Slocalization

Sub-µW Ultra Wideband Backscatter Localization

Pat Pannuto, Benjamin Kempke, and Prabal Dutta

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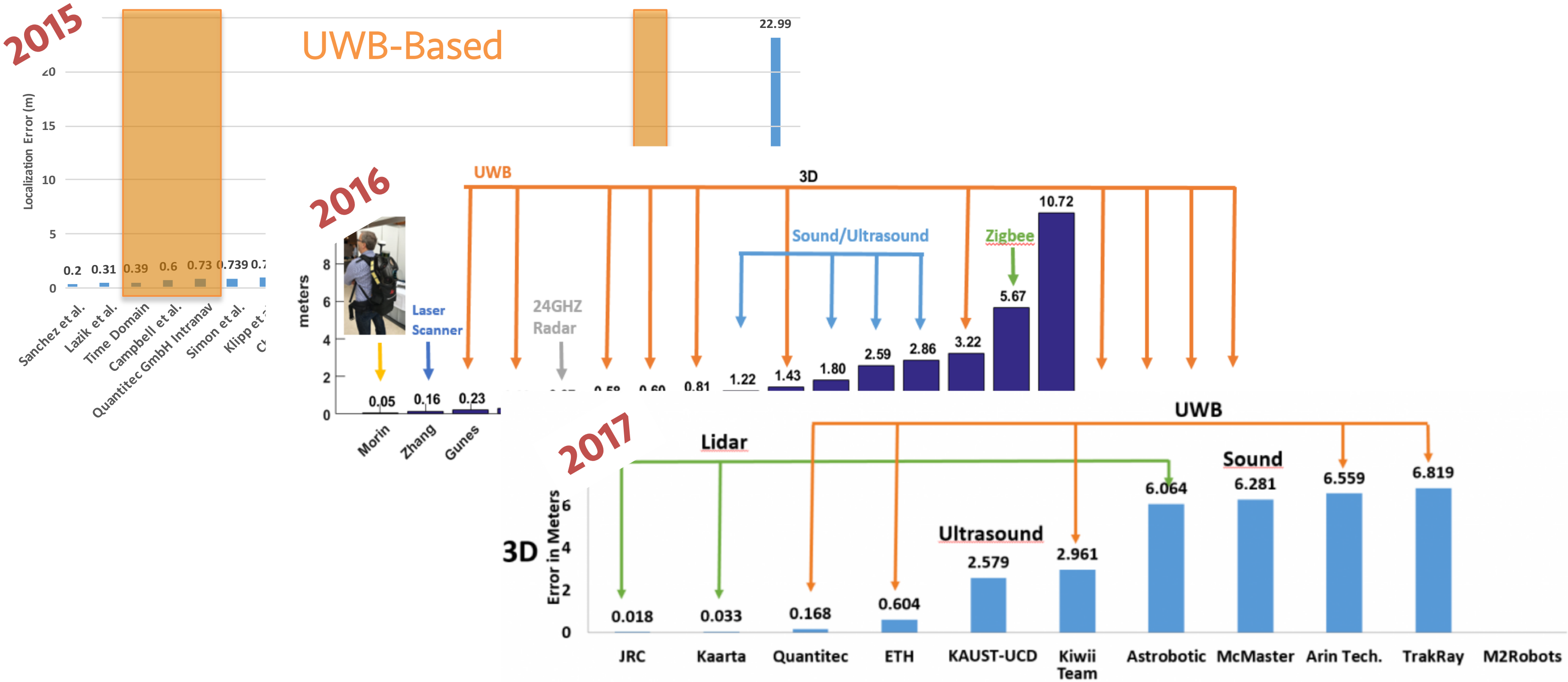
Let’s think bigger about localization: Can we locate every physical thing?

Can we make location a piece of first-class context, available to every device?

Ultra Wideband affords extremely high-fidelity localization



Ultra Wideband Radios (or impulse generators) are energy-hungry

System	Technology	Precision	Accuracy	Update Rate	Multiple Tags?	Top Tag Speed	Tag Power	Tag Volume	Max Tag/Anchor Dist
WASP [35]	NB (5.8 GHz) ToA	16.3 cm	50 cm (82%ile)	10 Hz	Yes	Several m/s	2-2.5 W	*Not Published*	*Not Published*
UbiSense [38]	UWB TDoA+AoA	99% w/in 30 cm	15 cm	33.75 Hz	Yes	*Not Published*	*Not Published*	24.5 cm^3	160 m
TimeDomain [2]	UWB TW-ToF	2.3 cm	2.1 cm	150 Hz	Yes	*Not Published*	4.2 W	97 cm^3	"hundreds of m"
Lazik et. al [27]	Ultrasonic TDoA	*Not Published*	3 cm (med) 12 cm (90%)	0.9 Hz	Yes	*Not Published*	1.1 W¶¶	88 cm^3	100 m
Harmonia [19]	UWB TDoA	*Not Published*	39 cm (med) 82 cm (90%)	56 Hz	No	*Not Published*	120 mW**	*Not Published*	*Not Published*
Tagoram [42]	NB (UHF) SAR	*Not Published*	12.3 cm (med)	At most 30 Hz	No	0.5 m/s	N/A	8 cm^3	10 m
WiTrack [3]	UWB ToF	*Not Published*	12 cm (med) 31 cm (90%)	At most 400 Hz	No	*Not Published*	N/A	32,700 cm^3 (avg torso [6])	*(Not Published)* > 11 m
RF-IDraw [40]	NB (UHF) Interferometry	3.6 cm (med) 3.7 cm (90%)	19 cm (med) 38 cm (90%)	At most 53 Hz	No	0.5 m/s*	N/A	8 cm^3	9 m
PolyPoint [20]	UWB ToF	31 cm	39 cm (med) 140 cm (90%)	16 Hz	No	*Not Published*	150 mW	9 cm^3	50 m
Harmonium [21]	UWB TDoA	9 cm (med) 16 cm (90%)	14 cm (med) 31 cm (90%)	19 Hz	No	2.4 m/s††	75 mW	1.5 cm^3	78 m
Chronos [39]	Bandstiched UWB ToF	*Not Published*	65 cm (med) 170 cm (90%)	12 Hz	No	*Not Published*	1.6 W§	2.7 cm^3¶	*Not Published*
SurePoint	**UWB ToF**	**12 cm (med) 28 cm (90%)**	**29 cm (med) 50 cm (90%)**	**1-12 Hz**	**Yes**	**at least 2.4 m/s**	**280 mW**	**3 cm^3**	**50 m**

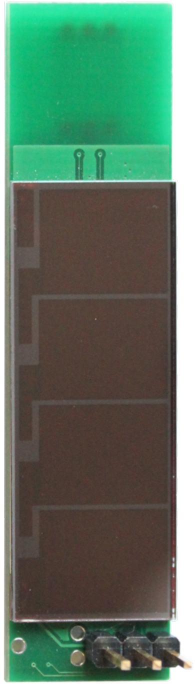
Lowest power UWB is 75 mW

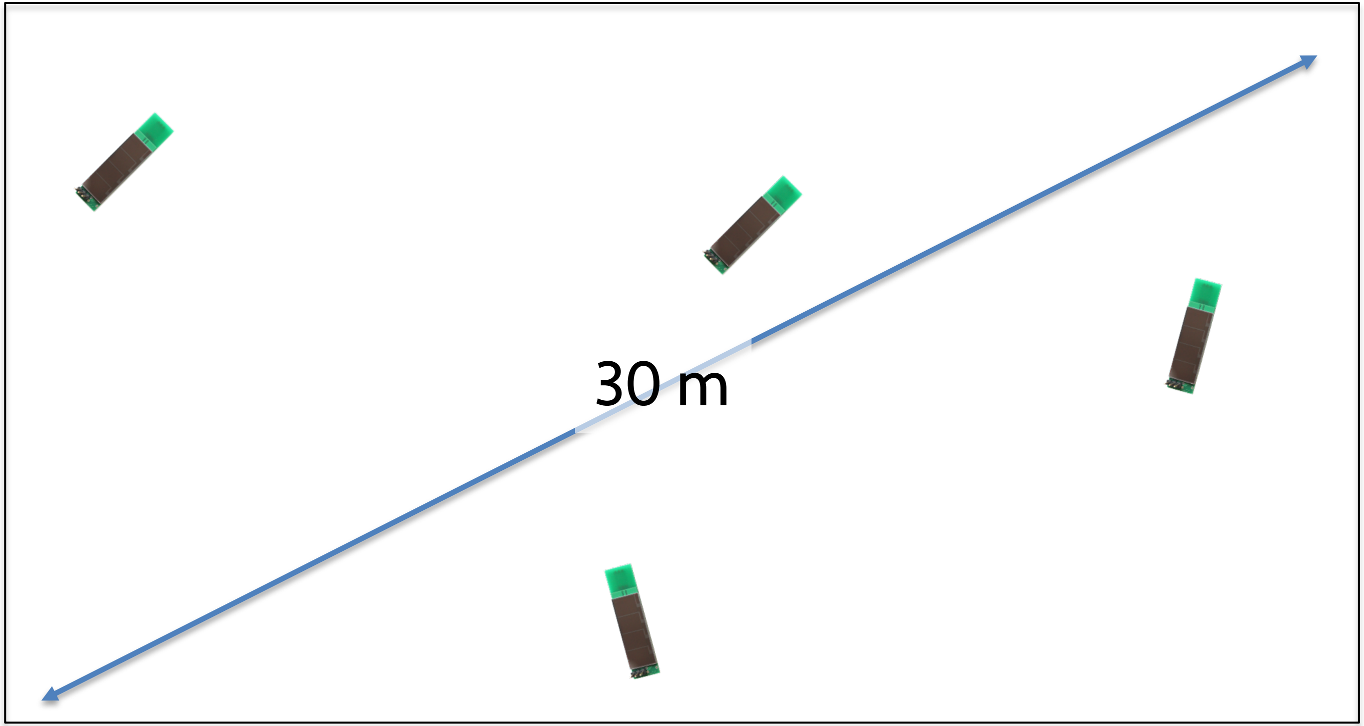
Table from: SurePoint: Exploiting Ultra Wideband Flooding and Diversity to Provide Robust, Scalable, High-Fidelity Indoor Localization. Benjamin Kempke, Pat Pannuto, Bradford Campbell, and Prabal Dutta. SenSys'16.

Backscatter renaissance is redefining low-power for wireless

- Wireless communication from W/mW to µW/nW
  - Zhang, Pengyu, Jeremy Gummeson, and Deepak Ganesan. "Blink: A high throughput link layer for backscatter communication." MobiSys'12
  - Kellogg, Bryce, Aaron Parks, Shyamnath Gollakota, Joshua R. Smith, and David Wetherall. "Wi-Fi backscatter: Internet connectivity for RF-powered devices." SIGCOMM'14
  - Zhang, Pengyu, Pan Hu, Vijay Pasikanti, and Deepak Ganesan. "Ekhonet: High speed ultra low-power backscatter for next generation sensors." MobiCom'14
  - Zhang, Pengyu, Dinesh Bharadia, Kiran Joshi, and Sachin Katti. "Hitchhike: Practical backscatter using commodity wifi." SenSys'16
  - Ma, Yunfei, Nicholas Selby, and Fadel Adib. "Minding the billions: Ultra-wideband localization for deployed RFID tags." MobiCom'17
  - Varshney, Ambuj, Oliver Harms, Carlos-Perez Penichet, Christian Rohner, Frederik Hermans, and Thiemo Voigt. "LoRea: A Backscatter architecture that achieves a long communication range." SenSys'17
  - Carlos Pérez Penichet, Claro Noda, Ambuj Varshney, Thiemo Voigt. "Battery-Free 802.15.4 Receiver" IPSN'18

Slocalization: Ultra wideband backscatter whole-room localization for <1 μW





~~There has to be a catch….~~
There is a new tradeoff to introduce

- <1 μW tag
  - (COTS, can do order of magnitude or more better with VLSI)
- Covers areas 30m+
- Decimeter accurate
- (Nearly) unlimited number of concurrent tags
- 1-15+ minutes per location fix
  - Introducing the latency/energy tradeoff for localization

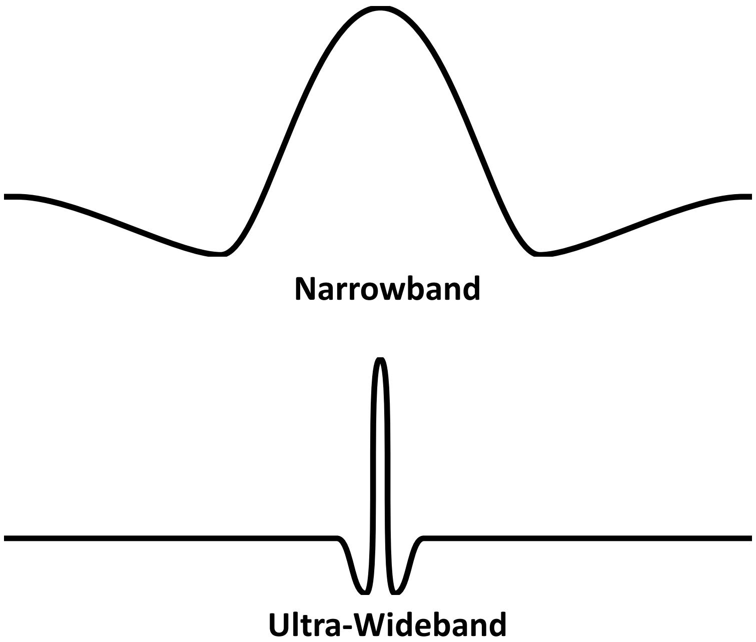
Can we locate every physical thing? Most things don't move!

- Location is fundamental to contextual relationships
  - *Little is more basic to human perception than physical juxtaposition, and so ubiquitous computers must know where they are*
    - *Mark Weiser, The Computer for the 21st Century*
- Towards "search not file" for the physical world

Outline

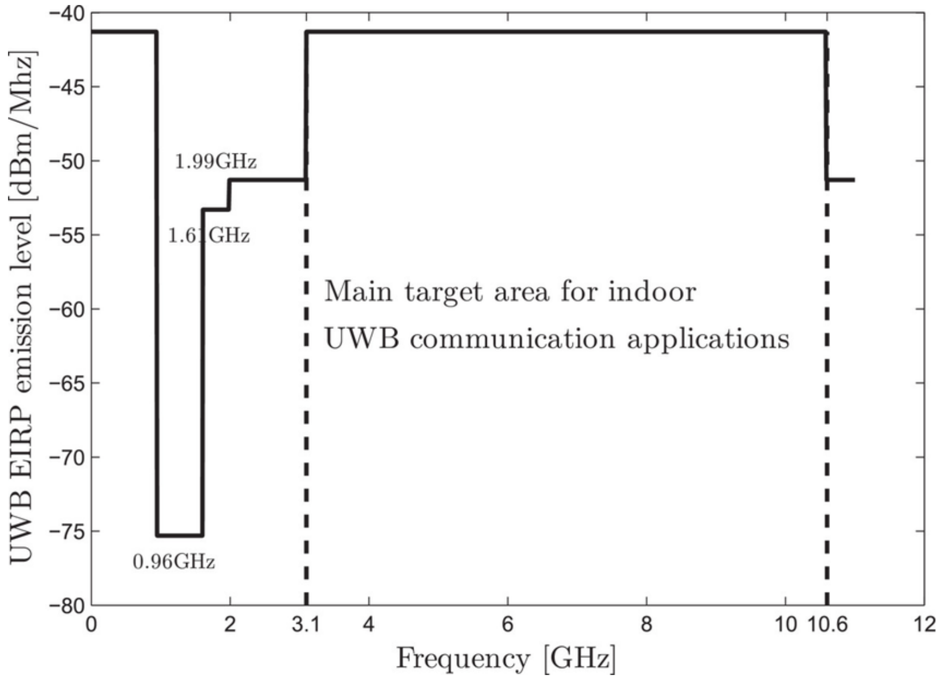
- Most things don't move
- Building blocks of Slocalization
  - UWB localization
  - UWB backscatter
  - Putting them together
- Does it actually work?
- What comes next

Why RF, why UWB for ubiquitous localization?



Mautz, Rainer. "Indoor positioning technologies." (2012).

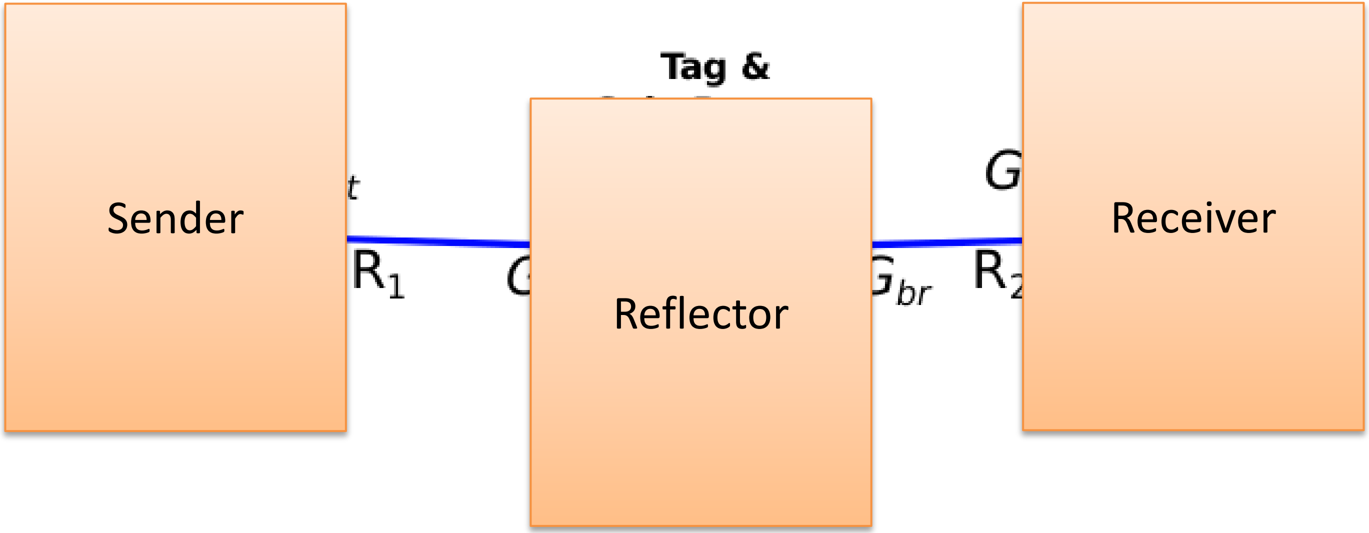
UWB can transmit 54 million times less power than traditional narrowband devices



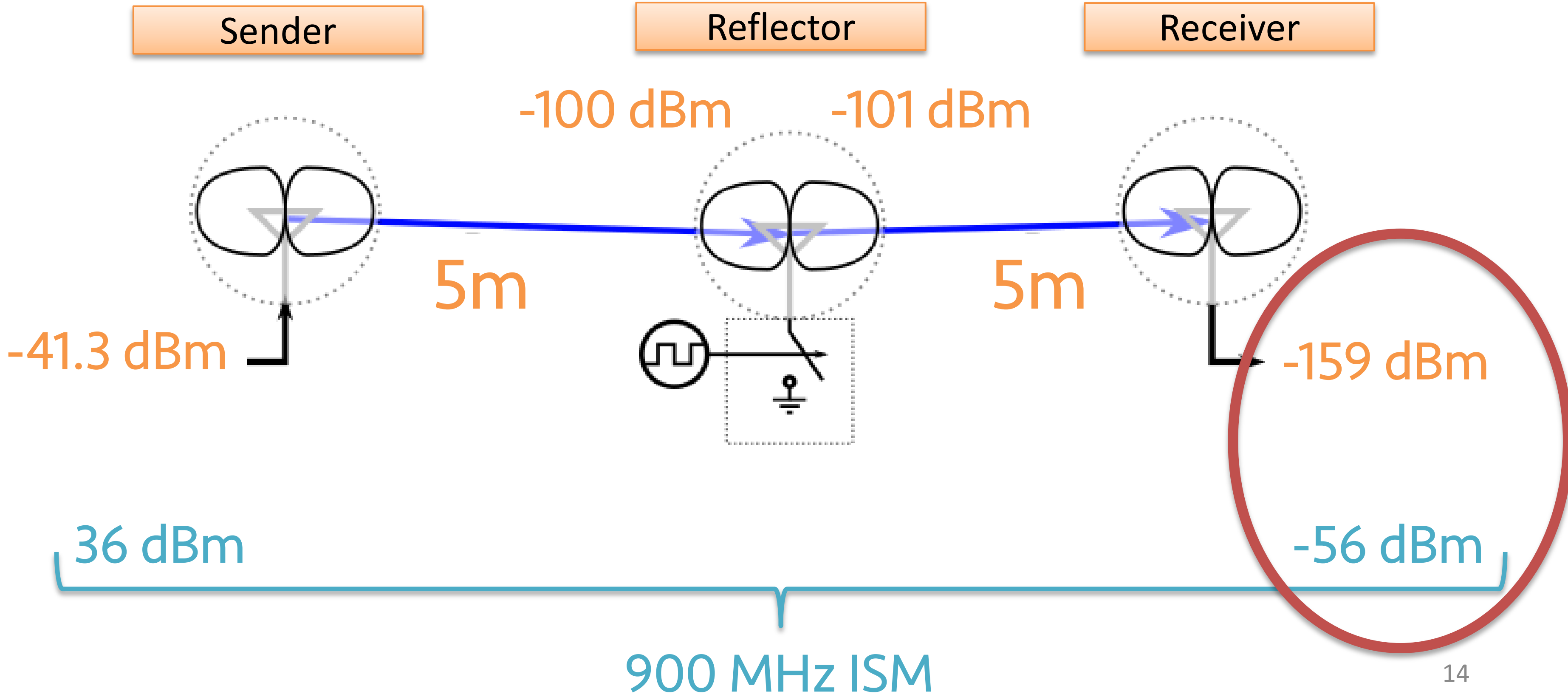
- 3-10 GHz UWB → -41.3 dBm
- 900 MHz ISM → 36 dBm
- 900 MHz unlicensed
  - Control → -13.3 dBm
  - Periodic → -21.2 dBm

Vijaya Yajnanarayana. "Spectral efficient IR-UWB communication design for low complexity transceivers" (2014).

UWB Backscatter is passive reflection of a lot less energy



UWB Backscatter is passive reflection of a lot less energy



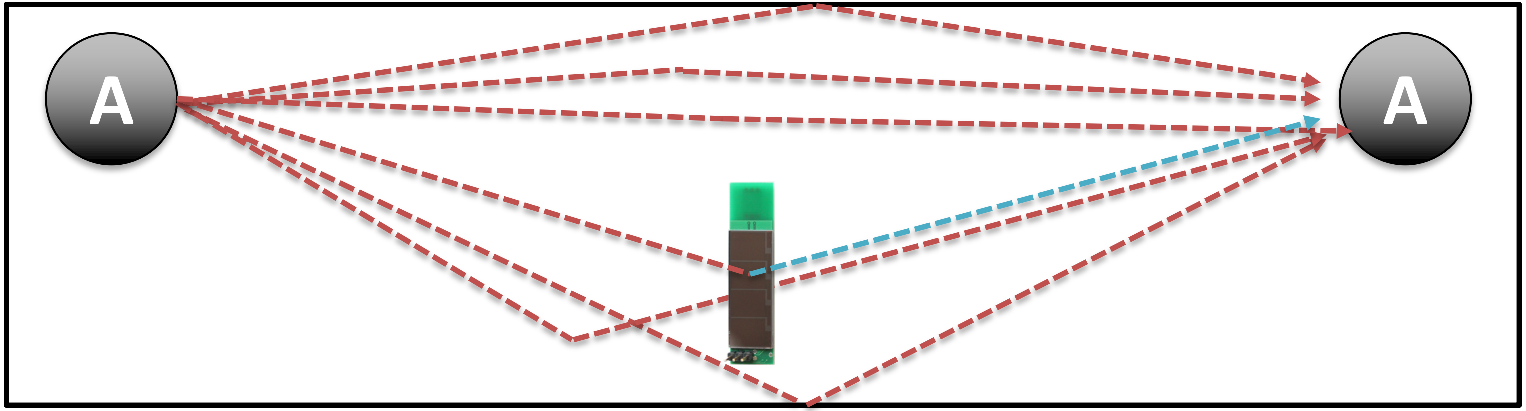
UWB Backscatter is passive reflection of a lot less energy

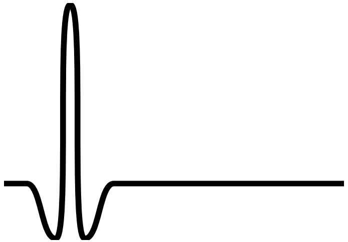
Packet Error Rate	Data Rate	Typical Receiver Sensitivity	Units
1%	110 kbps	-106	dBm/500 MHz
10%	110 kbps	-107	dBm/500 MHz
	[illegible] kbps	-102	dBm/500 MHz
1%	850 kbps	-101	dBm/500 MHz
	6.8 Mbps	-93 (*-97)	dBm/500 MHz
10%	110 kbps	-106	dBm/500 MHz
	850 kbps	-102	dBm/500 MHz
	6.8 Mbps	-94 (*-98)	dBm/500 MHz

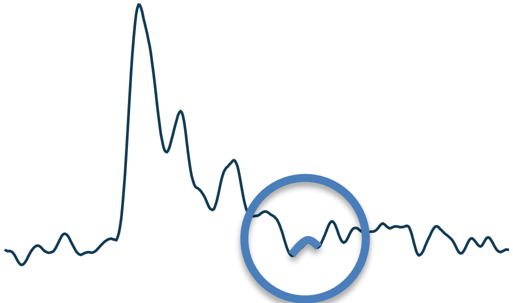
Typical receiver sensitivity ranges from -94 to -106

How do we recover a signal that is way below the noise floor?

- Exploit tag stationarity and environmental stability







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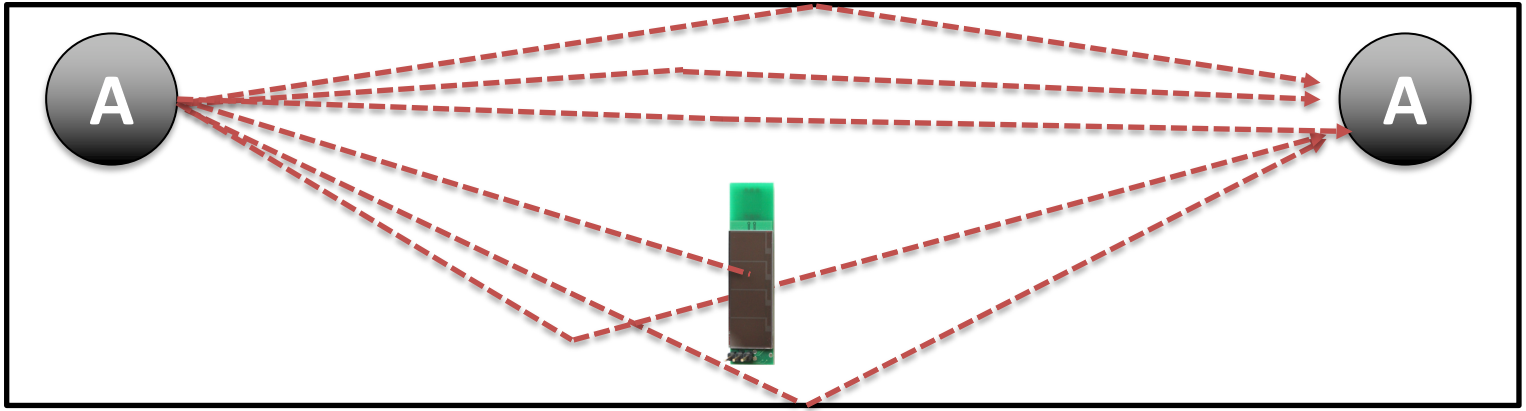
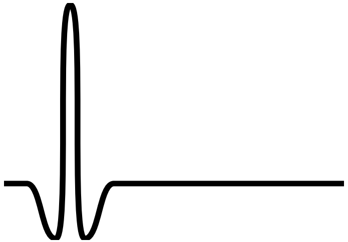
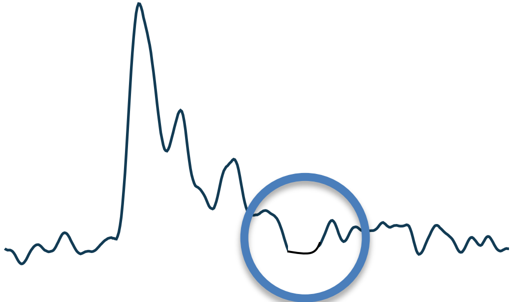
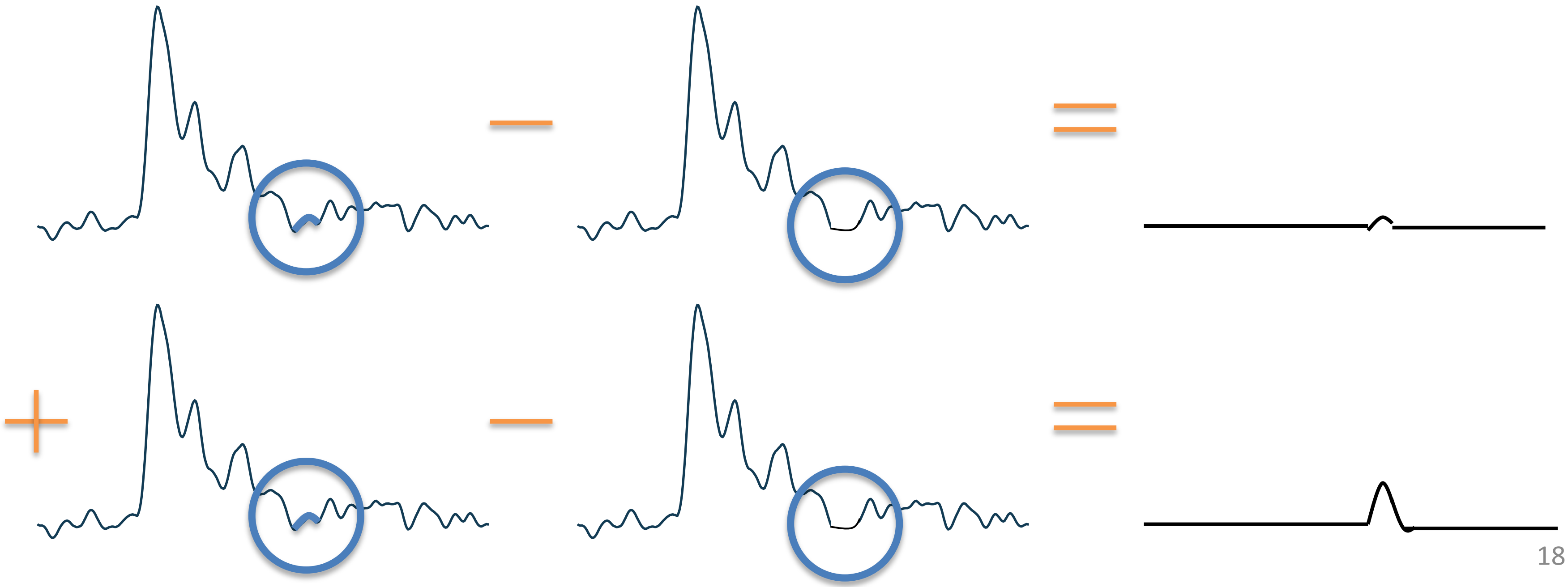




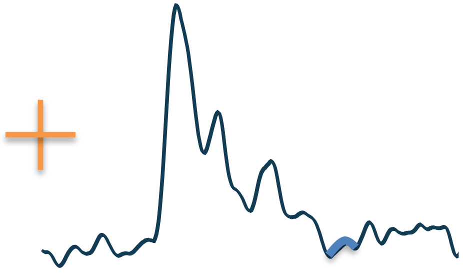


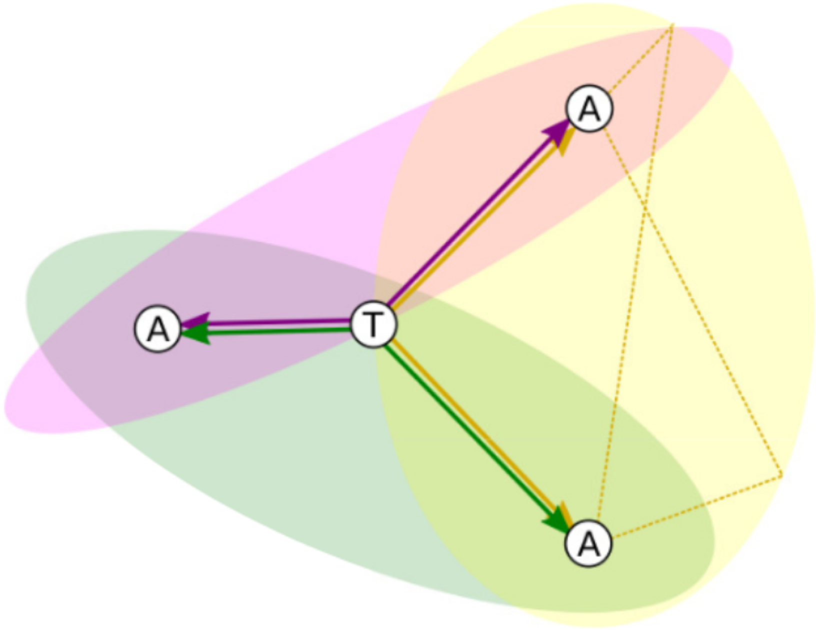
Ideally, the only change in the channel impulse response is the tag reflection

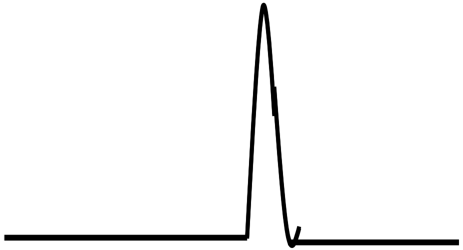
- Subtracting the environment finds the tag



The goal is to estimate the time difference of arrival (TDoA) and laterate





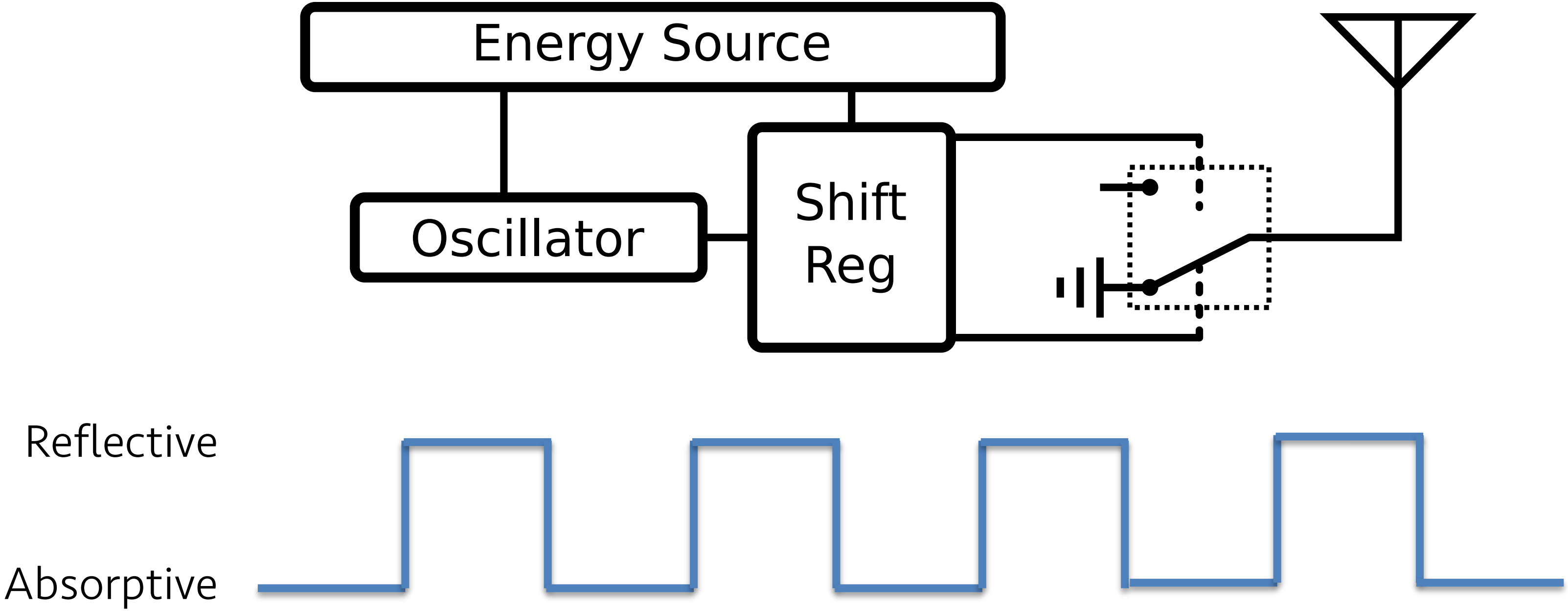


- First peak is anchor—anchor path, then anchor—tag—anchor

Extracting the tag signal in the real world has a few additional challenges

- The environment is not actually static
  - But noise is largely white & Gaussian
  - And we can filter out the rest
- When to add and when to subtract?

If you know what the tag is doing, then you know when to add or subtract



Extracting the tag signal in the real world has a few additional challenges

- The environment is not actually static
  - But noise is largely white & Gaussian
  - And we can filter out the rest
- When to add and when to subtract?
  - Problem: Need to know when the tag is reflecting or absorbing
  - Solution: Guess and brute force search
    - Tag stability limits Slocalization range
- More details in the paper…

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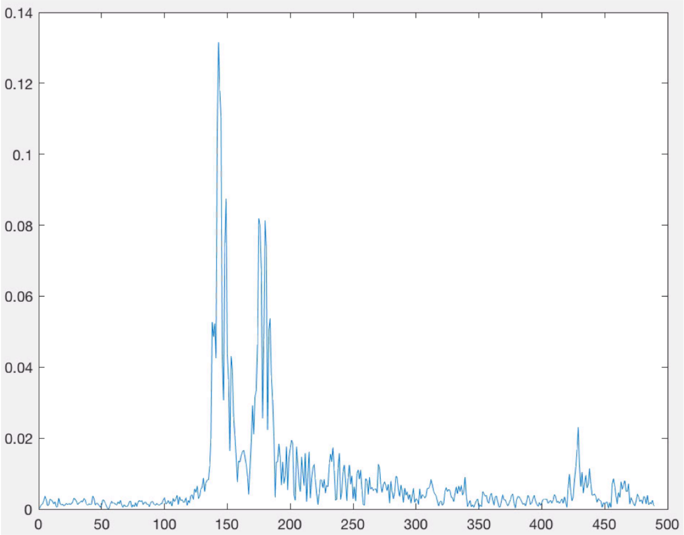
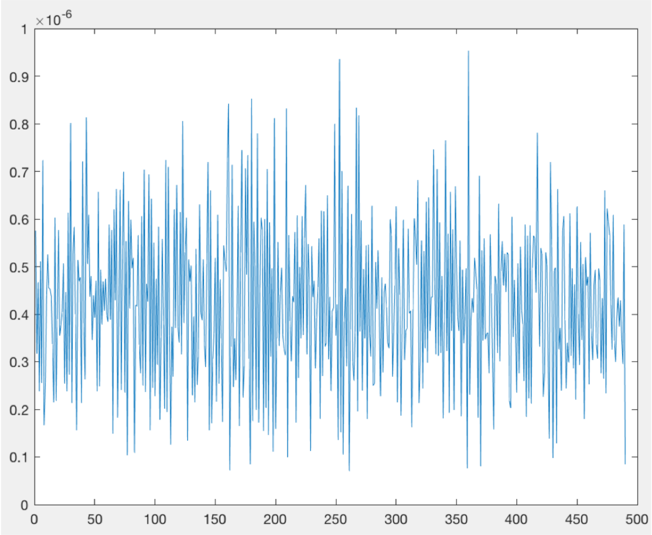
Recovery of modulated signal improves with greater integration time

- $R_1 = 6$ m, $R_2 = 24$ m



Raw Channel Impulse Response

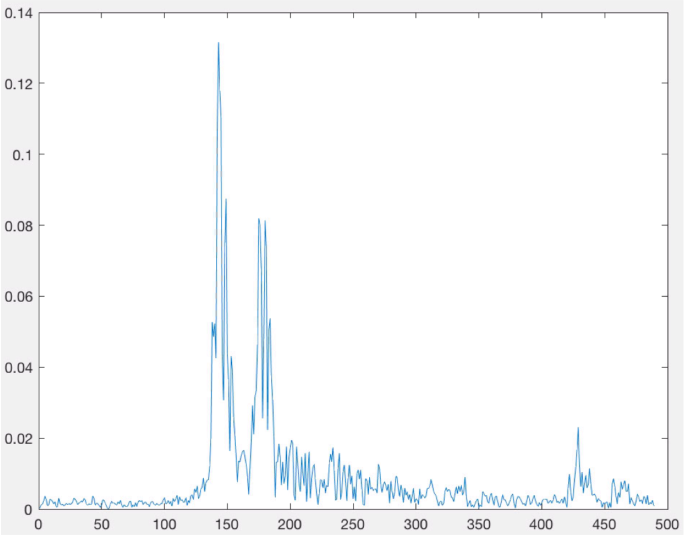


Correlated Channel Impulse Response

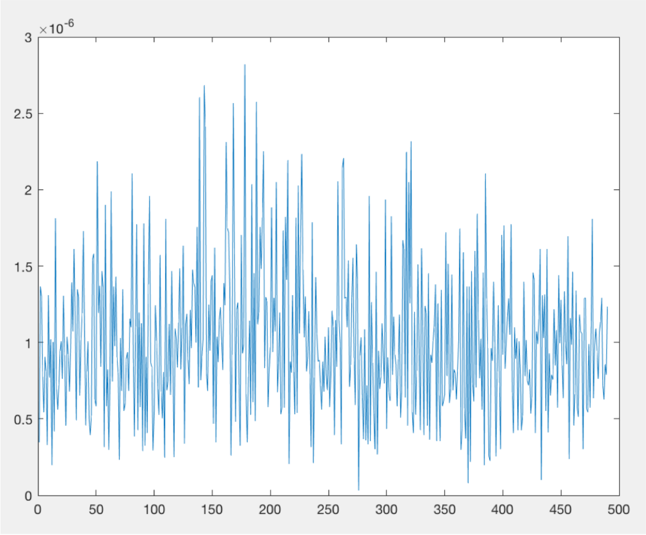
6 seconds

Recovery of modulated signal improves with greater integration time

- R_1 = 6 m, R_2 = 24 m



Raw Channel Impulse Response

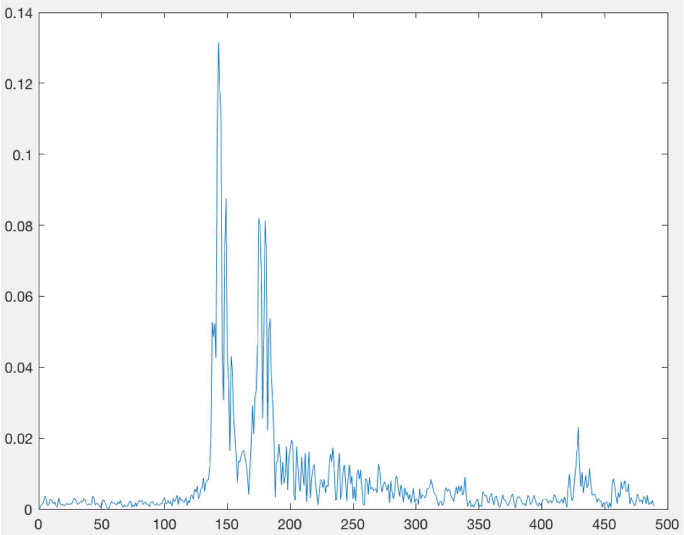


Correlated Channel Impulse Response

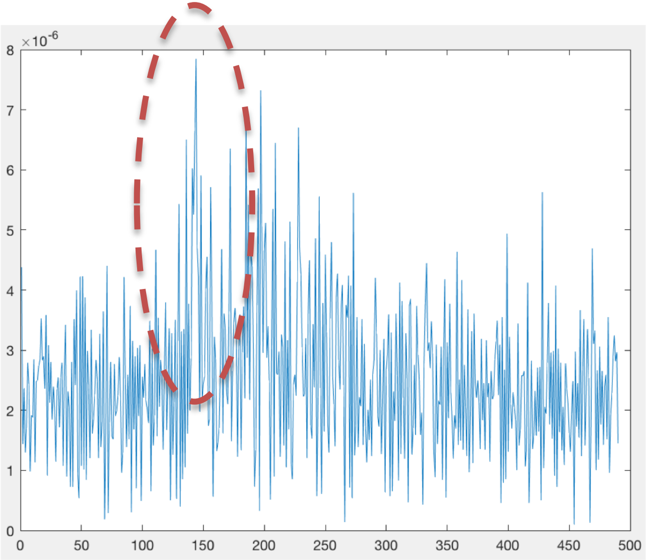
50 seconds

Recovery of modulated signal improves with greater integration time

- $R_1 = 6$ m, $R_2 = 24$ m



Raw Channel Impulse Response

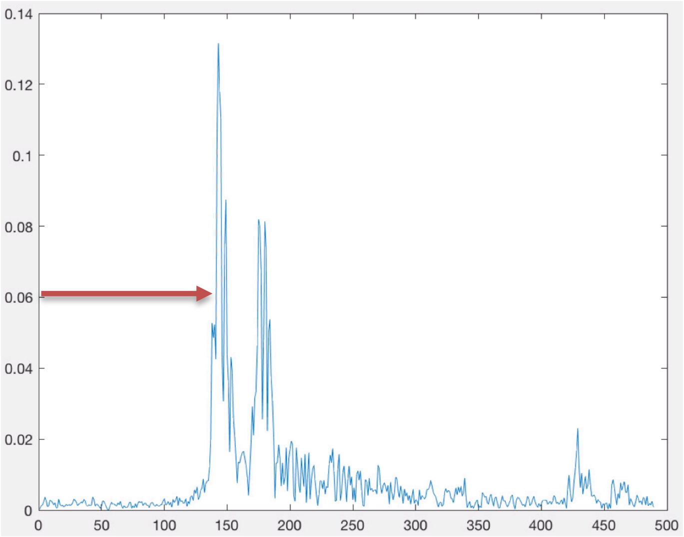


250 seconds

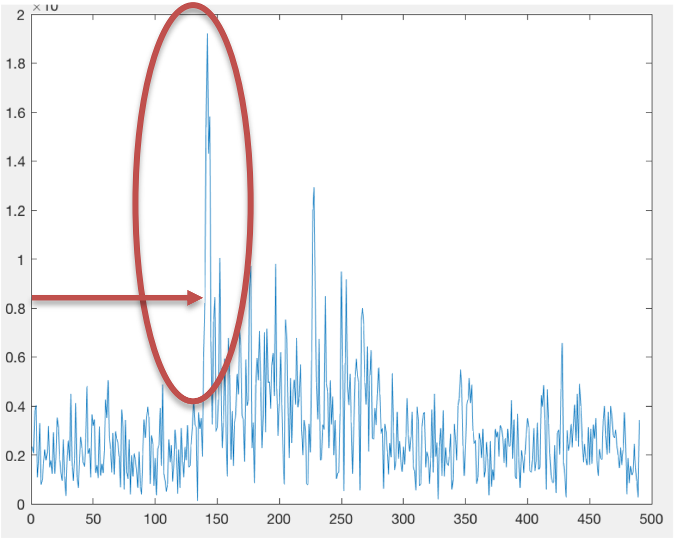
Correlated Channel Impulse Response

Recovery of modulated signal improves with greater integration time

- $R_1 = 6$ m, $R_2 = 24$ m



Raw Channel Impulse Response

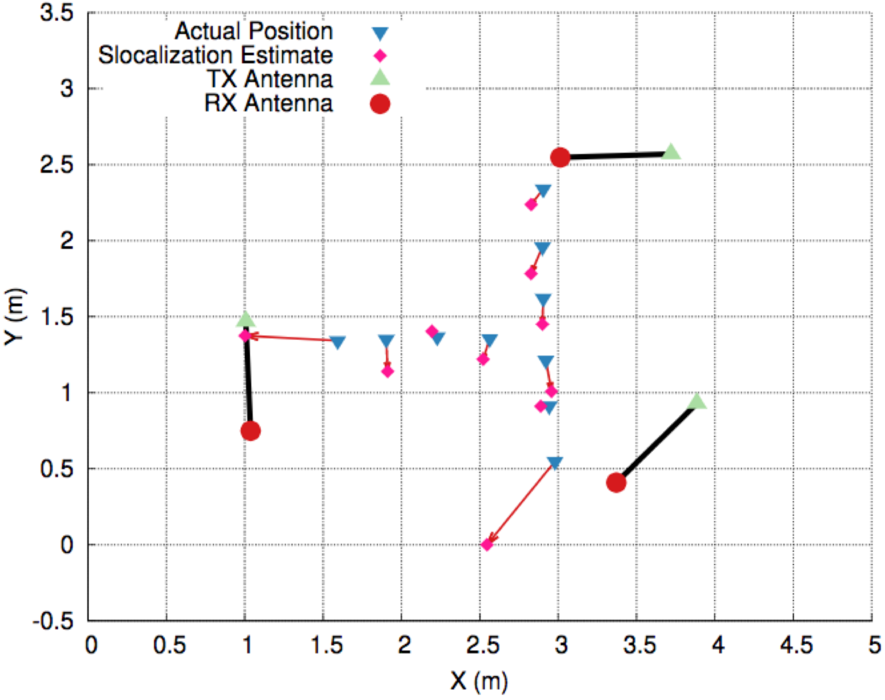


Correlated Channel Impulse Response

500 seconds
(8.3 minutes)

Can we localize?

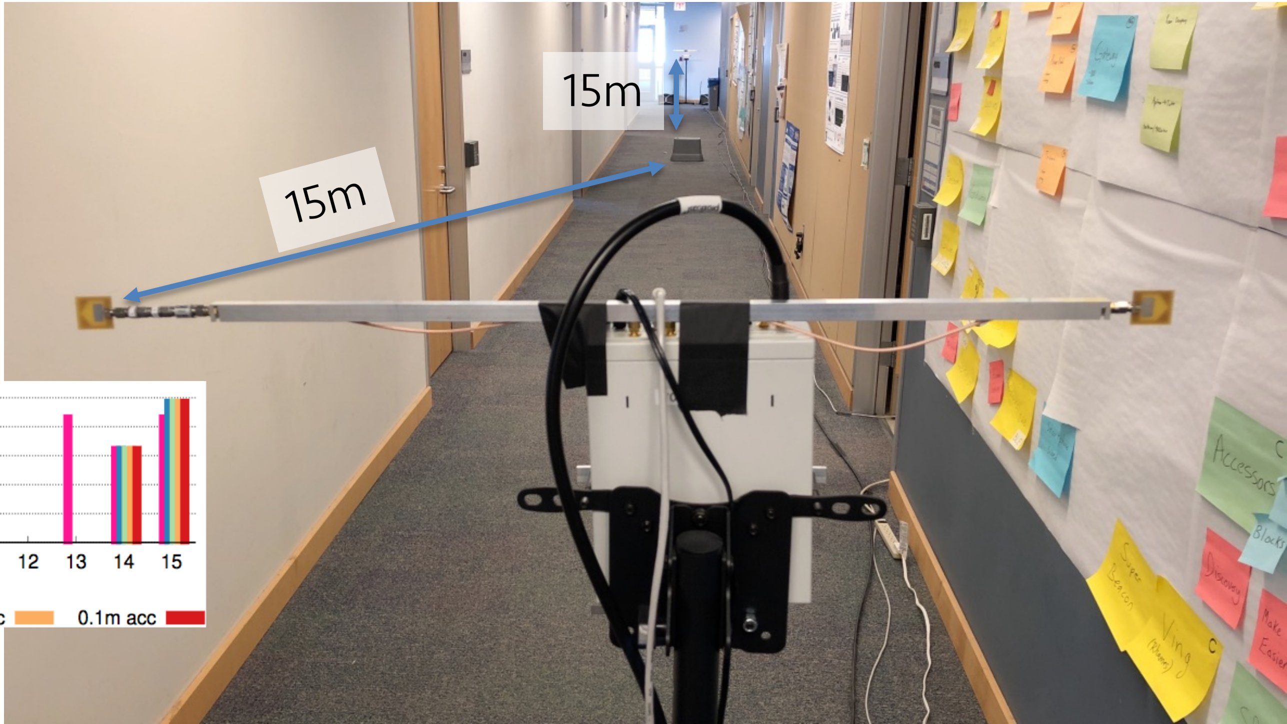
- Yes!

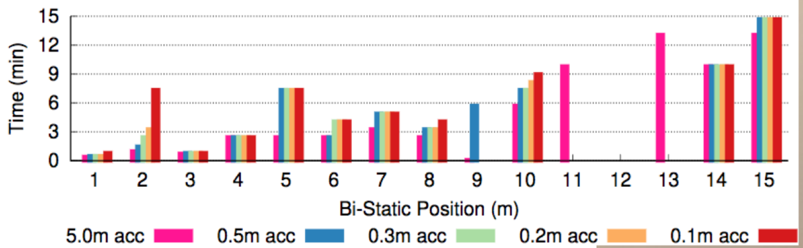


	Min	Max	Mean	Median
2D XY Euclidean Error (m)	0.05	0.70	0.25	0.18
3D Euclidean Error (m)	0.08	0.70	0.30	0.26

Can we really cover whole rooms?

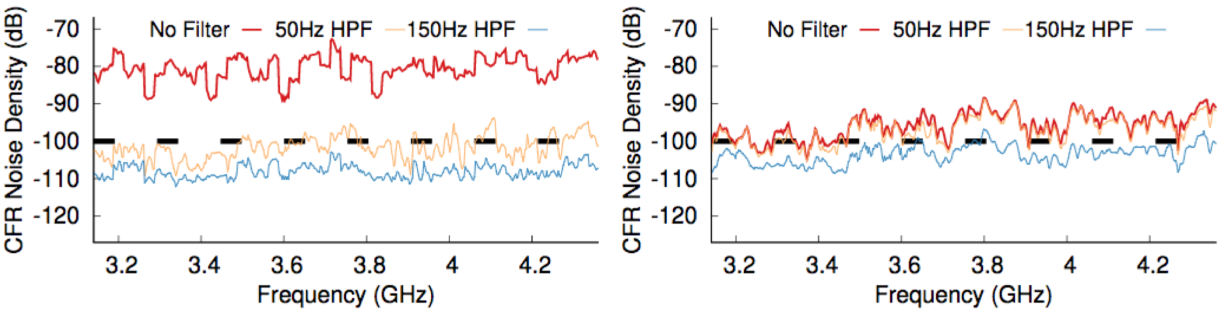
- 15 minutes can cover 30 meters





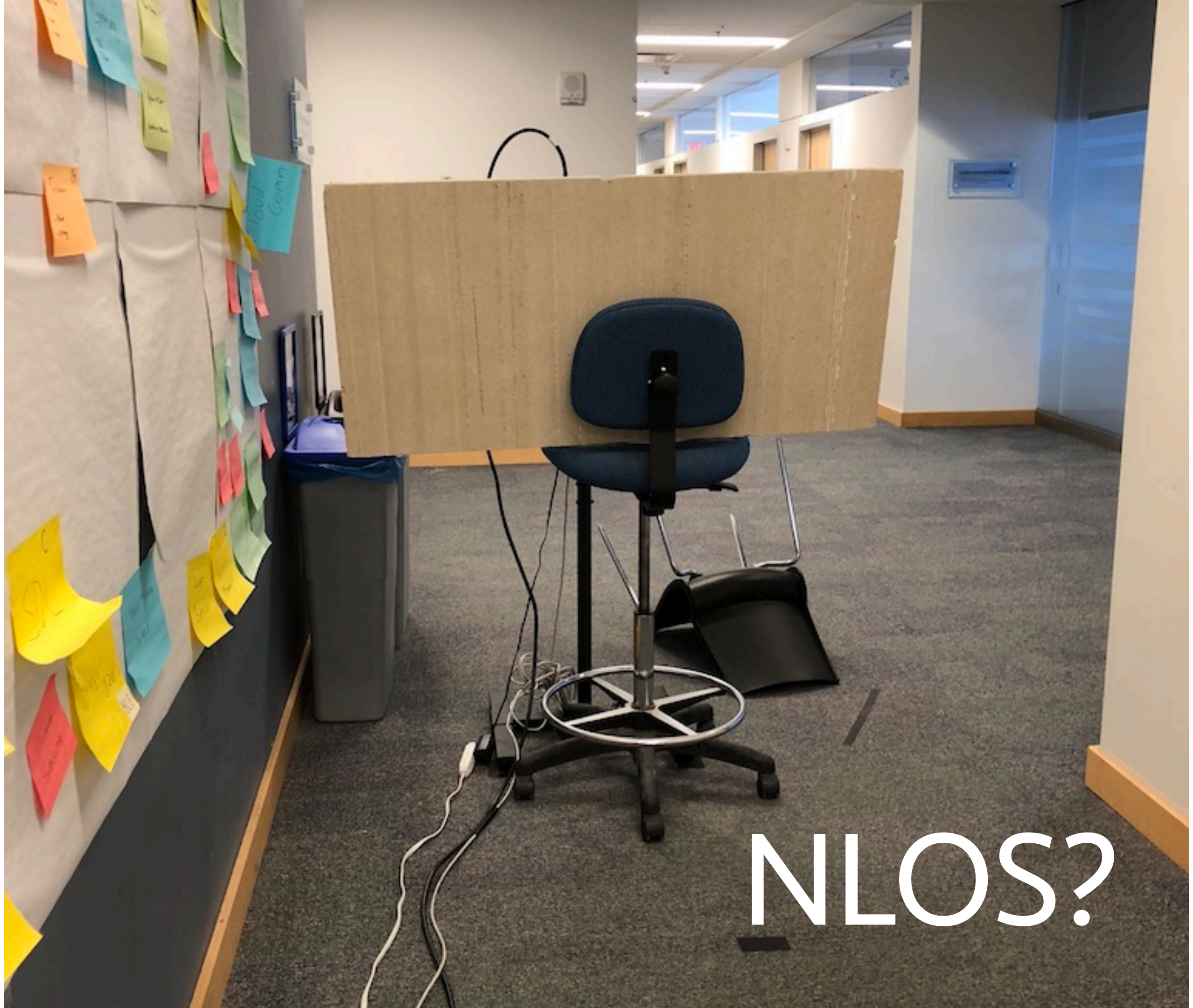
Environmental Factors?

- Most environment noise is < 150Hz, filter
  - Sets floor for tag frequency (and in turn active power)



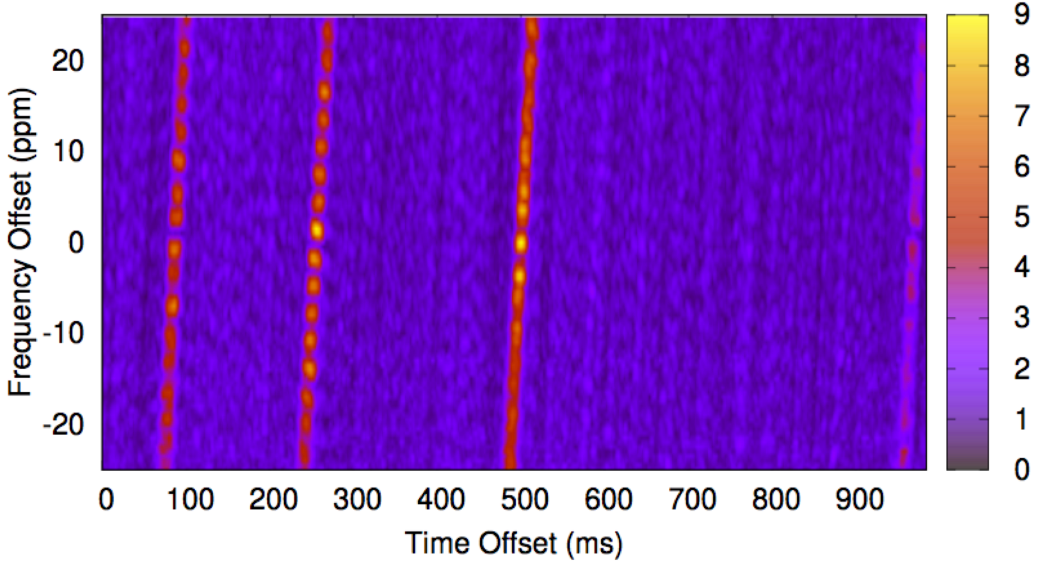
(b) CFR Noise Walking **(c) CFR Noise Fluorescents**

  - Problem: A fan at a bad speed is a bad day for slocalization


NLOS?

Does it scale to multiple tags?

- Can use PN codes for concurrent tags



- ... But processing is expensive

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Numerous diversity sources allows Slocalization to scale to very many tags

- Frequency division scales linearly in frequencies
  - Caveat: 256.00 Hz low-power RTCs exist, less so 256.20 Hz, etc
  - Caveat: Power draw scales linearly with switching frequency
- PN codes scale linearly in tag length
- Temporal code rotation scales *factorially*, but is very slow
  - Idea: Exploit tag stationarity further, rotating PN codes over time

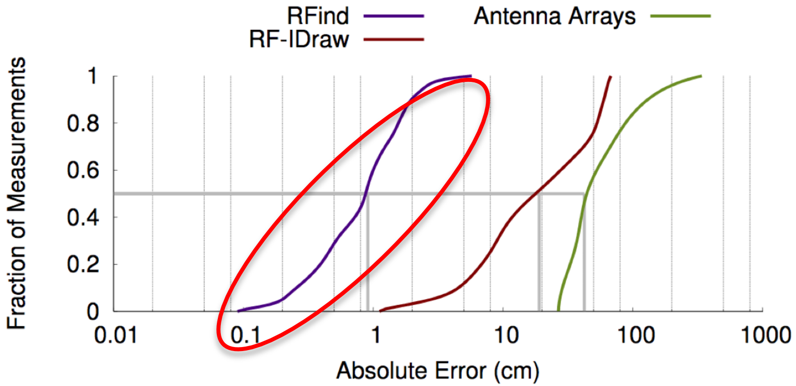
$$f_{\text{STEPS}} * \text{PN}_{\text{bits}} * \text{Codes} = 1{,}280 \ * 63 \ * 4! = 1{,}935{,}360 \text{ concurrent tags}$$

in roughly a few hours

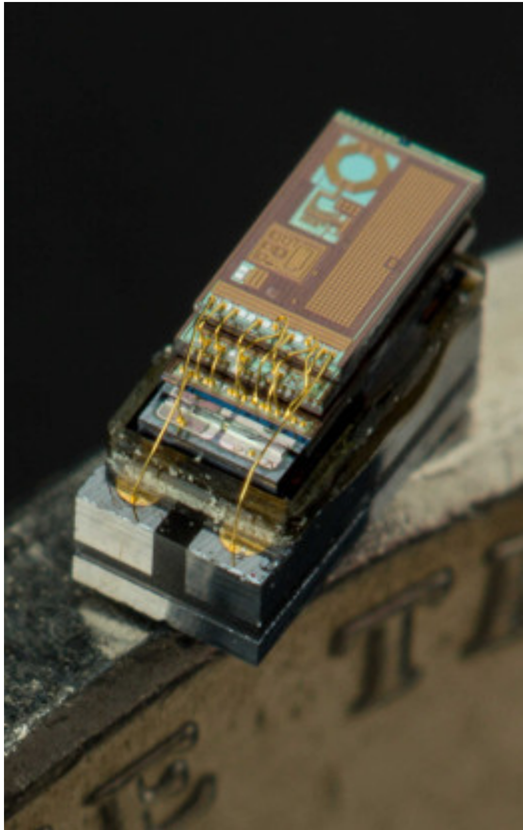
Feasibility? Power? | Time | ***Time***

Can we localize every physical thing? Even dust?

- Super-resolution technique from MobiCom'17
  - Use frequency information to refine localization



- Key idea:
  - If traditional localization can get close (7cm), refine estimate based on the estimate from each frequency



Minding the Billions…, Ma, Selby, Adib. MobiCom'17

Slocalization:
Sub-µW Ultra Wideband Backscatter Localization

- Decimeter accurate, FCC-compliant, sub-µW localization
- Ultra wideband backscatter platform
- Ultra wideband backscatter recovery from below noise floor
- Demonstrated over 30m anchor-tag-anchor in LoS & NLoS
- Designs, firmware, processing, etc:
  - github.com/lab11/slocalization