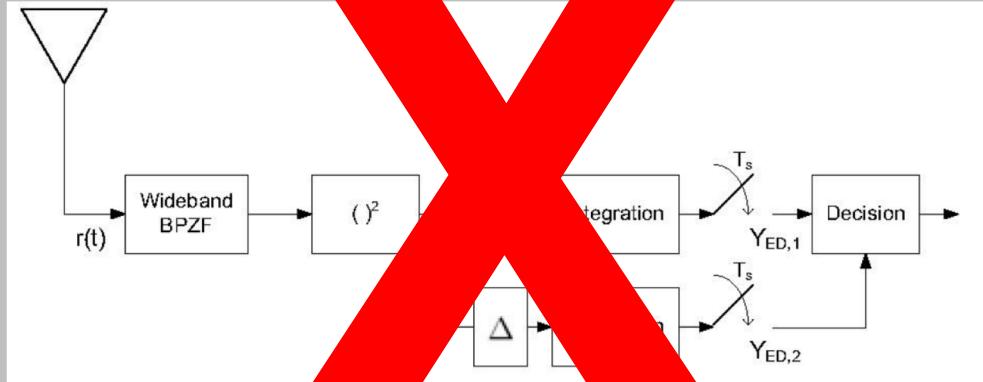


Commercial UWB receivers expect standard packets and modulation

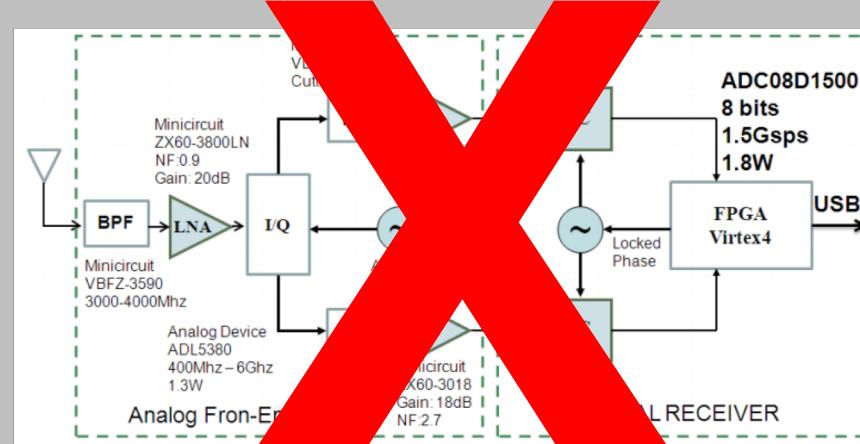


# UWB receivers from research are too expensive, noisy, or niche

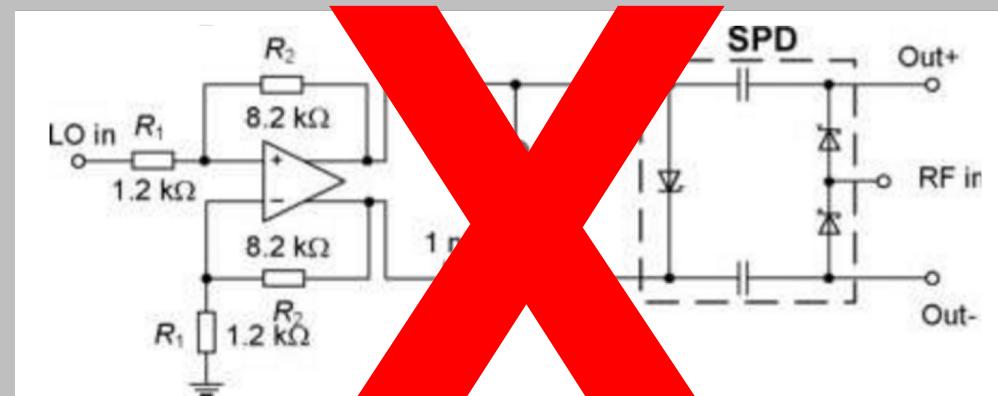
- UWB Receivers
  - High-Speed ADCs
  - Energy detection receivers
  - Sampling Receivers



Rabbachin, Alberto, et al. "UWB energy detection in the presence of multiple narrowband interferers." *Ultra-Wideband, 2007. ICUWB 2007. IEEE International Conference on*. IEEE, 2007.

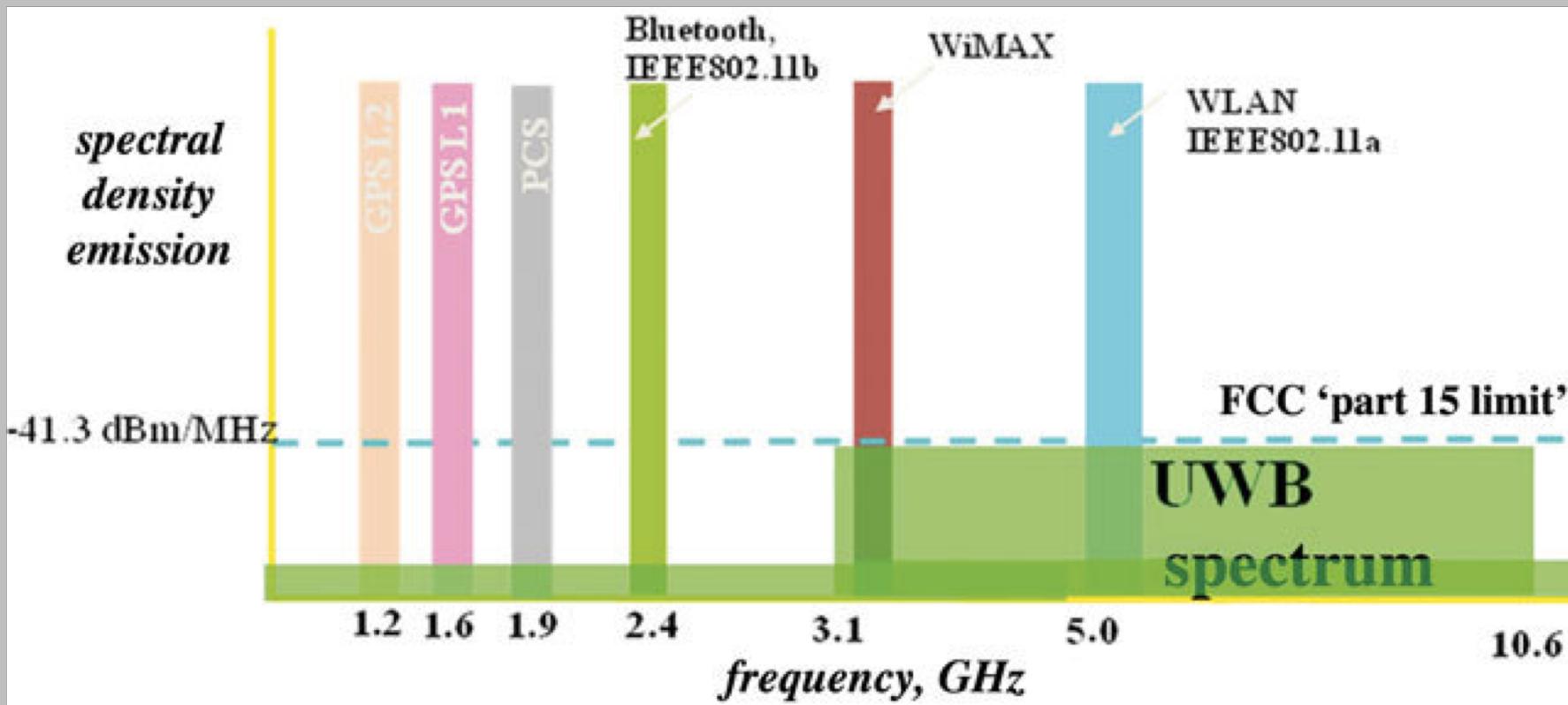


Segura, Marcelo, et al. "Experimental demonstration of self-localized ultra wideband indoor mobile robot navigation system." *Indoor Positioning and Indoor Navigation (IPIN), 2010 International Conference on*. IEEE, 2010.



Hantscher, Sebastian, et al. "Hardware concepts for sequential sampling of repetitive pulse radar echoes in cost-efficient ultra-wideband transceivers." *Microwave and Optical Technology Letters* 52.3 (2010): 585-591.

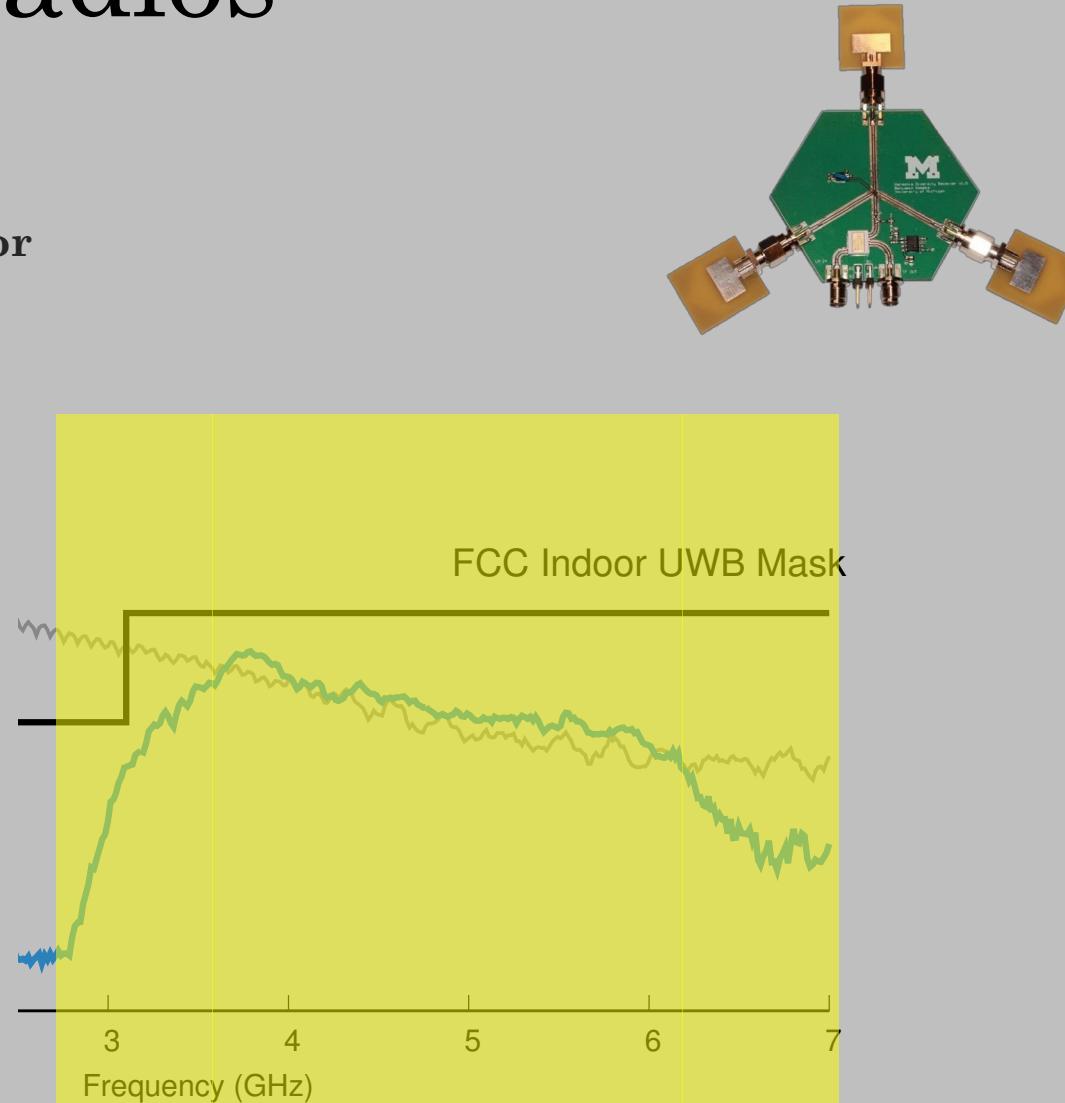
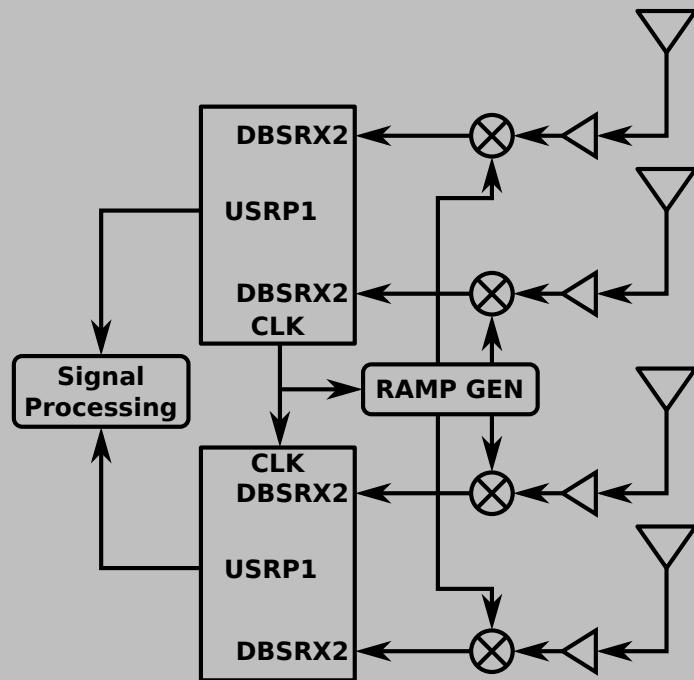
# In the real-world, UWB is not alone



[http://www.theiet.org/resources/journals/eletters/4811/images/640\\_uwb-spectrum2.jpg](http://www.theiet.org/resources/journals/eletters/4811/images/640_uwb-spectrum2.jpg)

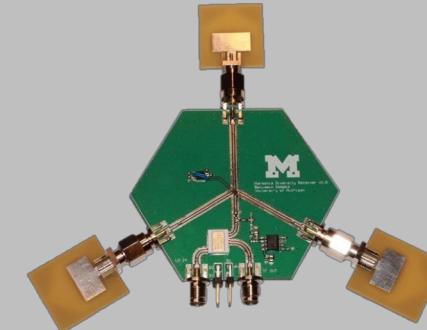
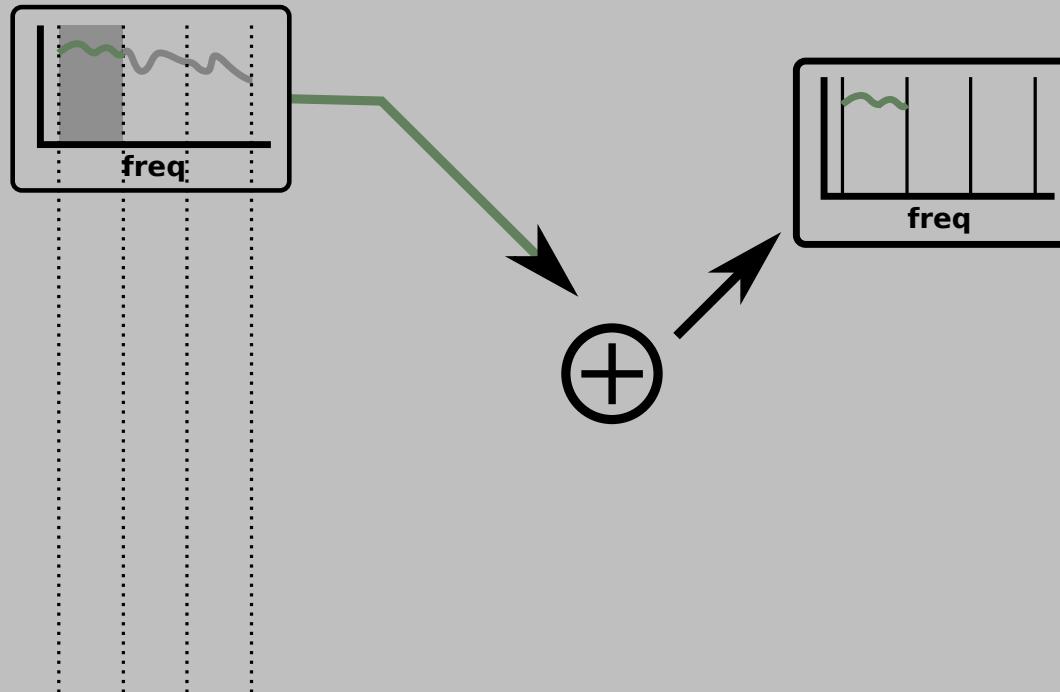
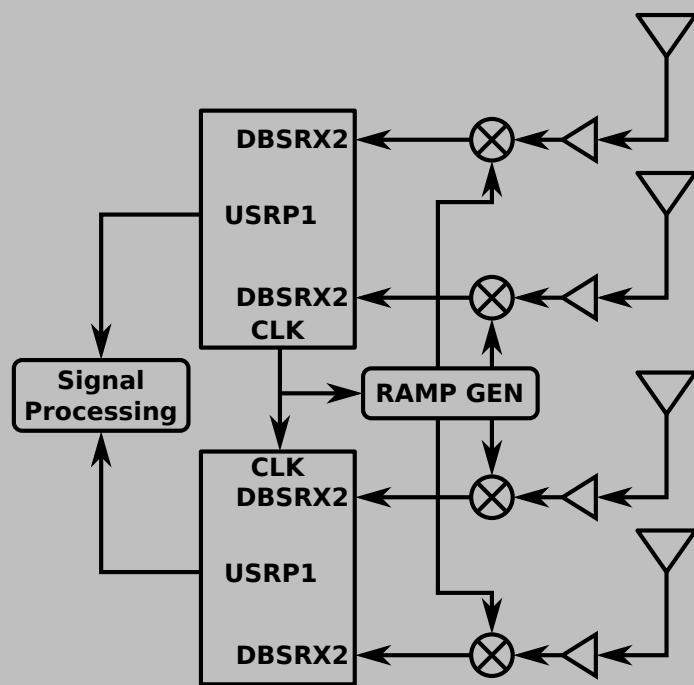
# Harmonium: UWB Reception with Narrowband Radios

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



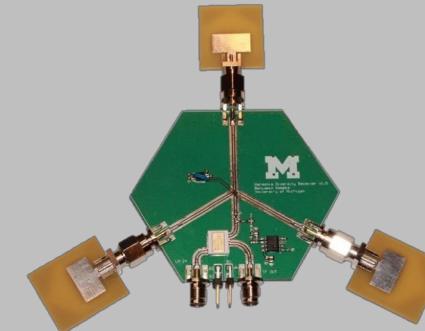
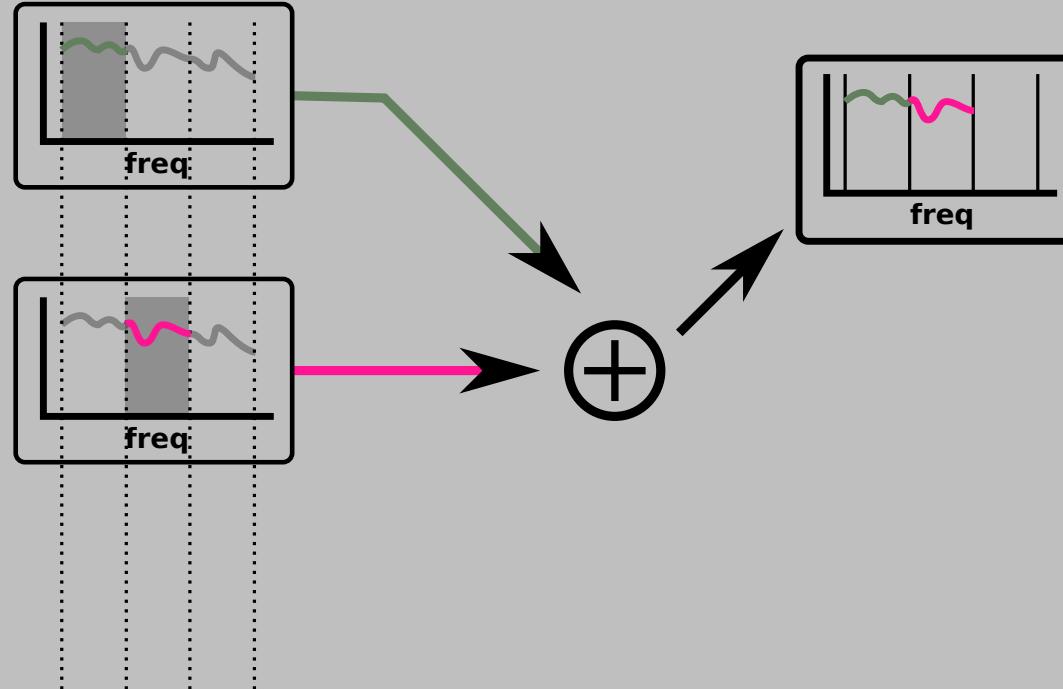
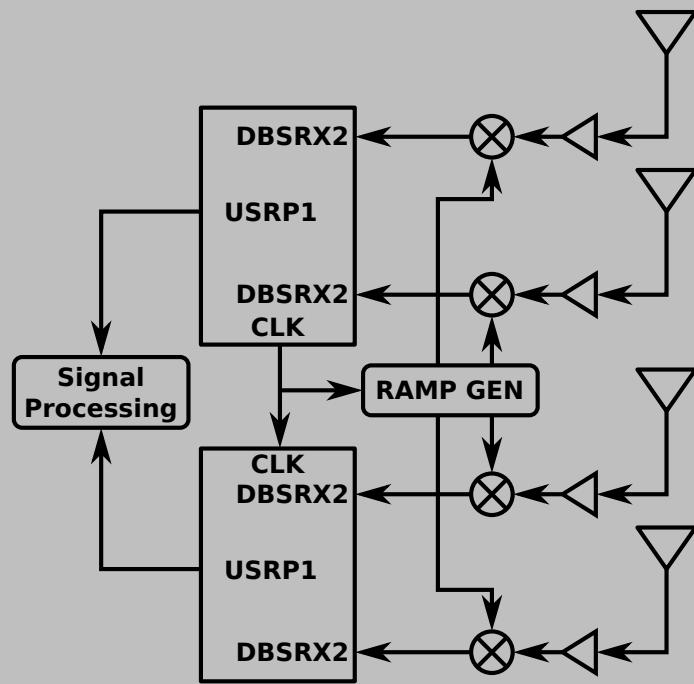
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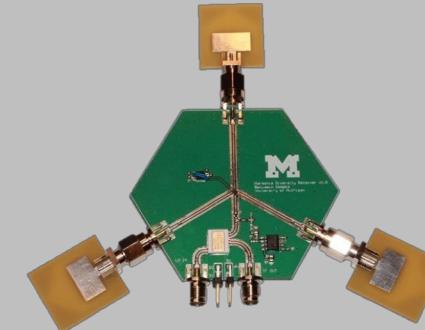
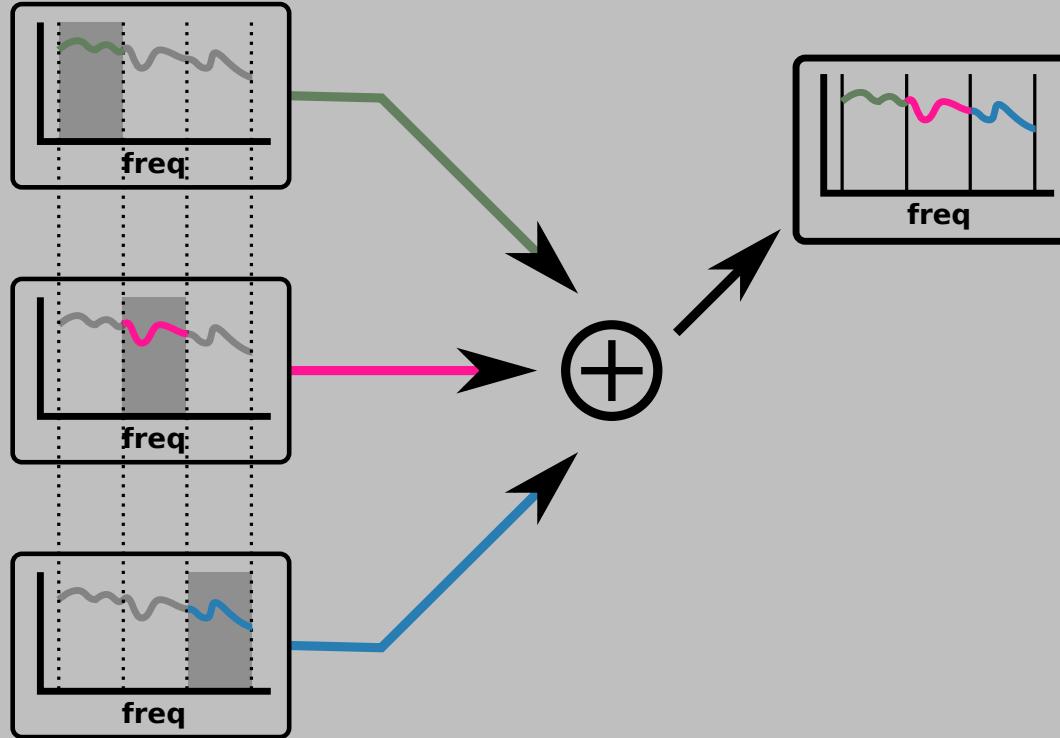
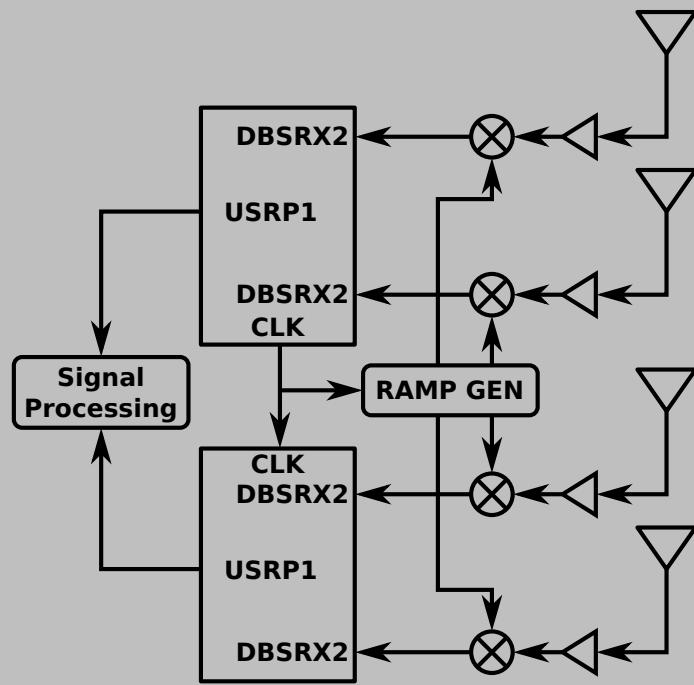
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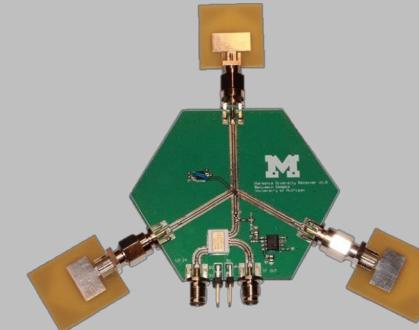
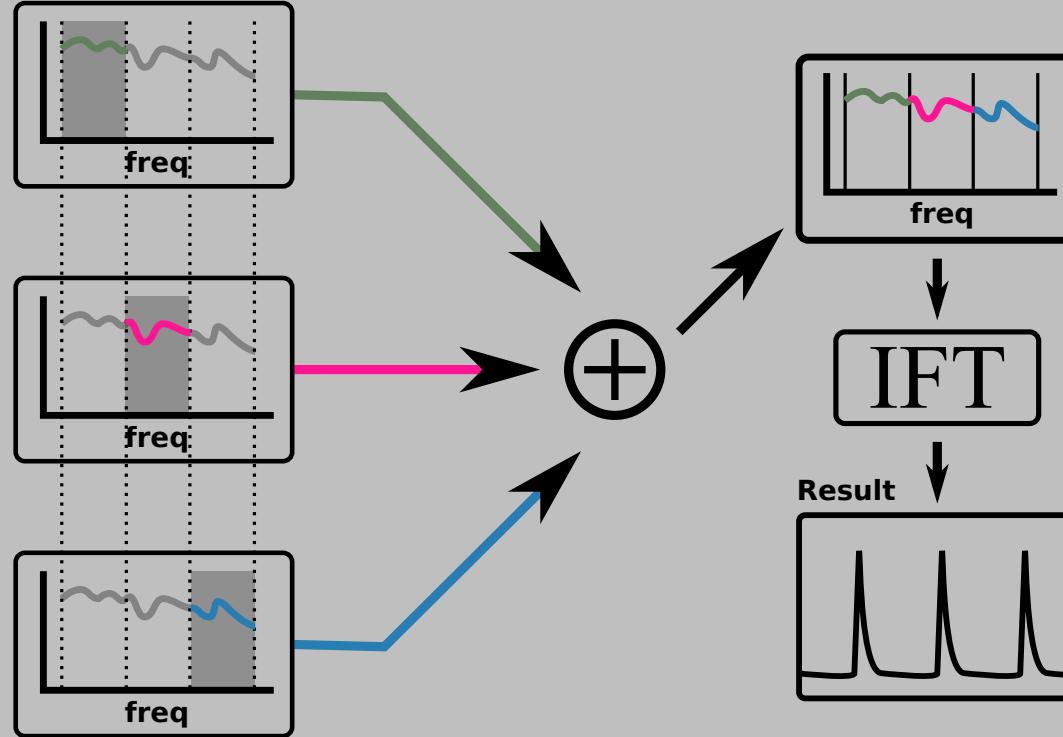
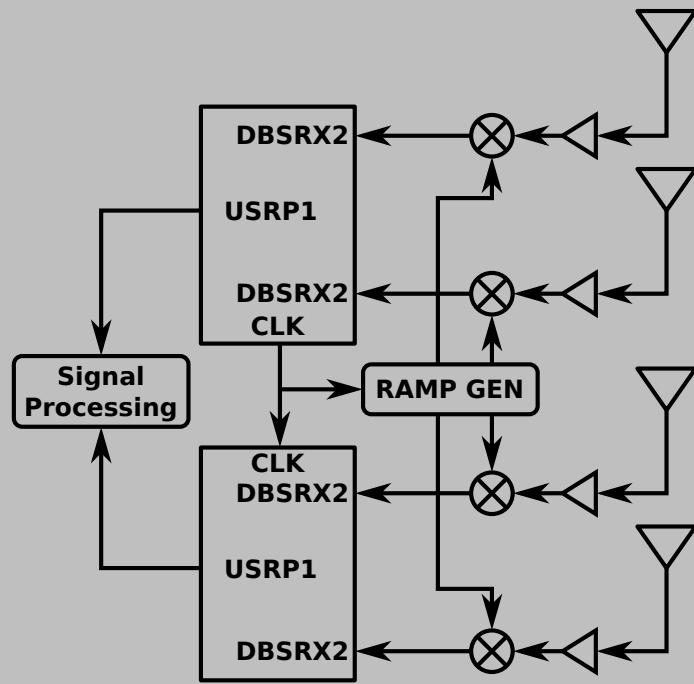
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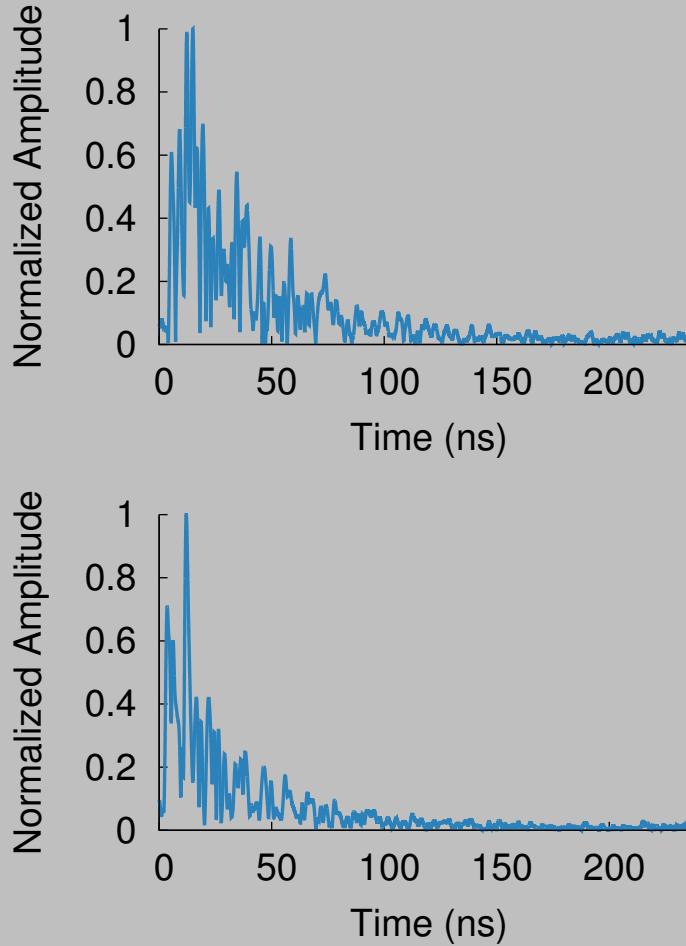
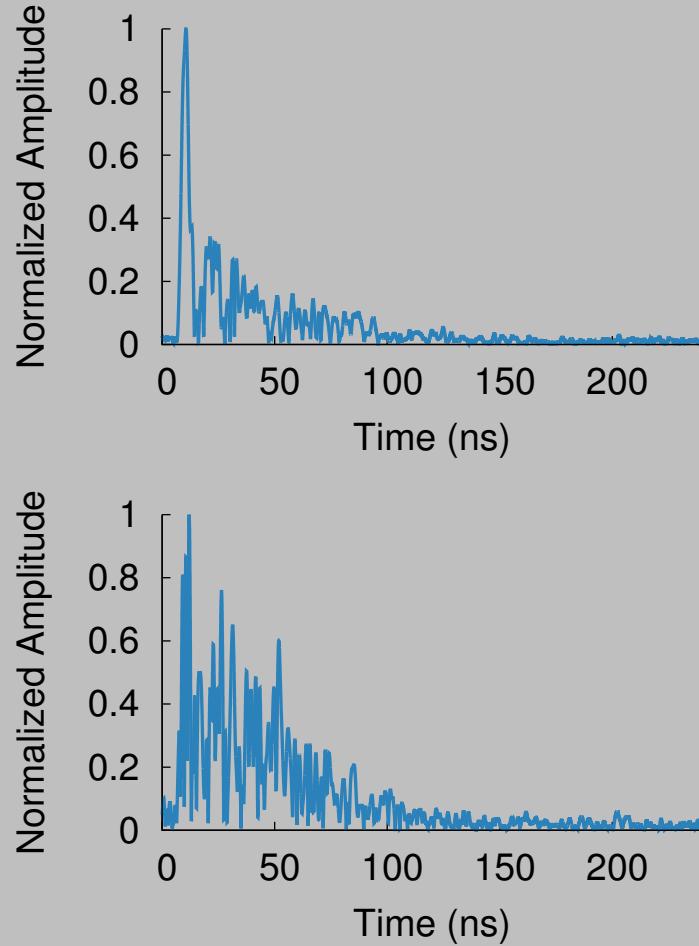


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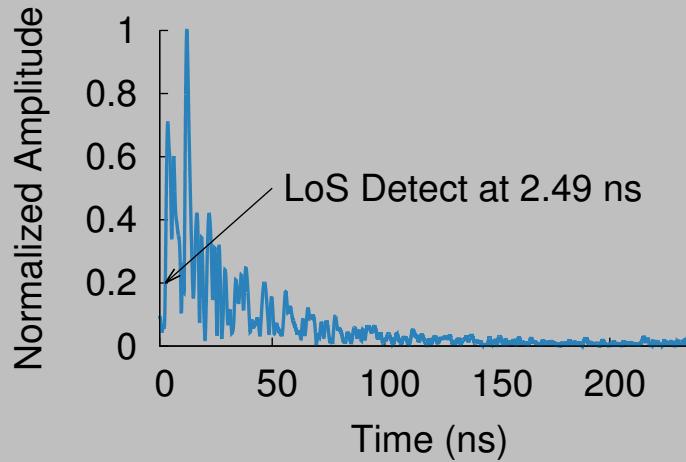
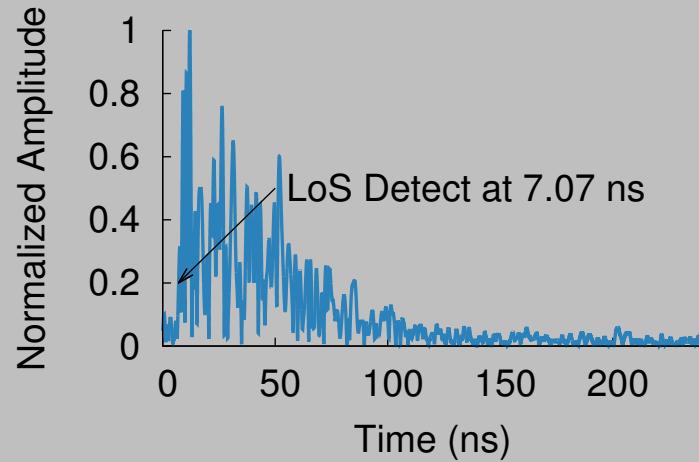
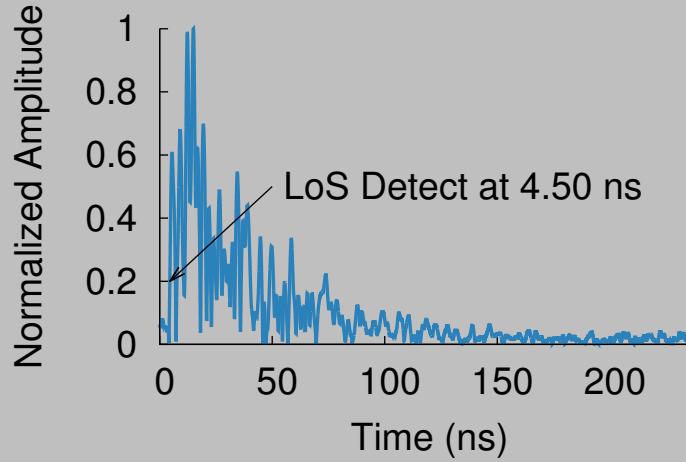
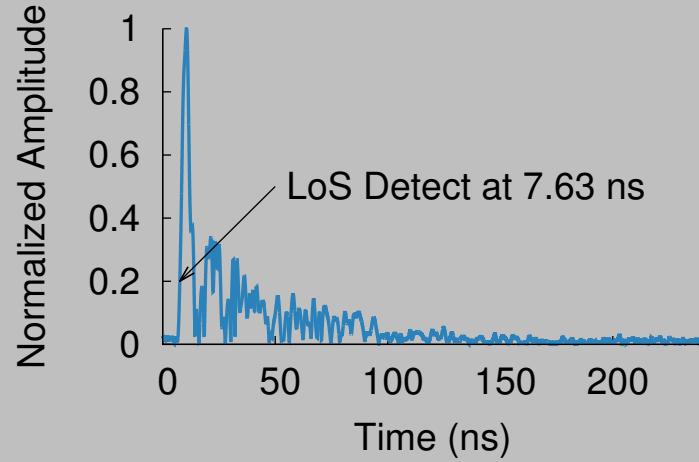
- Concept of operation:
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  - Antenna diversity



# Harmonium reconstructing UWB signals in the real world

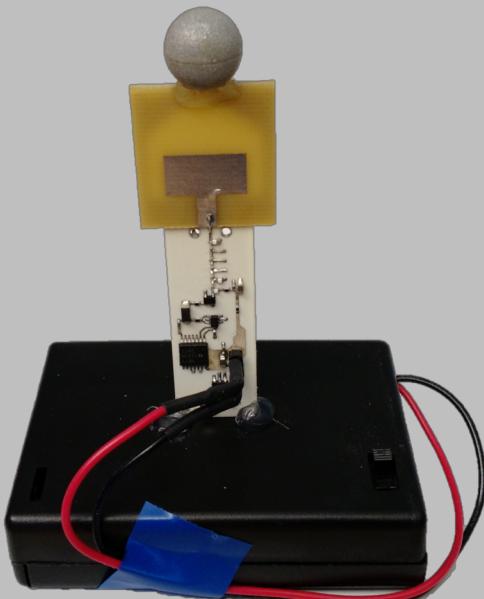


# Time-Domain Representation to Time-of-Arrival

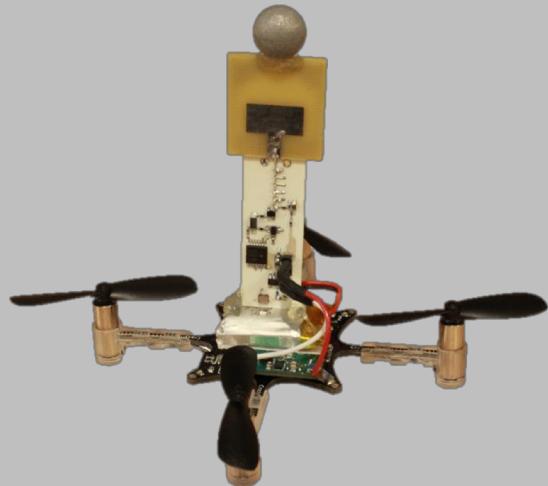


# How well does Harmonium actually work?

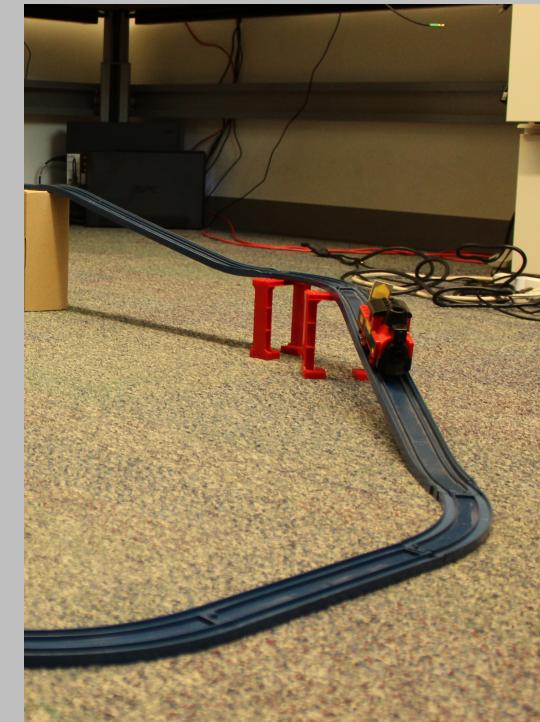
**Experiment #1:**  
Stationary Accuracy



**Experiment #2:**  
Mobile Localization  
Accuracy

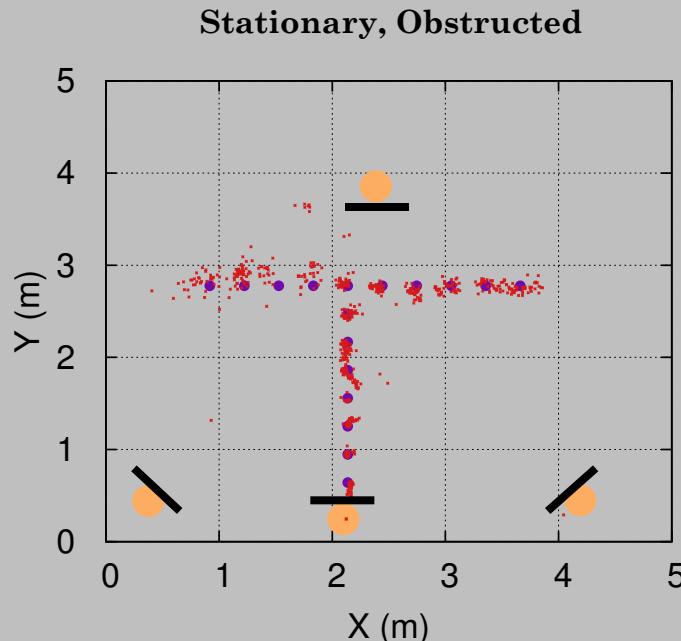
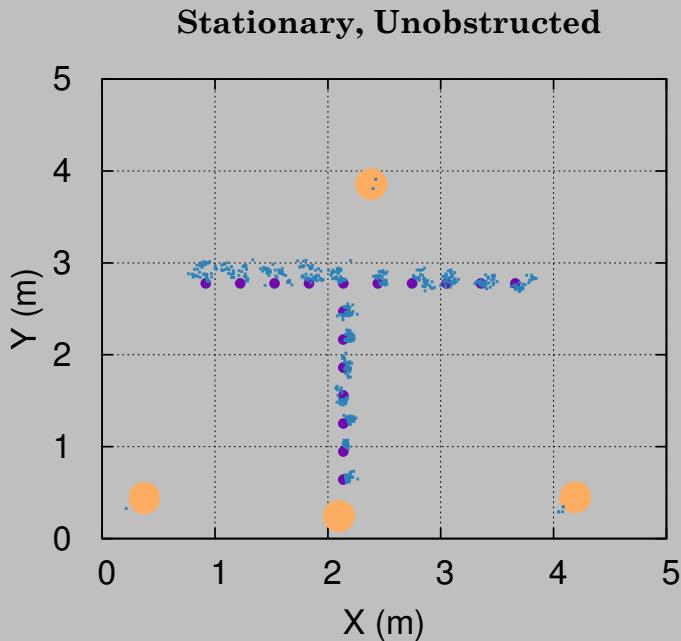


**Experiment #3:**  
Mobile Localization  
(Reproducibility)

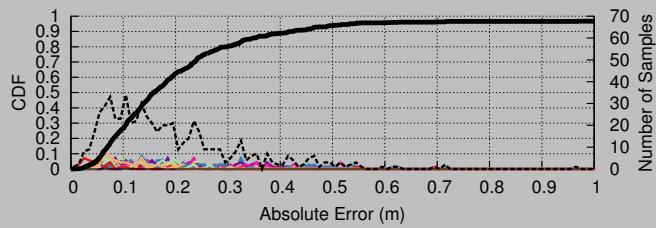
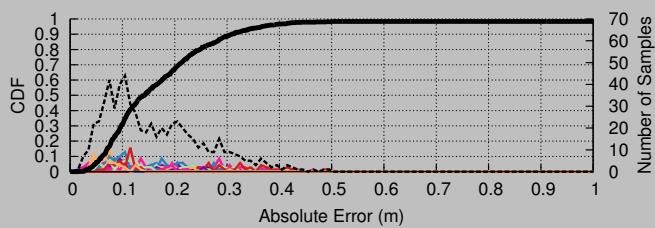


# Experimental Evaluation #1: Stationary Accuracy

14 cm  
median  
error



16 cm  
median  
error



# Commercial UWB receivers fail in the presence of narrowband interferers

- Spectrum is becoming increasingly crowded
- UWB fails with modest narrowband interference

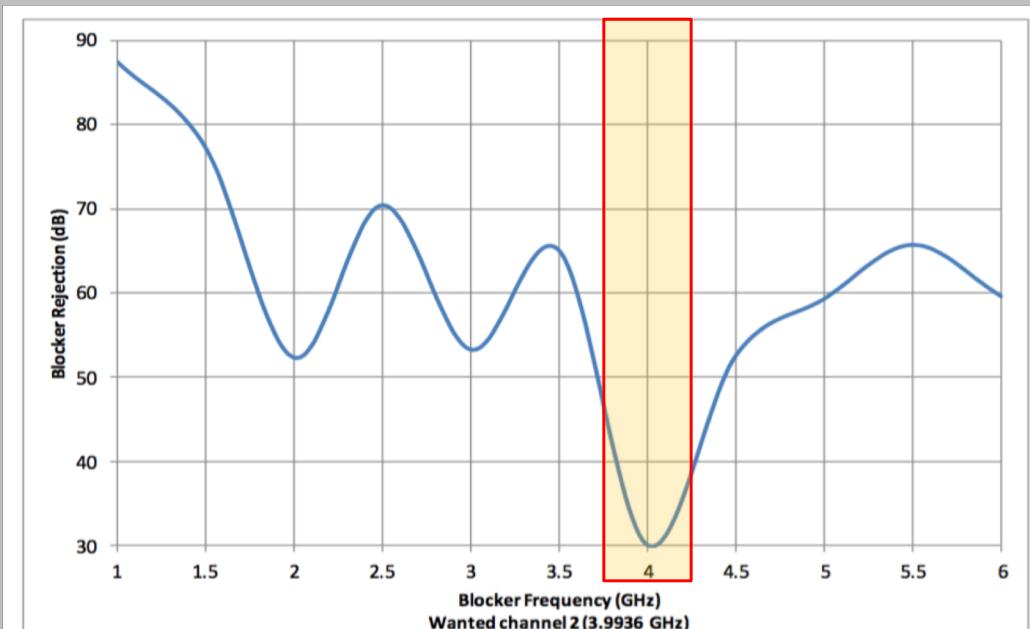
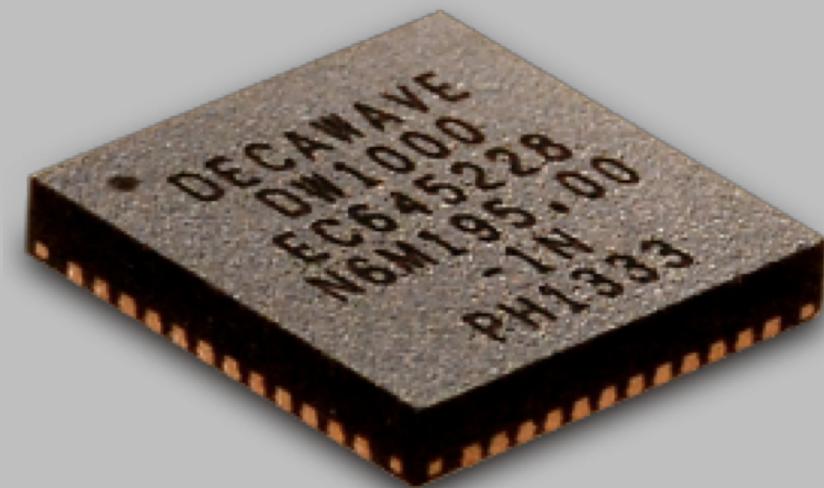
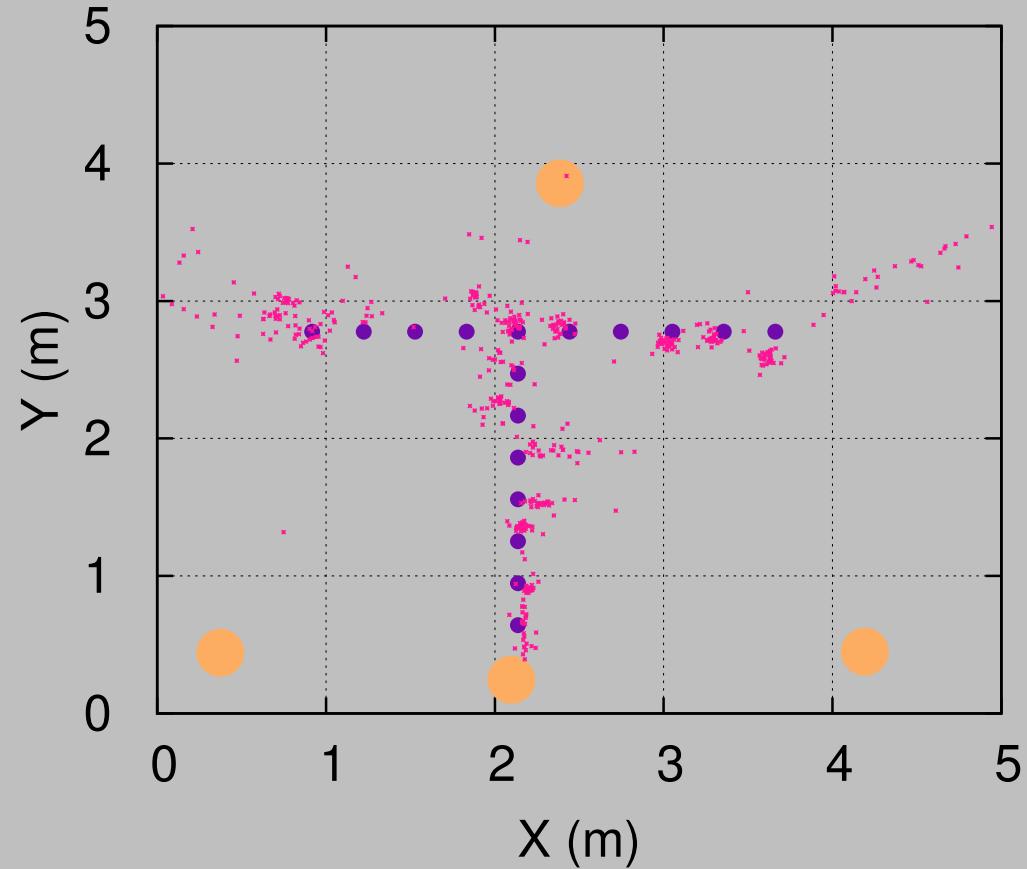
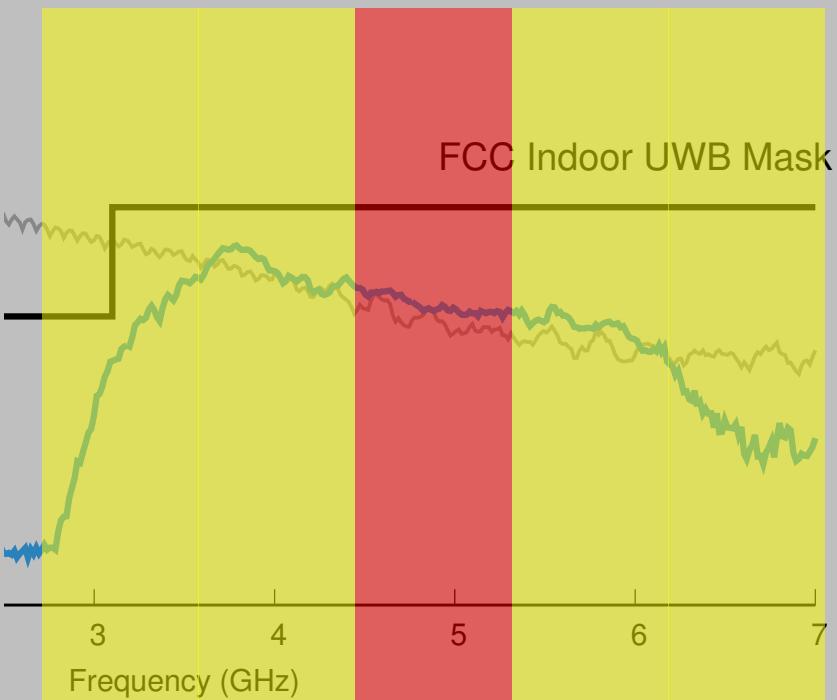


Figure 3 : RX Interferer Immunity on Channel 2

DW1000 Datasheet



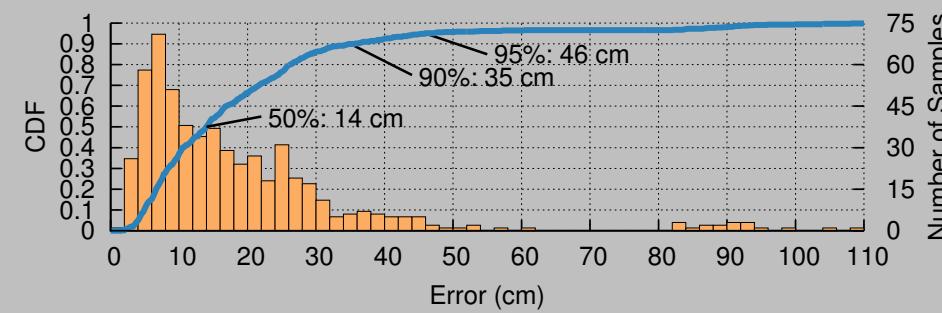
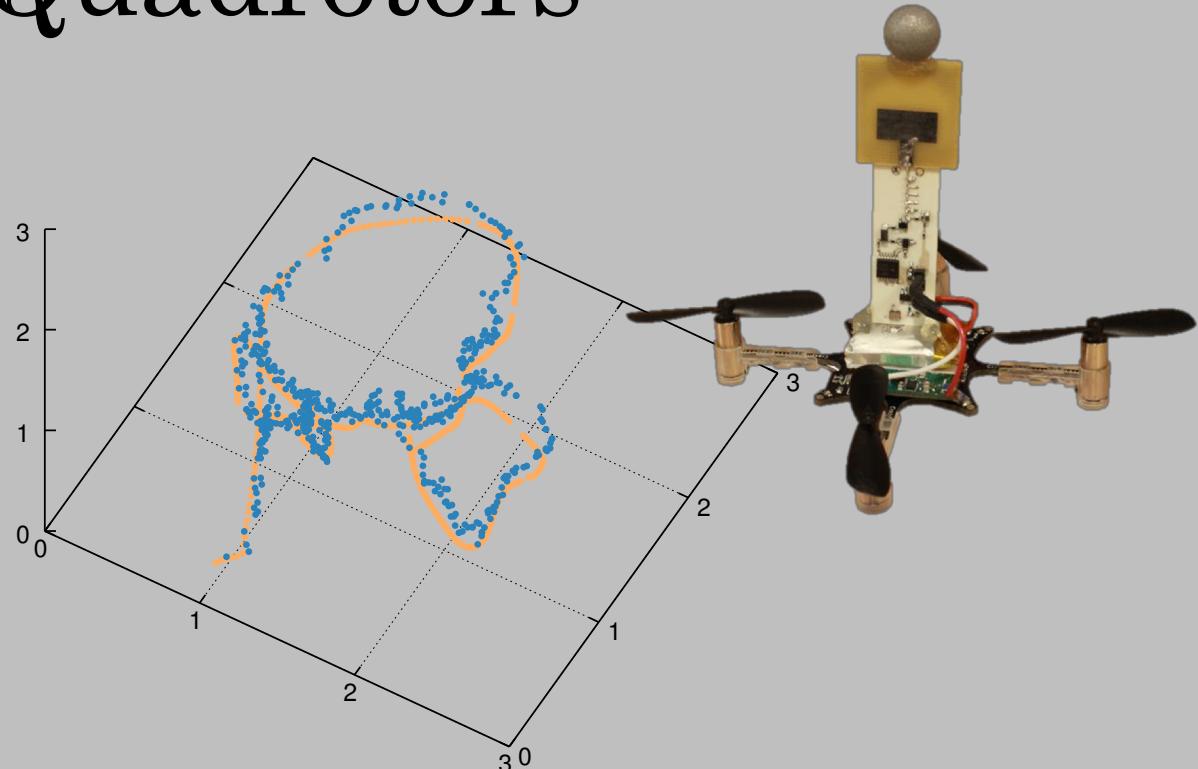
Harmonium still able to achieve accurate location estimates in the presence of narrowband interference



28 cm median error

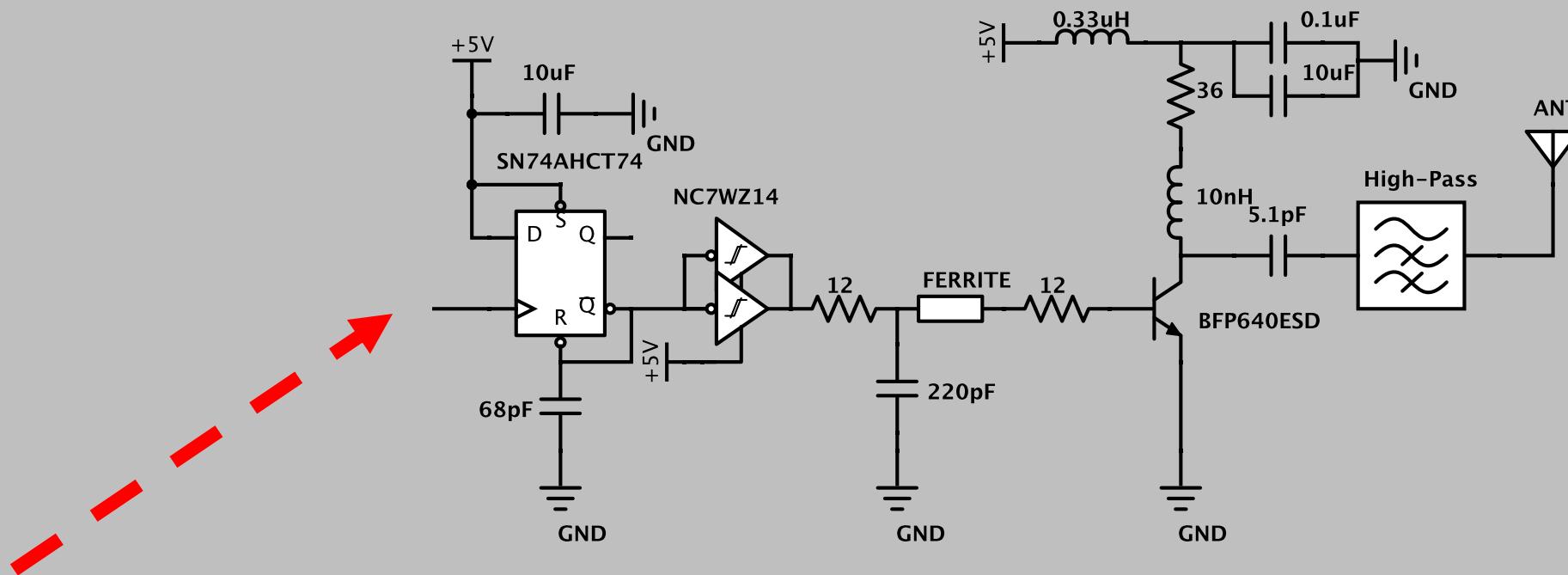
# Experimental Evaluation #2: Tracking Micro-Quadrotors

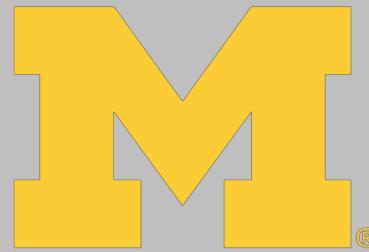
- 14 cm median error
- 46 cm 95%ile error
- Up to 1.4 m/s
- 19 Hz sampling



# Future Extensions

- Digital Communication
- Multi-tag support





# Conclusions

Harmonium introduces novel UWB transmitters, receivers, and signal processing techniques

Harmonium increases anchor complexity to realize minimal tags

- $1.5 \text{ cm}^3$ , 75 mW, 3 g

Harmonium is a robust, high-precision indoor localization technology

- 14 cm median error
- 16 cm median error “through “the walls”
- 28 cm median error in the face of narrowband interference



Ben Kempke, Pat Pannuto, and Prabal Dutta

# Backup Slides

# The Disadvantages of UWB Reception with Narrowband Receivers

- Maximum attainable update rate goes down proportional to the number of required observations
- More complex signal processing required to reconstruct wideband channel representation