NIST

PSCR

UWB Localization and Mapping Using Computational Imaging

Fabio da Silva, Anthony Kos, Grace Antonucci, Jason Coder, and Craig Nelson

NIST Boulder

#PSCR2019

DISCLAIMER

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately.

Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

*Please note, unless mentioned in reference to a NIST Publication, all information and data presented is preliminary/in-progress and subject to change

UWB Localization and Mapping Using Computational Imaging

- Motivation/Goals/Challenges
- Information Theory Approach
- Physics of Field Compressive Sampling and Sensing
- Implementation
- Results and discussion

Motivation

What location information is still lacking in mission critical events such as a fire in a building?

Situational awareness challenge

- Can we infer what's going on inside?
- How fast can we have the information?
- How accurate is the information?
- Can we track the situation in real time?

Goal

Localization and mapping with RF signals

RF Paradigm Challenge

- 1 m resolution
- One-way comms minimum
- Real-time (0.1 s refresh rate)
- Range of 1-100 m
- Infrastructure free
- Readily deployable (1-5 min)
- No (minimum) interference

Implementation

Radar-based technology

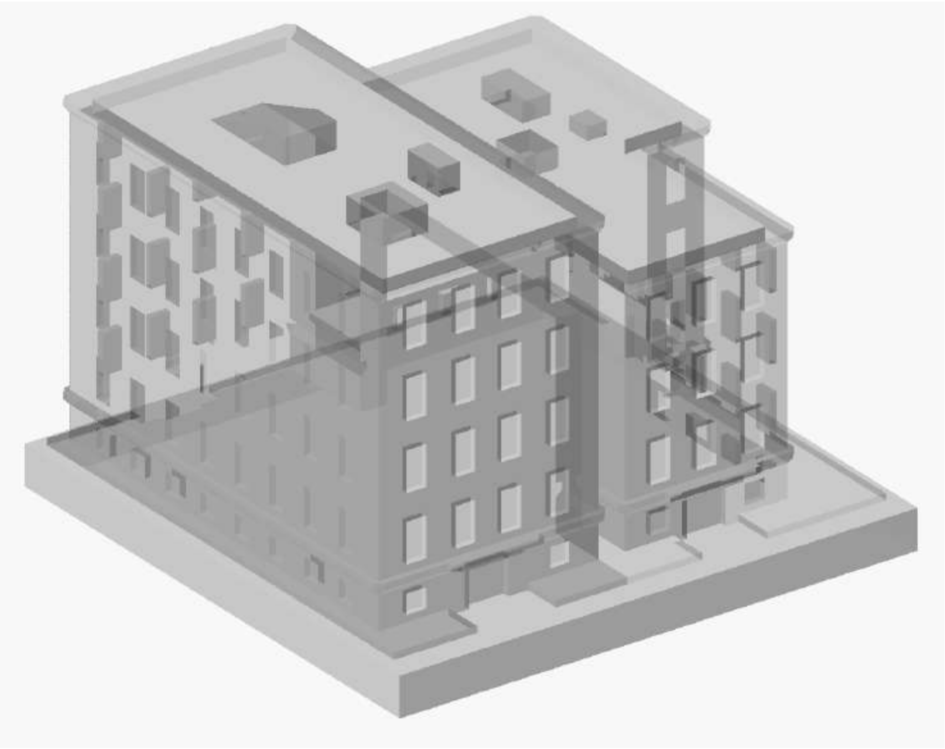
Implementation challenge

- Multi-static radar array Tx
- Few (one) receivers Rx
- Deployable footprint
- Signal controls
- Signal processing (model)
- Visualization

Information Theory Approach

How much information are we after?

- 3D structures are mostly empty
- What is not empty…
  - Can be static or dynamic
  - Is opaque to visible light
  - Is semi transparent to RF
  - **Is information**
- How do we measure this information?
  - We sample it first with RF waves
  - Then we sense what comes back:
    - **What comes back is all the information we have and need!**

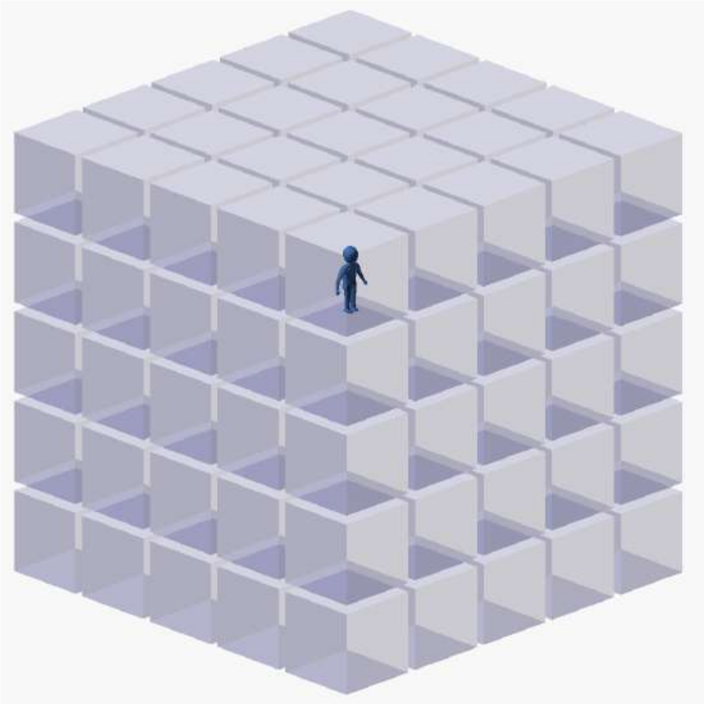


Information Theory Approach

How much information are we after?

- If the scene has volume $\boldsymbol{N}$ and
- What is not free space has volume $\boldsymbol{K}$
- Then the probability of not finding free space in the scene is $\boldsymbol{p} = \boldsymbol{K}/\boldsymbol{N}$
- The information in the scene is thus: $I = -p\ log(p) - (1-p)\ log(1-p)$
- From which we conclude, if $p \ll 1$:

$$M \geq K\ log\left(\frac{2N}{K}\right)$$



Physics of Field Compressive Sampling and Sensing

How are measurements modeled? The **sampling** part.

Physics of Field Compressive Sampling and Sensing

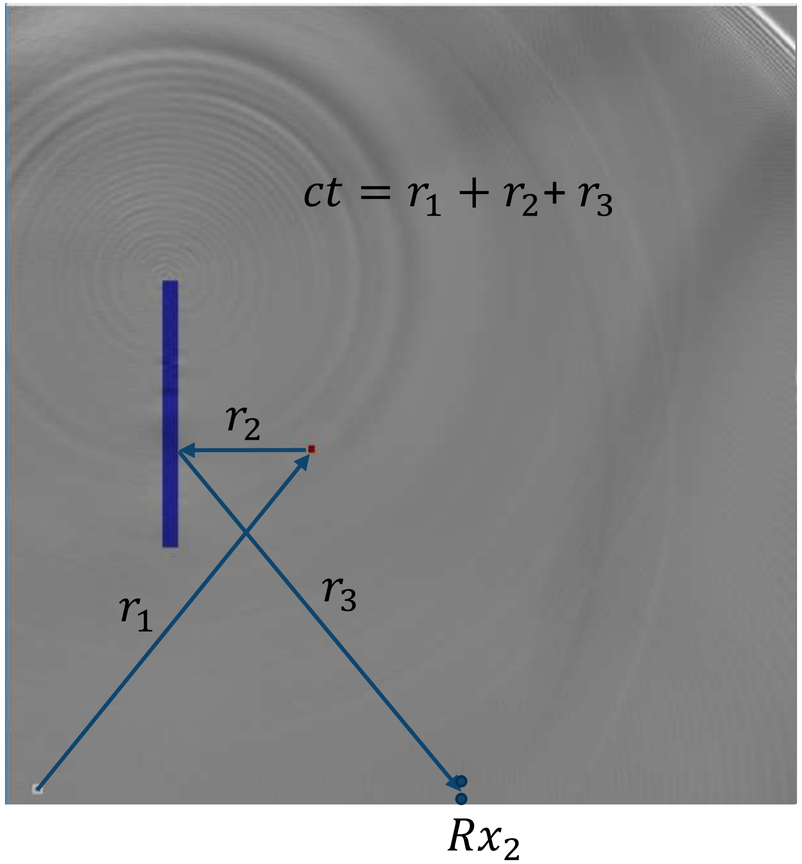
How are measurements modeled? The **sensing** part.

- **Background subtraction**
- **The geometry of sensing synchronously:**

$$ct = \sum_{i=0}^{n} r_i$$

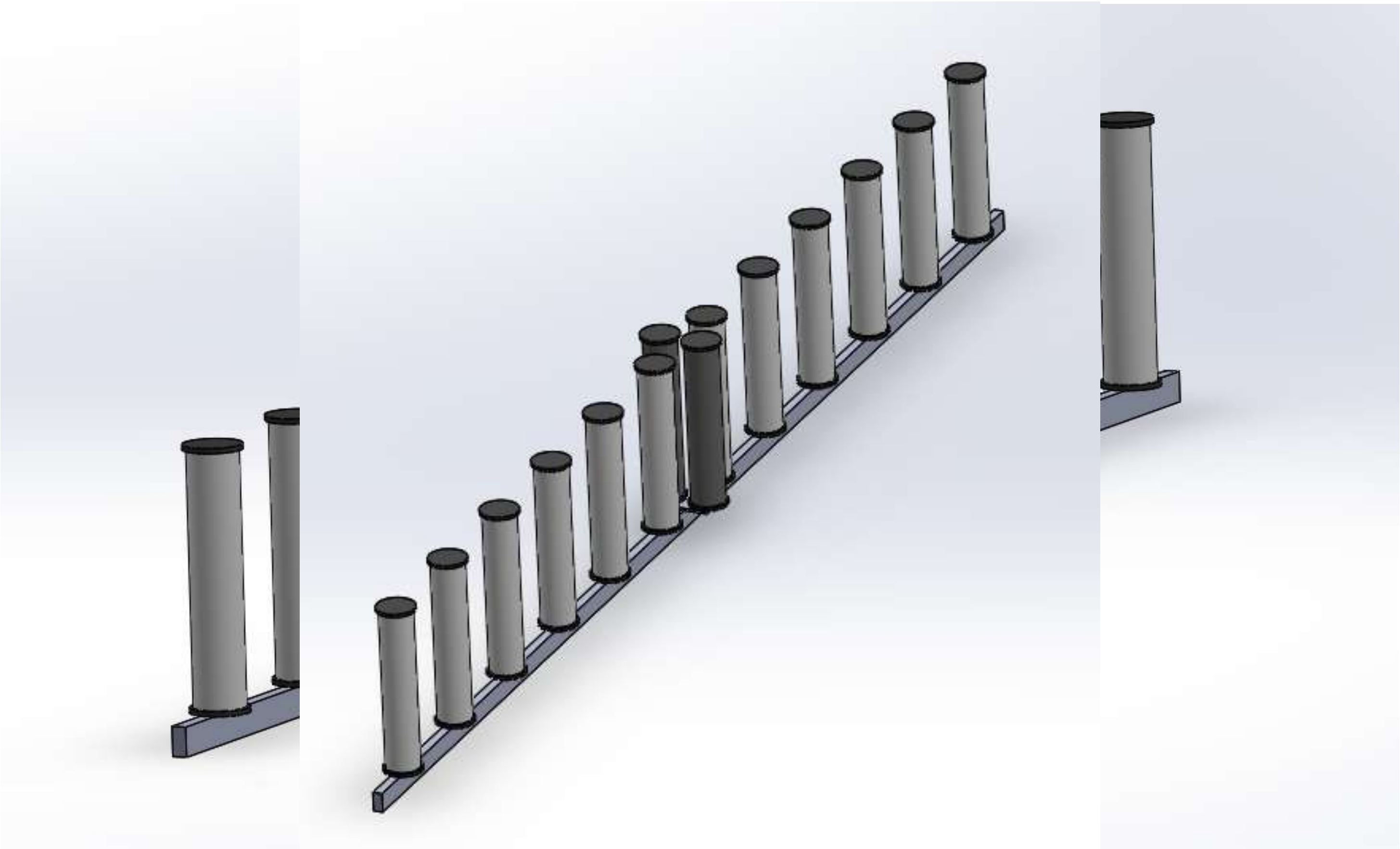
- **The weight functions**

$$W = \prod_{i=0}^{n} \frac{1}{r_i}$$



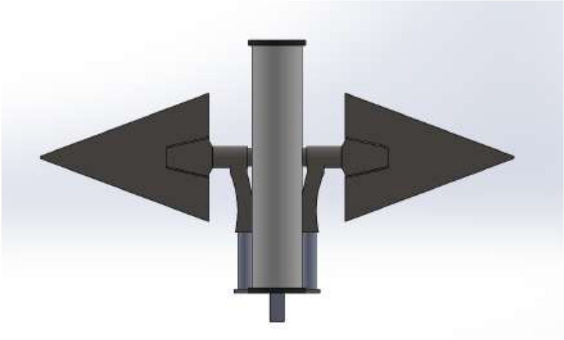
Implementation

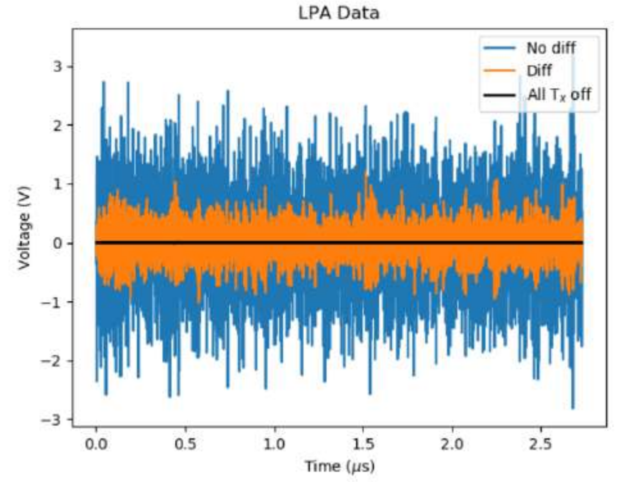
Antenna array setup

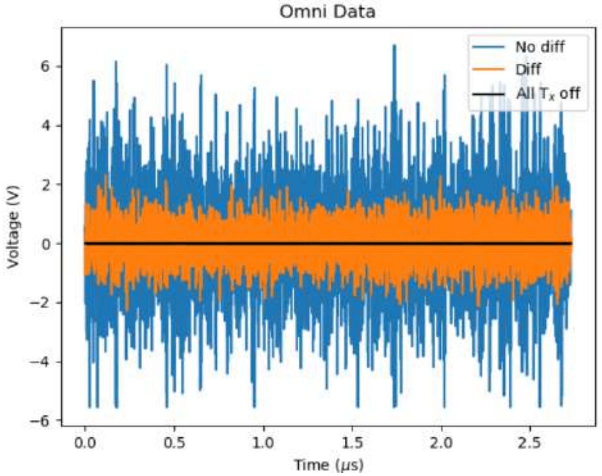


Implementation

Background subtraction

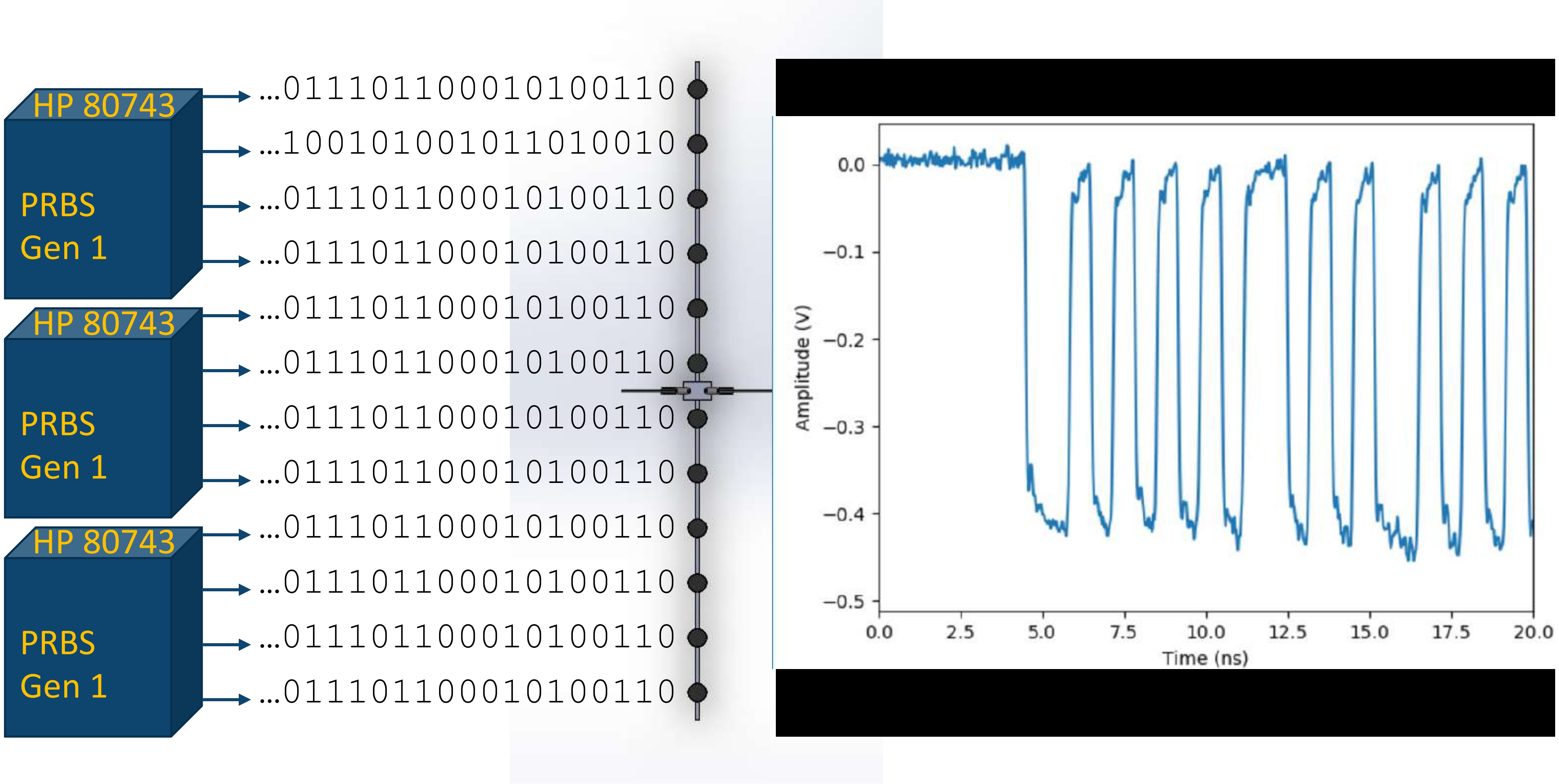






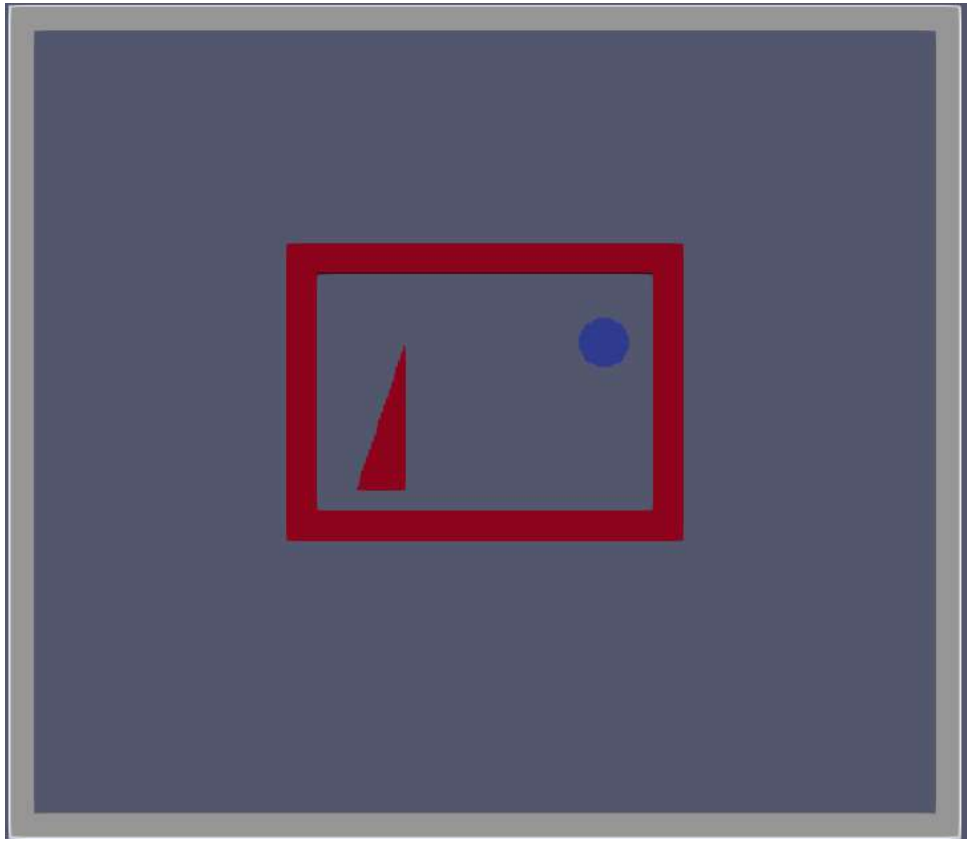
Implementation

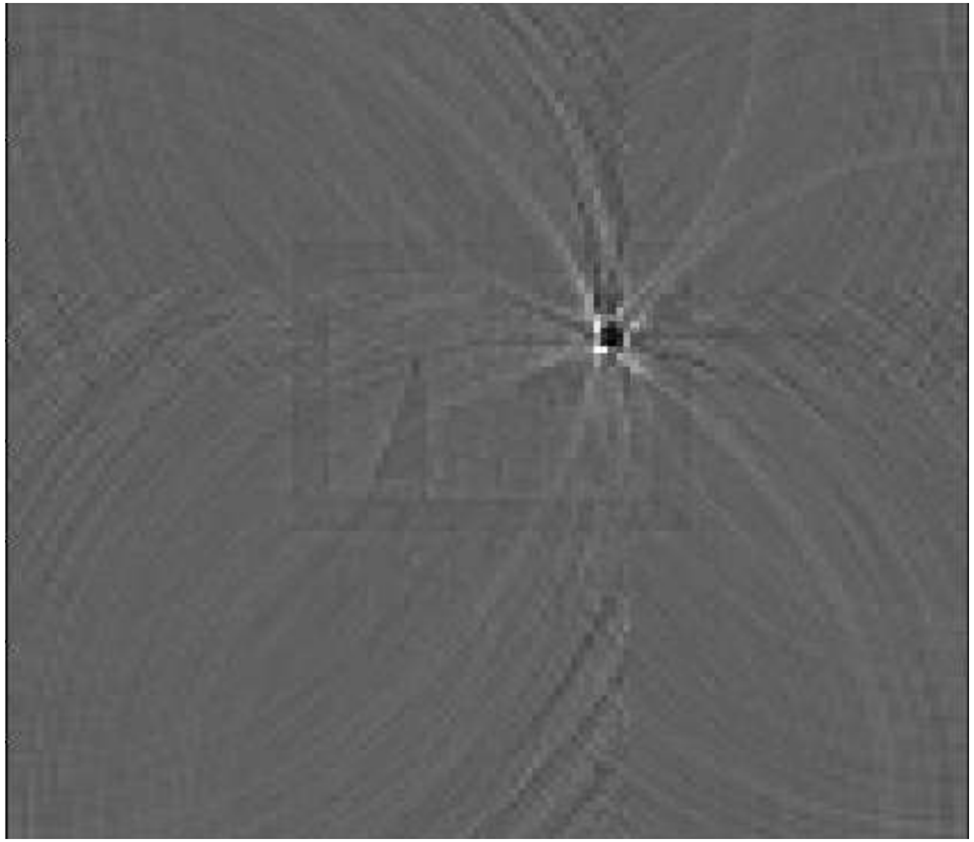
Pseudo-random binary sequences



Implementation

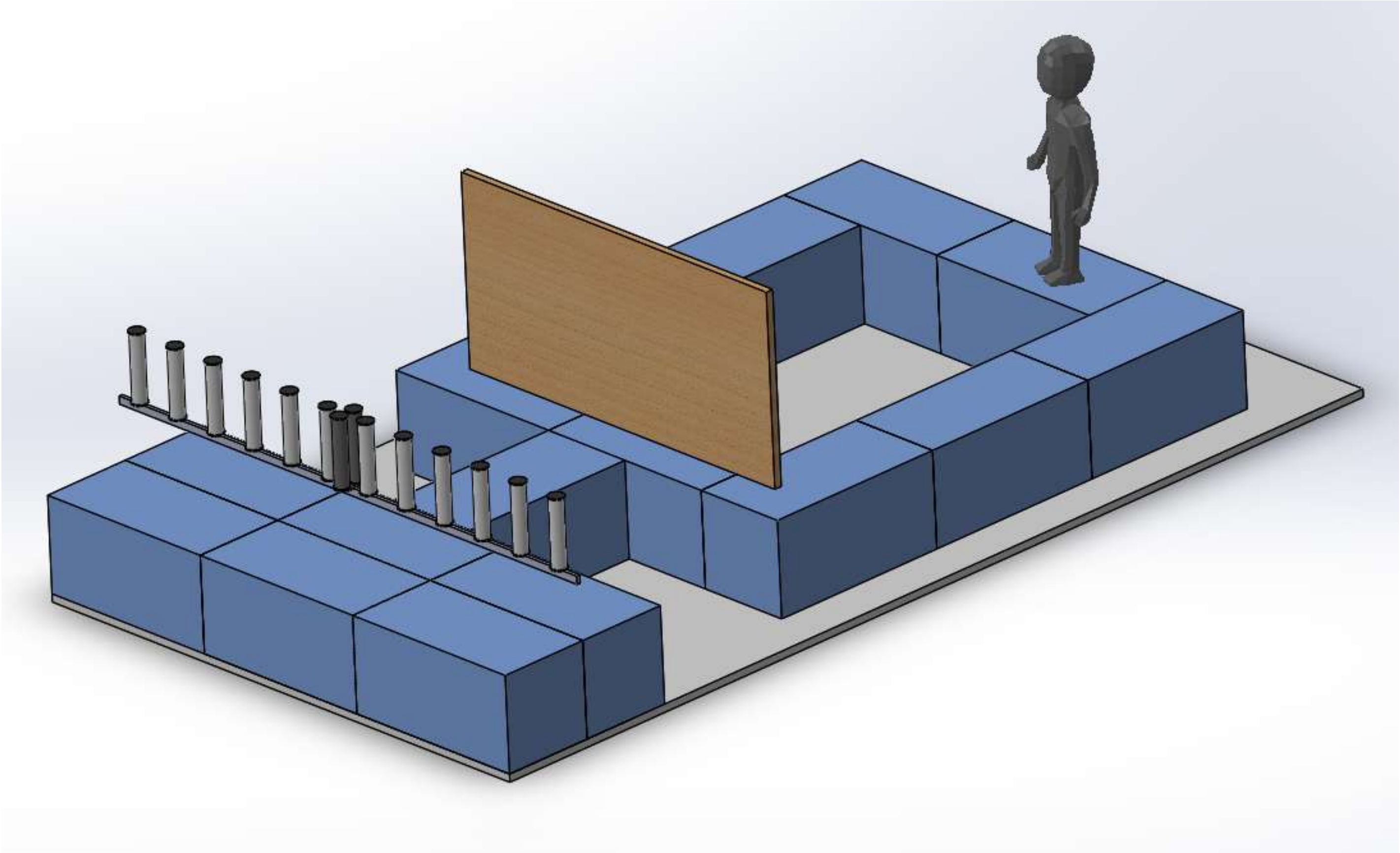
Image recovery





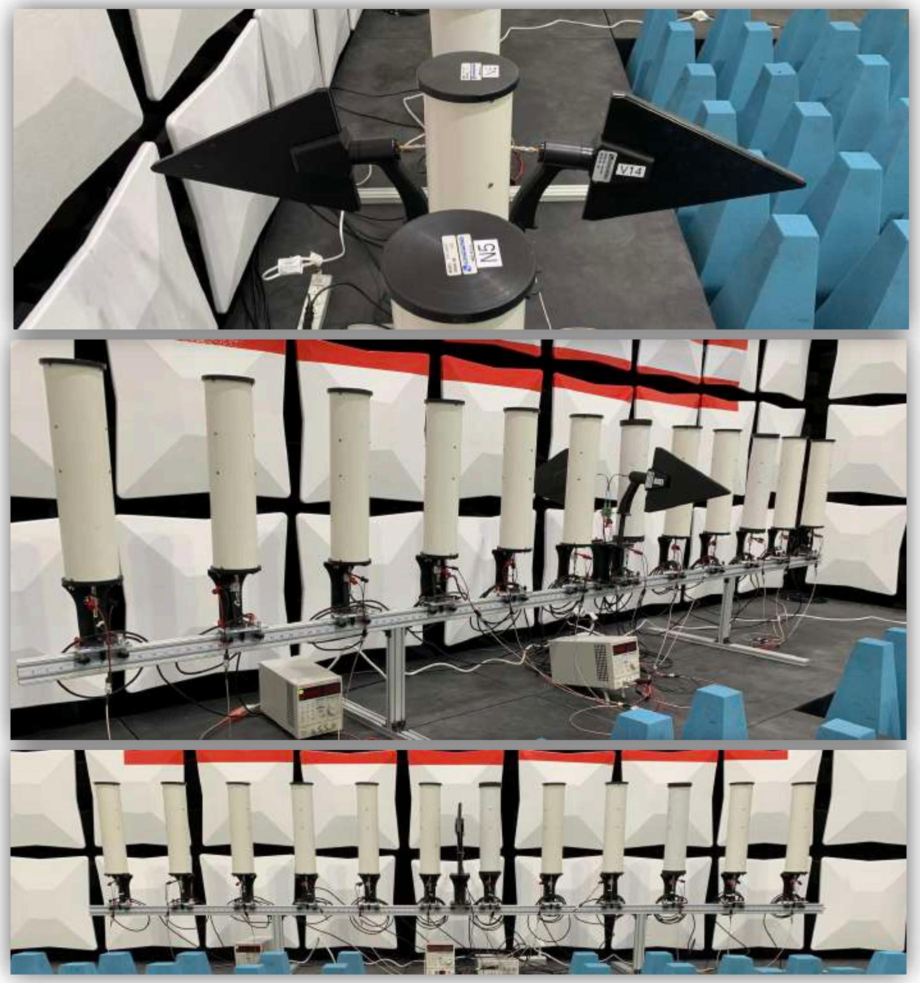
Results

Imaging



Results

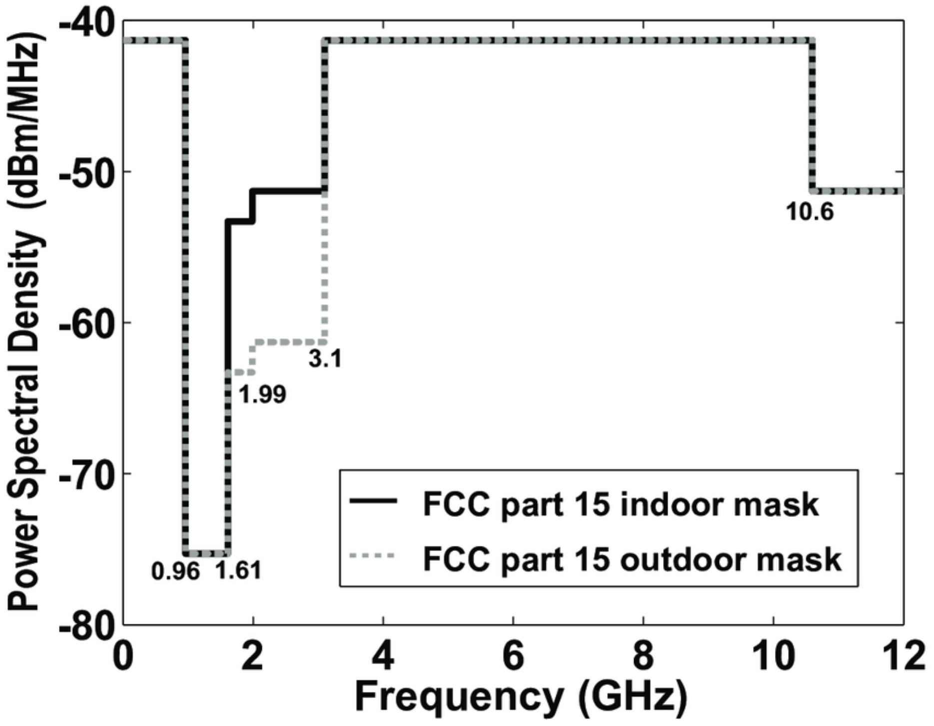
Imaging



Results

Interference

- **Typical sensing times: 4 µs**
- **RMS Power: 5.88 W (12 Tx)**
- **Bandwidth: 1 GHz (500-1500 MHz)**
- **RMS Power: 6.55 dBm/MHz**
- **Duty cycle: 0.02 % (50 Hz rate)**
- **RMS (duty cycle): -60.44 dBm/MHz**



Discussion

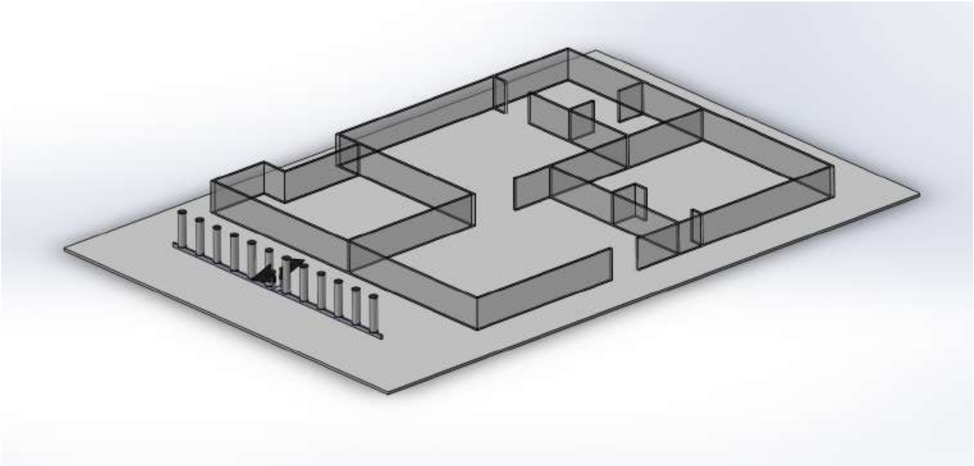
A realistic prototype goal

RF Paradigm Challenge

- Cm resolution: less than 0.3 m
- One-way comms minimum: ✓
- Real-time (0.1 s refresh rate): ✓
- Range of 1-100 m: ✓
- Infrastructure free: ✓
- Readily deployable (1-5 min): ✓
- No (minimum) interference: ?

Situational awareness challenge

- Can we infer what's going on inside?
  - Yes, 10 m deep with 10 W of RF power
- How fast can we have the information?
  - Real time (0.1 s refresh rate) for position
  - 60 s for mapping
- How accurate is the information?
  - Position/mapping still affected by delays
  - Systematic errors
- Can we track the situation in real time?
  - Yes, the system responds dynamically to the scene



THANK YOU

Come see our demo later today

#PSCR2019

Come back for the

Next Session

1:50 PM

Physics of Field Compressive Sampling and Sensing

How are measurements modeled? The **sampling** part.

- **Wave Equation for a general source:**

$$\nabla^2 E^{(0)} - \frac{1}{c^2}\frac{\partial^2 E^{(0)}}{\partial t^2} = S(t', \boldsymbol{r}')$$

- **Solution for a point source** $S(t', \boldsymbol{r}') = \delta(t', \boldsymbol{r}')$**:**

$$E^{(0)}(t, t', \boldsymbol{r}, \boldsymbol{r}') = G(t, t', \boldsymbol{r}, \boldsymbol{r}') = \frac{\delta(t' - [t - |\boldsymbol{r} - \boldsymbol{r}'|/c])}{|\boldsymbol{r} - \boldsymbol{r}'|}$$

- **First order scattering off an object:**

$$E^{(1)}(\boldsymbol{r}, t) = \int G(t, t', \boldsymbol{r}, \boldsymbol{r}')\, E^{(0)}(t', \boldsymbol{r}')x^{(0)}(\boldsymbol{r}')dt'd\boldsymbol{r}'$$

Physics of Field Compressive Sampling and Sensing

How are measurements modeled? The **sampling** part.

- **Second order scattering off an object:**

$$E^{(2)}(\boldsymbol{r},t) = \int G(t,t',\boldsymbol{r},\boldsymbol{r}')\,E^{(1)}(t',\boldsymbol{r}')\left[x^{(0)}(r') + x^{(1)}(r')\right]dt'd\boldsymbol{r}'$$

- **nth order scattering from J transmitters $E^{(n)}$ is:**

$$\int G(t,t',\boldsymbol{r},\boldsymbol{r}')\,E^{(n-1)}(t',\boldsymbol{r}')\left[x^{(0)}(r') + \cdots + x^{(n-1)}(r')\right]dt'd\boldsymbol{r}'$$

$$E^{(n)}(\boldsymbol{r},t) = \sum_{j=1}^{J} E_j^{(n)}(\boldsymbol{r},t)$$

Physics of Field Compressive Sampling and Sensing

How are measurements modeled? The **recovery** part.

- **The first-order scattering equation:**

$$E^{(1)}(\boldsymbol{r},t) = \int G(t,t',\boldsymbol{r},\boldsymbol{r}')\,E^{(0)}(t',\boldsymbol{r}')x^{(0)}(\boldsymbol{r}')dt'd\boldsymbol{r}'$$

- **Can be cast in matrix form for a receiver at the origin, $\boldsymbol{r} = 0$:**

$$y = A^{(0)} \cdot x^{(0)}$$

- **Recovery from first-order scattering:**

$$x = (A^T \cdot A)^{-1} A^T \cdot y \qquad \min_{x\in\mathbb{R}^d} \|x\|_1 \quad y = A \cdot x$$

Results

Interference

50 Ohm matched output power calculations				
Vpp	7	V		
Vrms	4.95	V		
Load	50	Ohm		
Burst duration	4	us		
Burst repetition rate	50	Hz		
Duty cycle	0.020%			
Total Burst Power Used Per Box (3 channels)				
	Peak	RMS		
Per transmitter	0.98	0.49	W	
Box 1 (3 channels)	2.94	1.47	W	
Box 2 (3 channels)	2.94	1.47	W	
Box 3 (3 channels)	2.94	1.47	W	
Box 4 (3 channels)	2.94	1.47	W	
Total	11.76	5.88	W	
	40.7	37.7	dBm	
Bandwidth start	200	200	3 dB point	Based on antenna specs
Bandwidth end	1500	1500	3 dB point	Based on signal specs through cable
Power density	0.009	0.005	W/MHz	
	9.56	6.55	dBm/MHz	
Duty cycle average	1.8E-06	9.0E-07	W/MHz	
	-57.43	-60.44	dBm/MHz	