Distributive Sensing Techniques for Context Aware Spectrum Mapping

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1. MOTIVATION

Using distributive sensing systems for geolocation of transmitters

Opportunities and Challenges

- Trend

Next-generation cognitive radios will be able to sense radio spectrum quickly and efficiently

- Need

There is a need for techniques to interpret and extract meaning from wide swaths of radio spectrum data

- Opportunity

Geolocation of transmitters along with the identification of unused and underutilized spectrum regions can provide context for Dynamic Spectrum Access decisions to avoid primary user interference

- Challenges

The challenges are both technical and regulatory

Spectrum opportunity sensing must consider

- Geographically distributed primary transmitters and receivers
- Mobile transmitters and receivers
- Underlay and overlay schemes

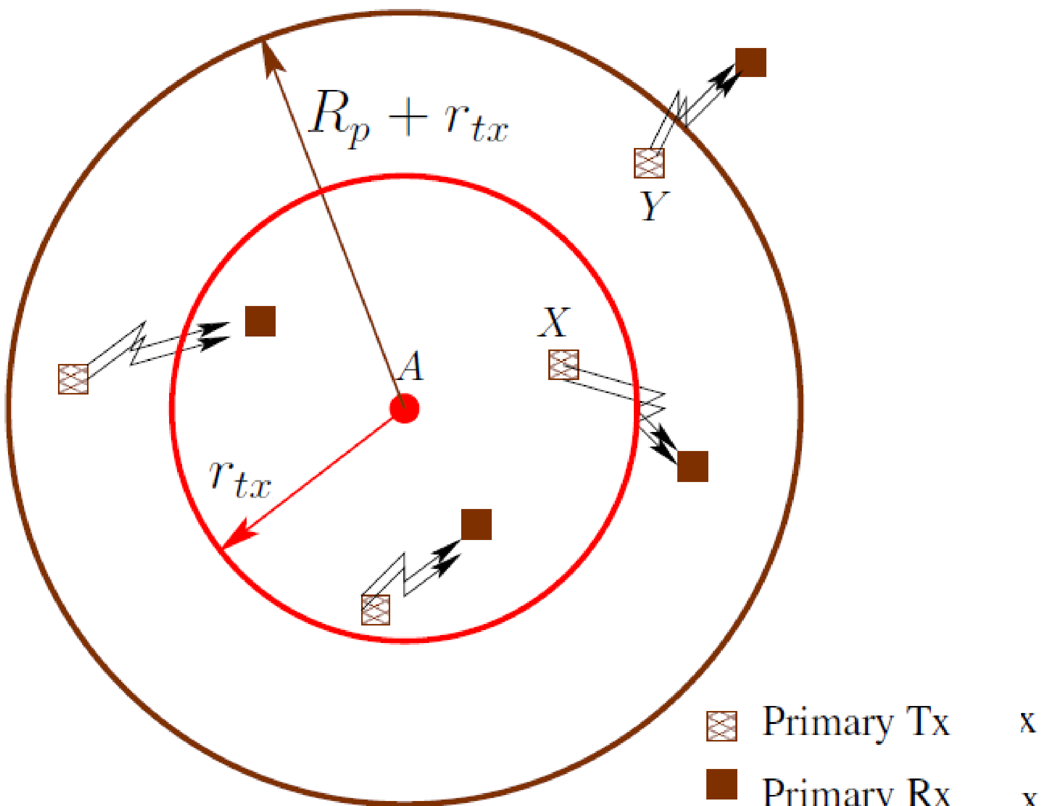


Fig. 2. Spectrum opportunity detection.

Reference: Q. Zhao and B.M. Sadler, “A Survey of Dynamic Spectrum Access,” in *IEEE Signal Processing Magazine*, p. 79, May 2007.

Outline

1. *Motivation*
2. *Background*
   - *Measurements used for localization*
3. *Case Study – Emitter Location Task*
   - *Simulation of the localization of a single emitter*
4. *Localization Algorithm*
   - *Formulation of the sensing problem*
   - *Compressive sensing for sparse signal recovery*
5. *Validation*
   - *Measurements acquired with mobile sensors*
6. *What's next?*
   - *Identify multiple transmitters*
   - *Using multiple receivers*
   - *Optimal placement and optimal path*

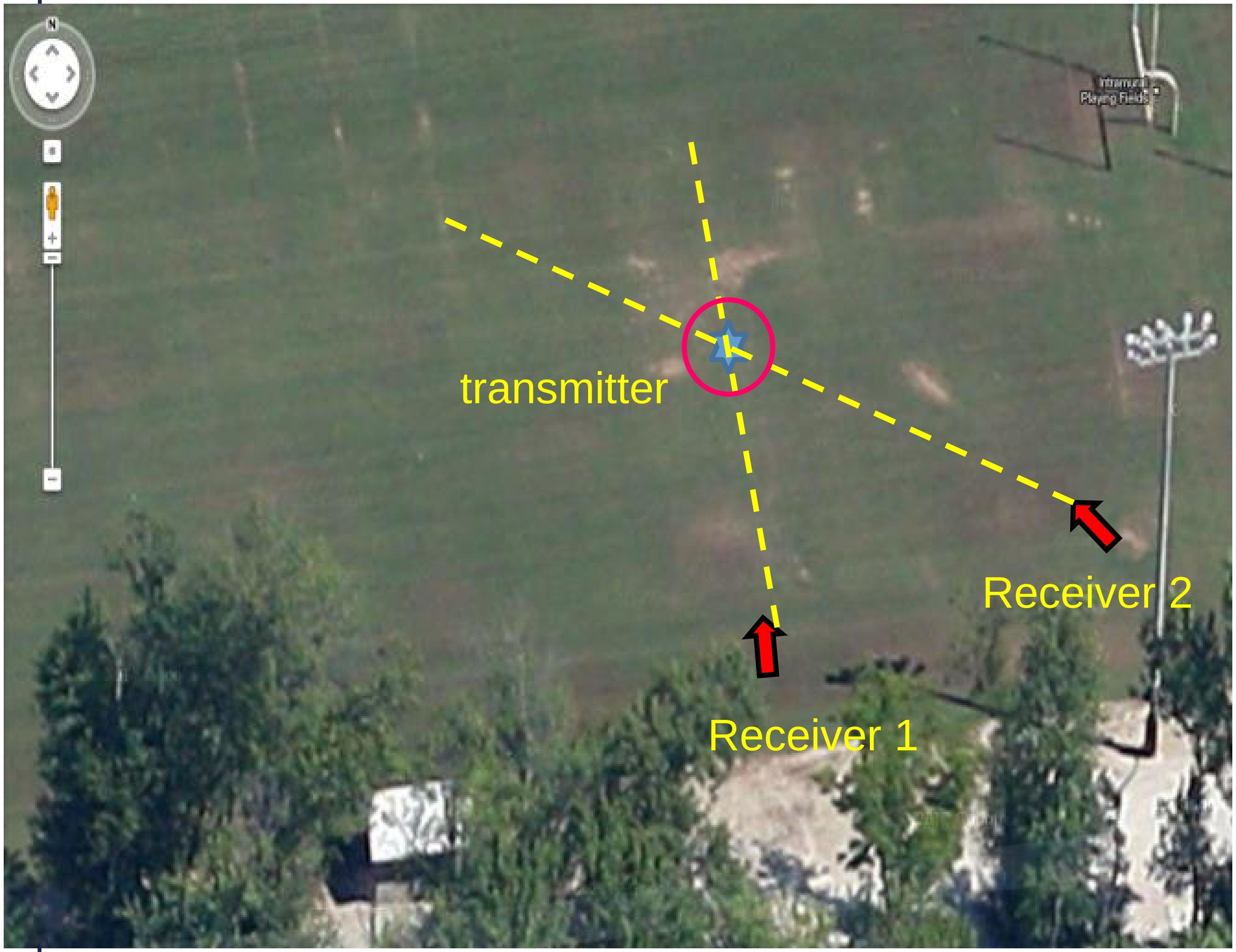
2. BACKGROUND

Measurements and methods of localization can be used to determine sensor requirements

Locate a CW emitter

Measurements that aid in source localization

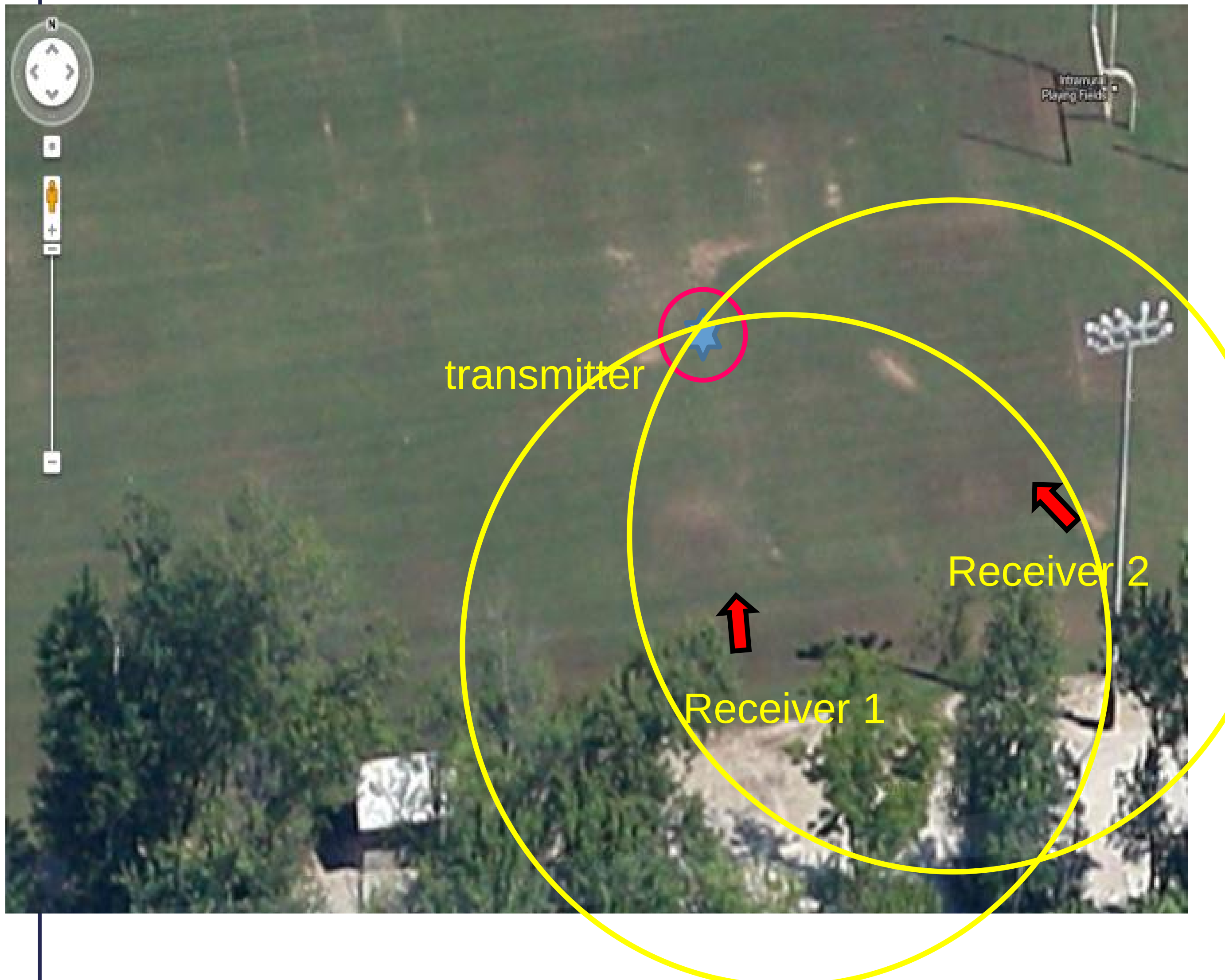
1. Angle of Arrival (AOA)



Locate a CW emitter

Measurements that aid in source localization

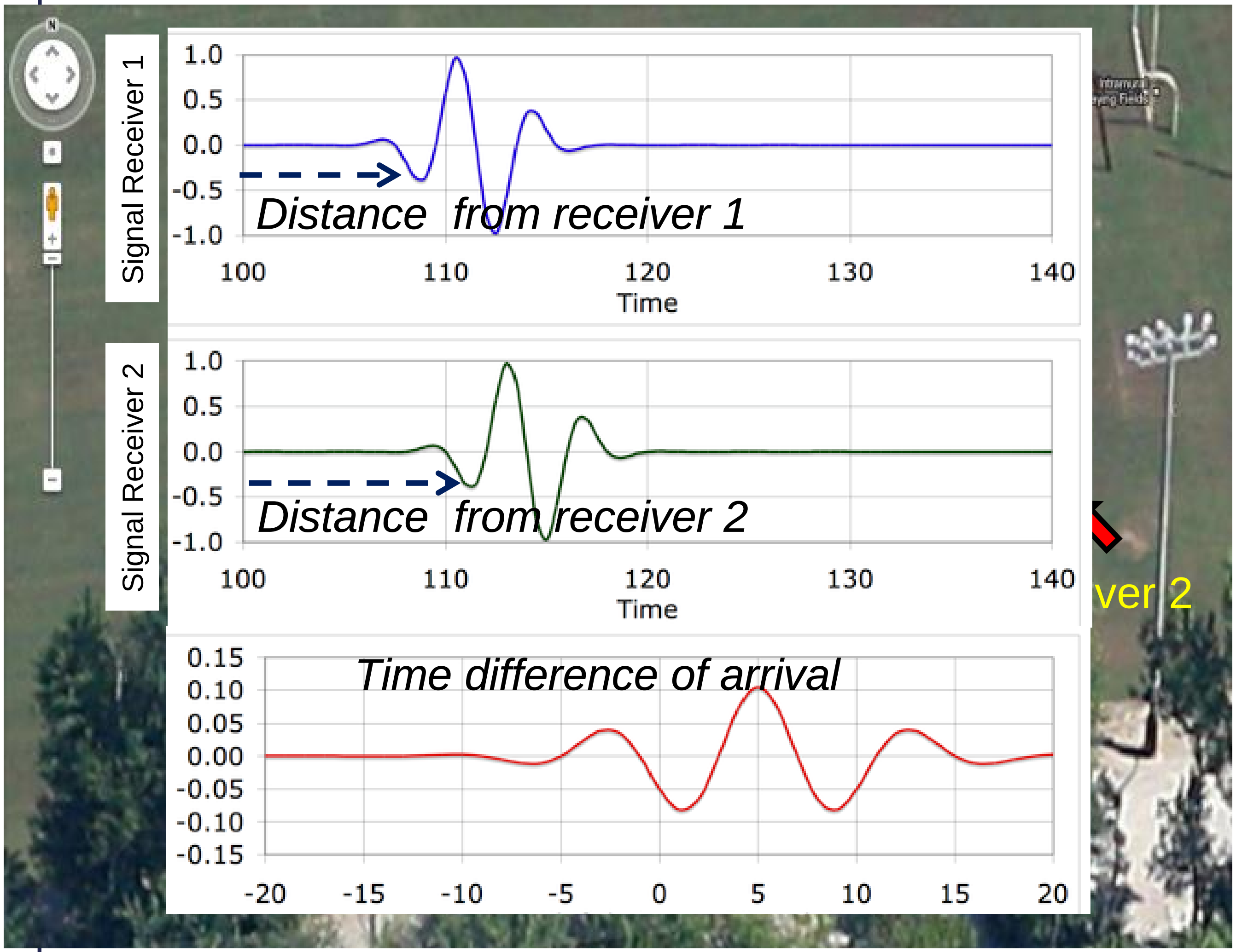
1. Angle of Arrival (AOA)
2. Received Signal Strength (RSS)



Locate a CW emitter

Measurements that aid in source localization

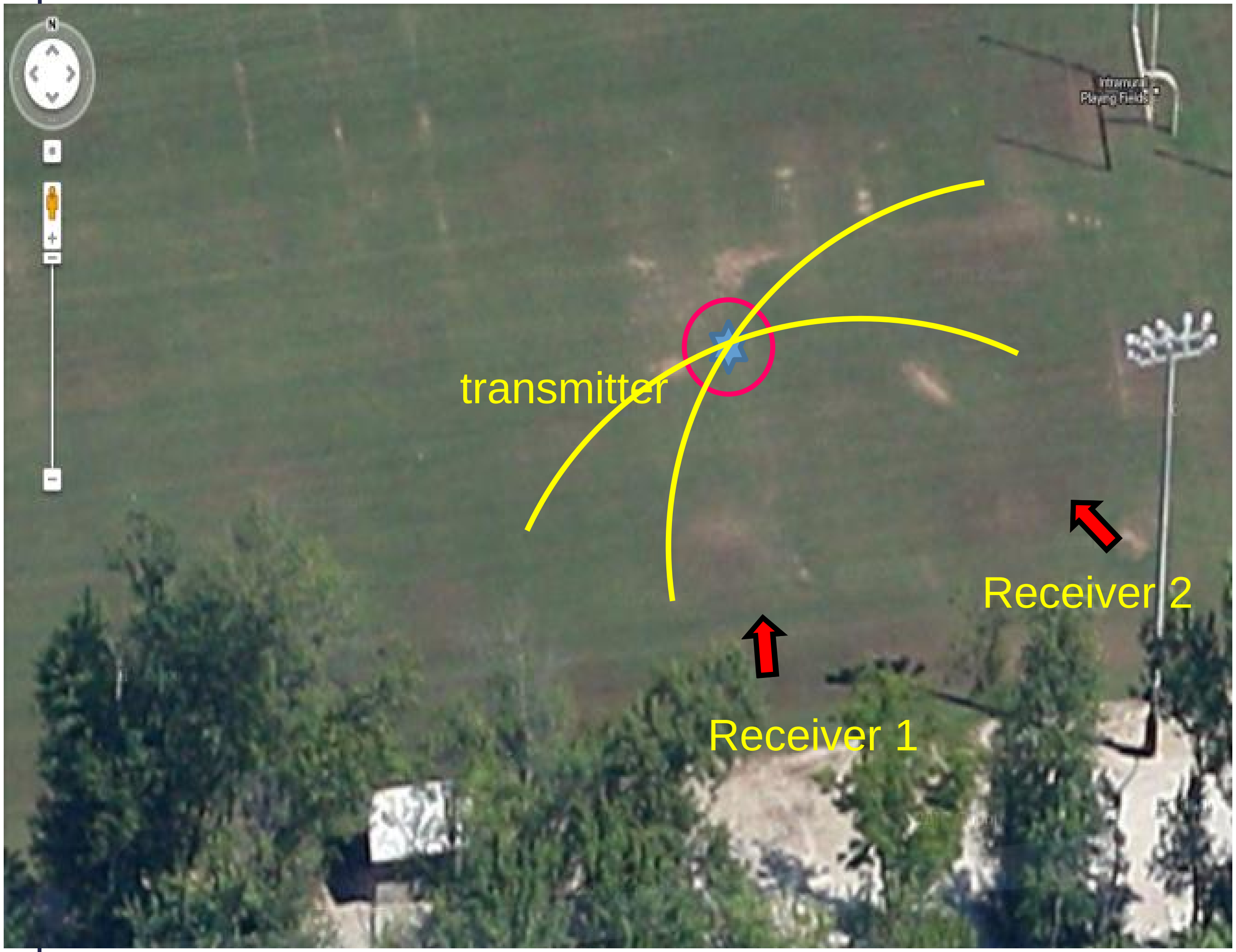
1. Angle of Arrival (AOA)
2. Received Signal Strength (RSS)
3. Time of Arrival (TOA)
4. Time Difference of Arrival (TDOA)



Locate a CW emitter

Measurements that aid in source localization

1. Angle of Arrival (AOA)
2. Received Signal Strength (RSS)
3. Time of Arrival (TOA)
4. Time Difference of Arrival (TDOA)
5. Frequency Difference of Arrival (FDOA) or Differential Doppler (DD)



Locate a CW emitter

Measurements that aid in source localization

Measurements that aid in source localization	*Advantages*	*Disadvantages*
1. Angle of Arrival (AOA)	Simplicity of location algorithm	Requires a phased array antenna usually limits the bandwidth of measurements
2. Received Signal Strength (RSS)	Simplicity of Receiver	Requires large sensor network or number of data points
3. Time of Arrival (TOA)	Accurate	Require precision timing
4. Time Difference of Arrival (TDOA)	Robust to environmental changes provide both sensors experience the same environment	Require precision timing, and precise knowledge of the sensors position
5. Frequency Difference of Arrival (FDOA) or Differential Doppler (DD)	Accurate	Require higher timing precision and communications overhead. Requires precisely known sensor velocity vectors

Assuming there will be a sensor system to enable dynamic spectrum access, we can mine the RF data to get location information - if we have algorithms that work on low accuracy information.

3. CASE STUDY

Suppose we want to find the location of a single, stationary emitter, continuous wave emission, omni-directional transmission

Locate a Single emitter

A single stationary transmitter, emitting a continuous-wave signal at 925MHz, is placed in 20x20meter region

A single sensor using a omni-directional receiver traverses a random path measuring Received Signal Strength (RSS) at each location.

How many positions (data) are needed to locate the signal source?

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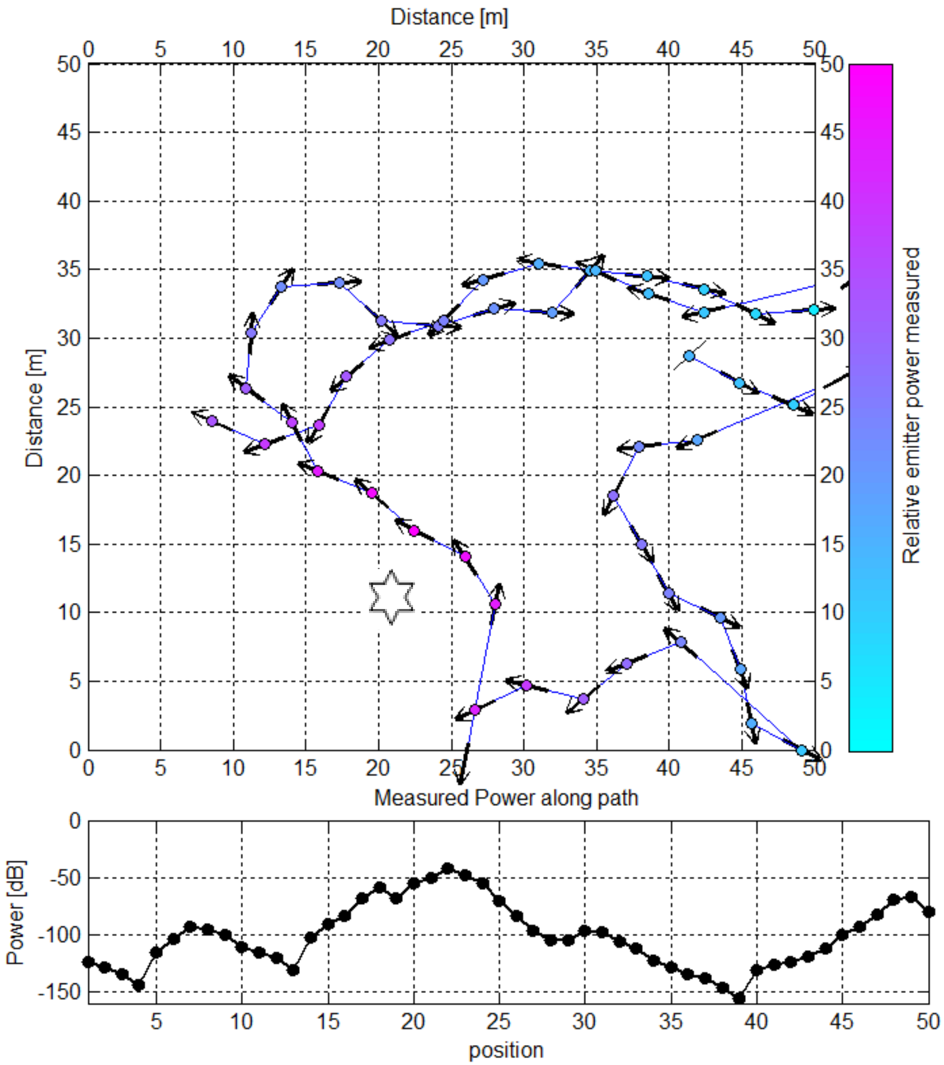
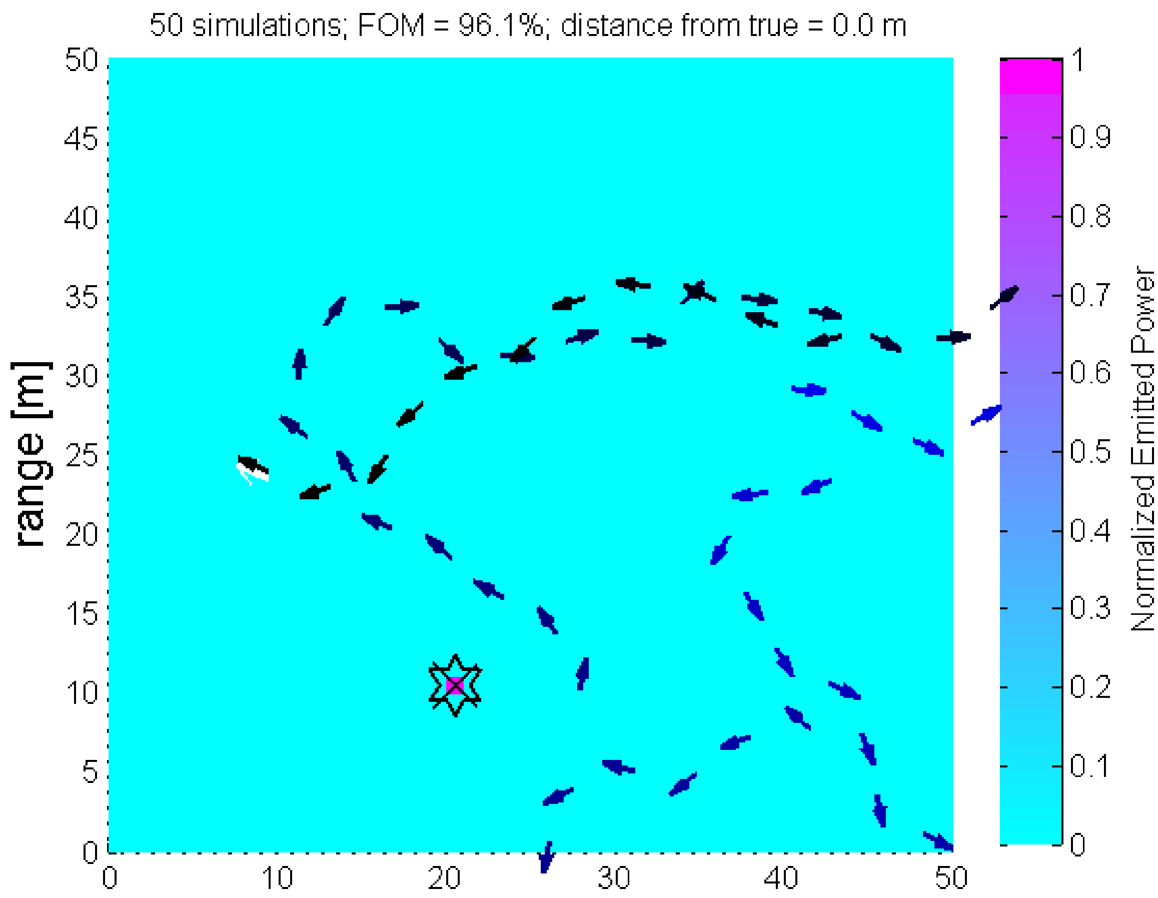
Simulation: Locate a single emitter

- *Transmitted signal is a continuous-wave signal*
- *single sensor receiver*
- *Omni-directional transmitter and receiver*
- *Sensor travels in a random path*
- *50 data points are collected*



Simulation: Locate a single emitter

- Reconstruct a map of emitted power based on sensor measurements
- Consider that power can be emitter from any or multiple points in the 50x50 pixels region
- After 7 simulated measures the algorithm's prediction is close to the ground truth
(FOM = 34.5%)
- After 18 simulated measures the algorithm predicts the exact location and the strength is nearly exact. (FOM = 94.9%)



4. LOCALIZATION ALGORITHM

An algorithm based on the mathematical principles developed in compressed sensing is used to solve the under-determined linear problem

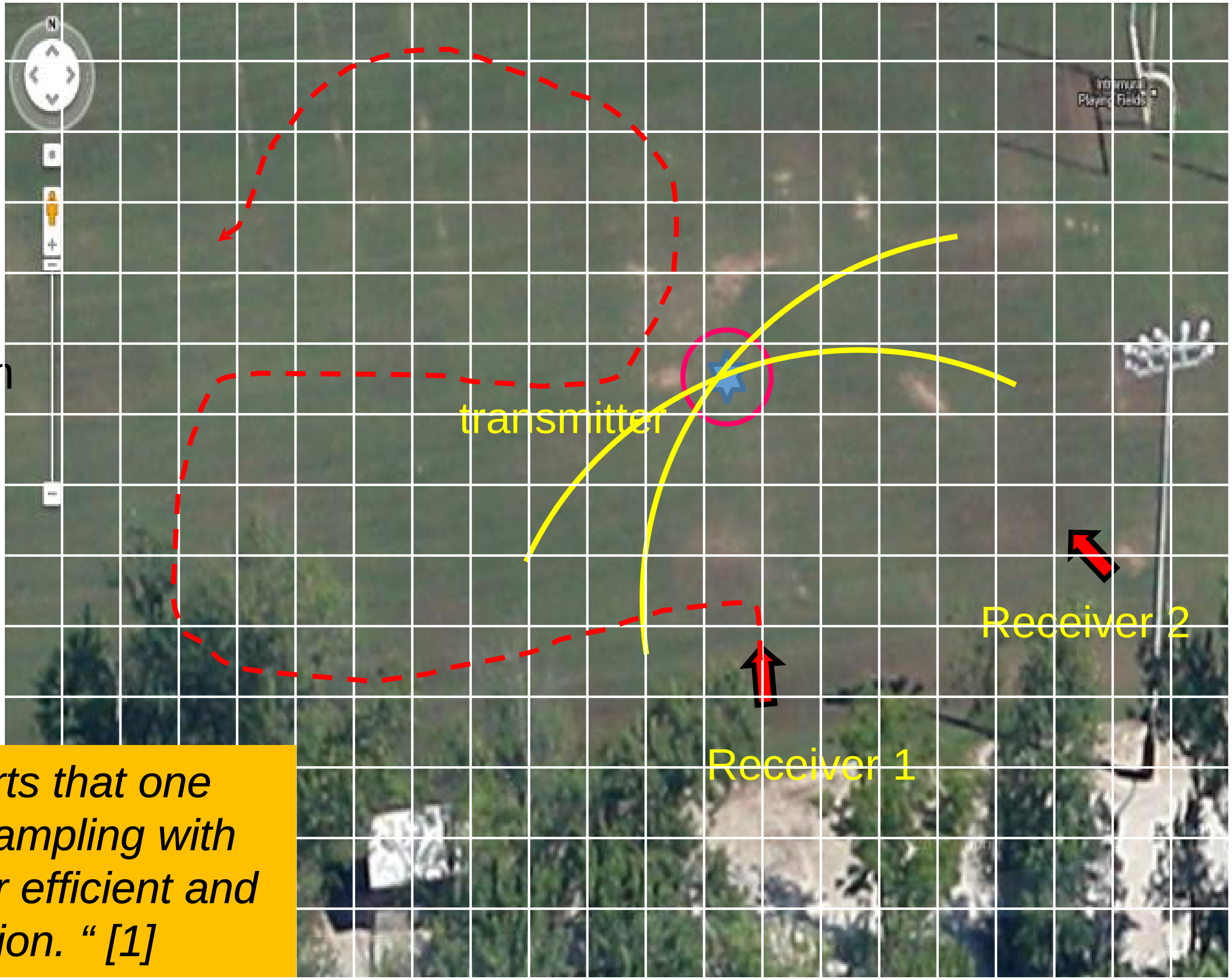
What is Compressed Sensing?

- A signal processing technique that allows the reconstruction of a signal from a *limited number* of linear combinations of the signal
- Most signals of interest are *sparse* or *compressible* - meaning that the information can be encoded with just a few numbers without much numerical or perceptual loss
- Shannon's/Nyquist theory exploits *prior knowledge* about the signal's bandwidth, CS exploits prior knowledge that the signal is sparse.
- Useful information can be captured via a sampling or sensing protocol which uses *incoherent* waveforms
- Numerical reconstruction can reconstruct the signal from *low rate sampling*

1) 'An Introduction to Compressive Sampling', Candes, E.J. , M.B Wakin., IEEE signal processing magazine, march 2009
2) 'Making Do with Less: An Introduction to Compressed Sensing', K. Bryan and T.Leise, SIAM Review 2013 55:3, 547-566

How to design the geolocation problem using CS?

1. Formulate the problem in a sparse basis
2. Design incoherent measurement system
3. Choose a mathematical algorithm that is computationally tractable to solve the convex linear minimization
   - Basis Pursuit
   - Denoising

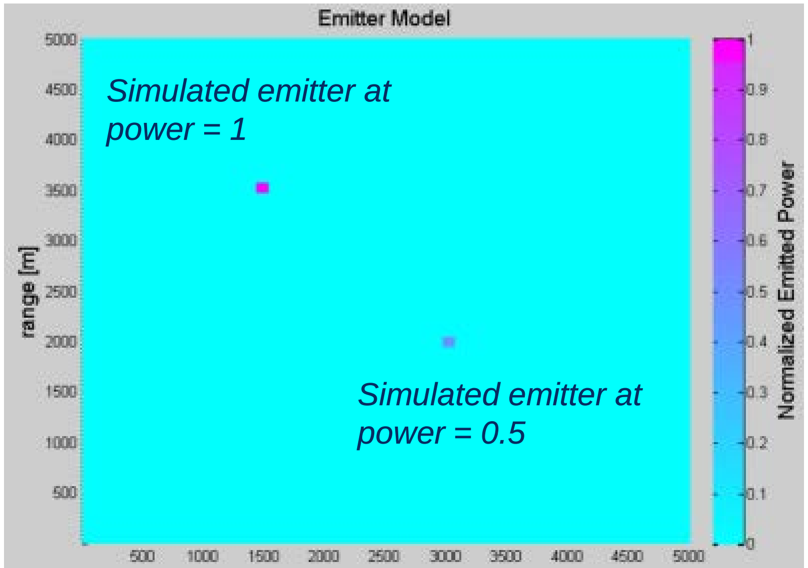


“The theory of CS asserts that one can combine low-rate sampling with computational power for efficient and accurate signal acquisition. “ [1]

1) ‘Compressive Sampling’, Baraniuk, R., Candes, E., Nowak, R. Vetterli, M., IEEE signal processing magazine, March 2009

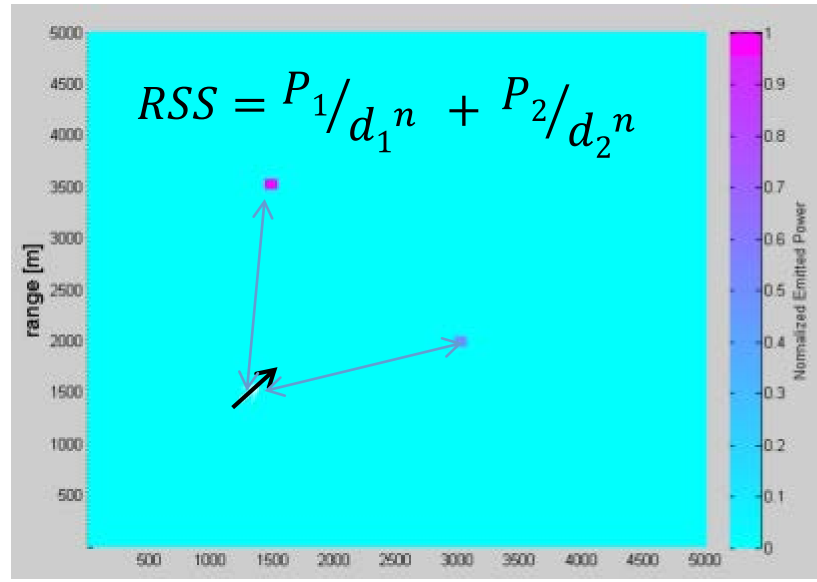
Formulation of the Problem

Transmitter Model



- Omnidirectional transmission
- Same frequency & coding
- Normalized emission power
- Located in two pixels (100m square)
- 50x50 or 2500 possible pixel locations

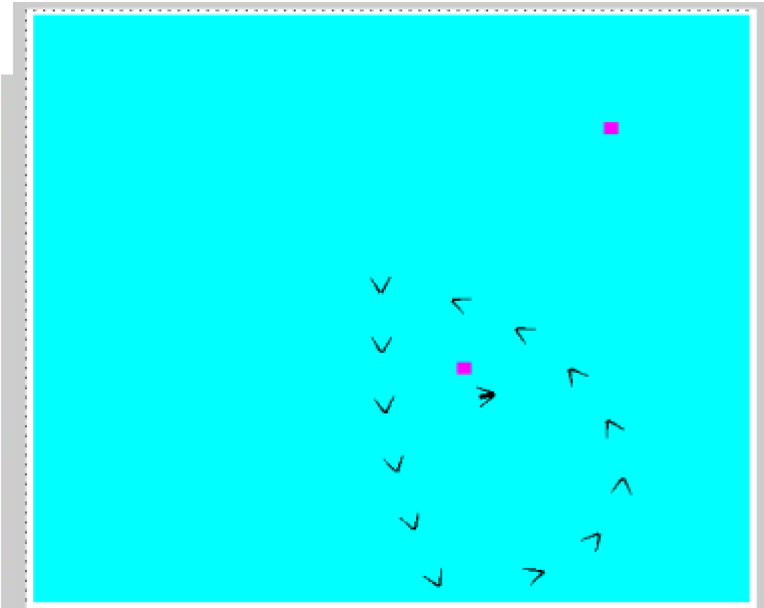
Receiver Model

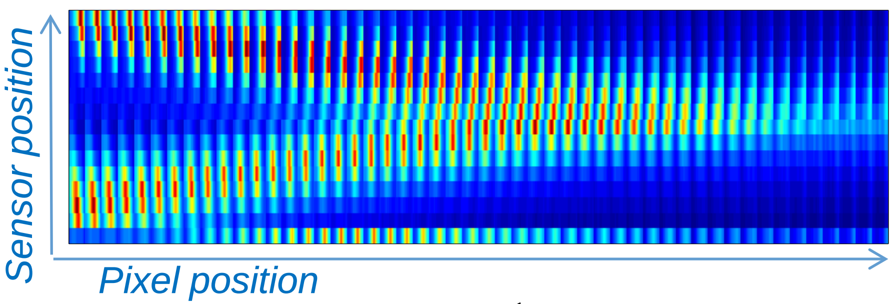


- Detects energy
- Received signal strength model
  - $RSS = 1/distance^n$
  - Where n = 2 for free space or n=4 for perfect reflection
- Antenna Sensitivity pattern
  - Omni-directional, or
  - RSS(Φ) = $\begin{cases} \cos(\Phi) \text{ for 0-180 degrees} \\ 0.1*\cos(\Phi) \text{ for 180-360 degrees} \end{cases}$

Using Compressed Sensing to Localize Source

Sensing Matrix (A)





$$A_{ij} = \frac{1}{\|sensor\ position(i) - pixel\ position(j)\|_2^2}$$

- Recast in linear matrix form as

$$y = Ax$$

Receiver measurements

Dictionary based on receiver positions

unknown emitter power

- Solve the underdetermined system for x
- Minimize the ℓ_1-norm of x

$$\min\{\|x\|_1\} = \sum_i |x_i|$$

Given that : $x_i \geq 0$

Subject to : $|Ax - y| = 0$

Basis pursuit problem is solved using linear programming techniques

What about Real Measurements?

- Recast in linear matrix form as

Receiver measurements

$$y = \tilde{A}x + \varepsilon$$

actual Dictionary

emitter power

Receiver measurement noise

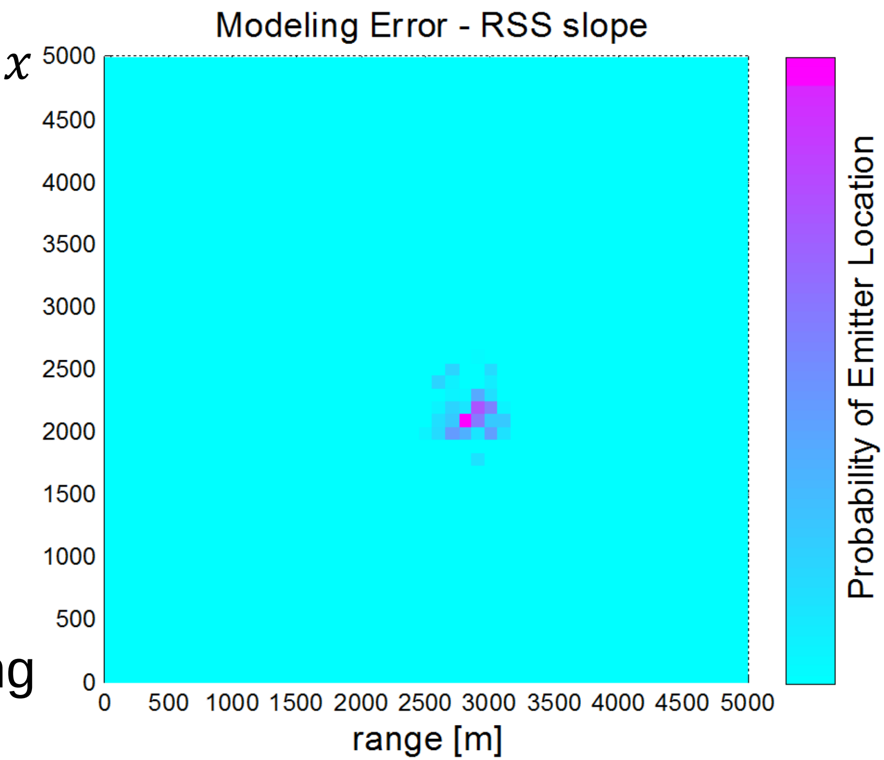
- solve the underdetermined system for x
- Minimize the ℓ_1-norm

$$\min\{\|x\|_1\} = \sum_i |x_i|$$

Given that : $x_i \geq 0$

Subject to : $|\tilde{A}x - y| \leq \tilde{\varepsilon}$

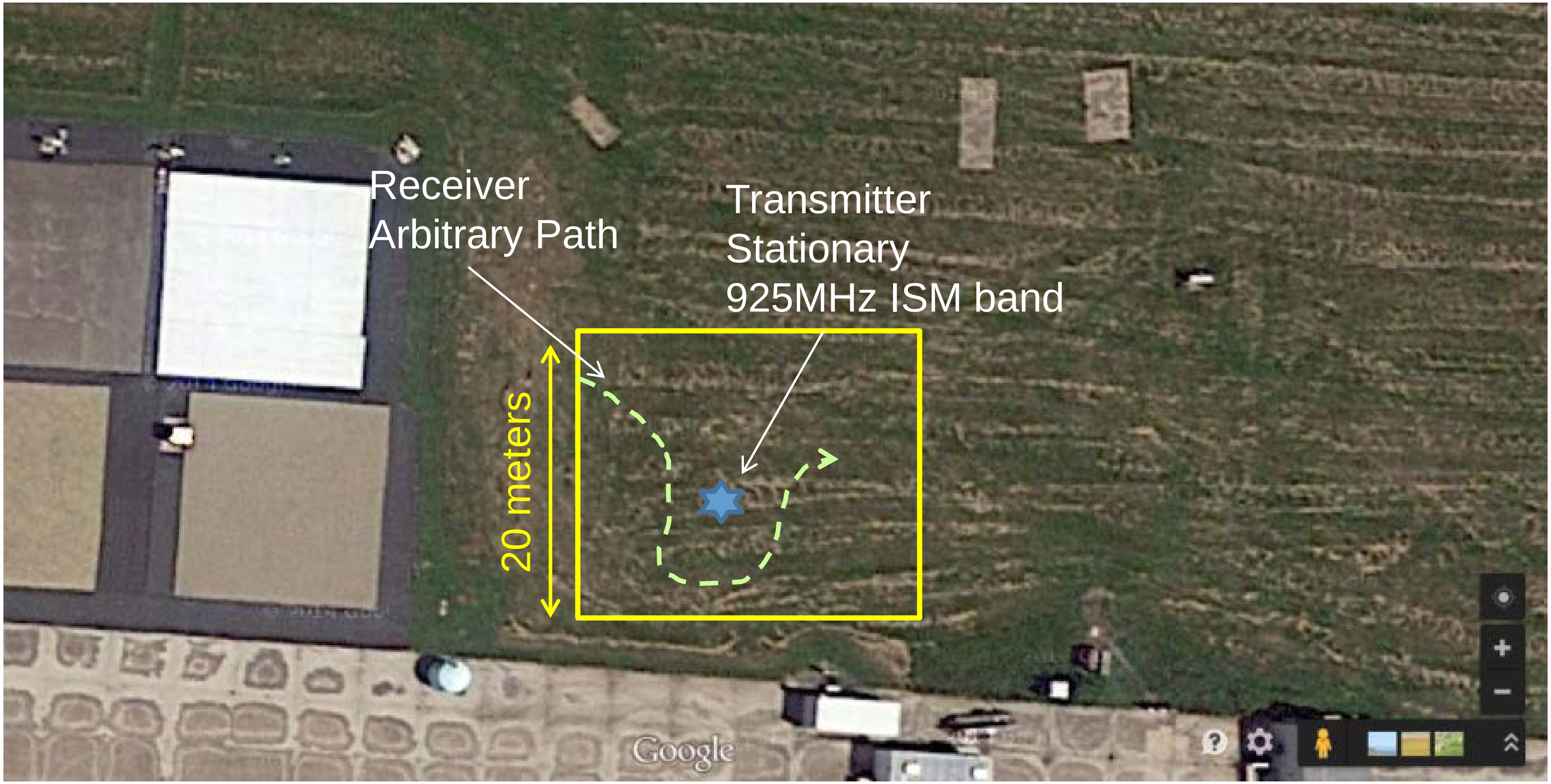
- Basis Pursuit Denoising problem is solved using using linear programming techniques



5. VALIDATION WITH MEASUREMENTS

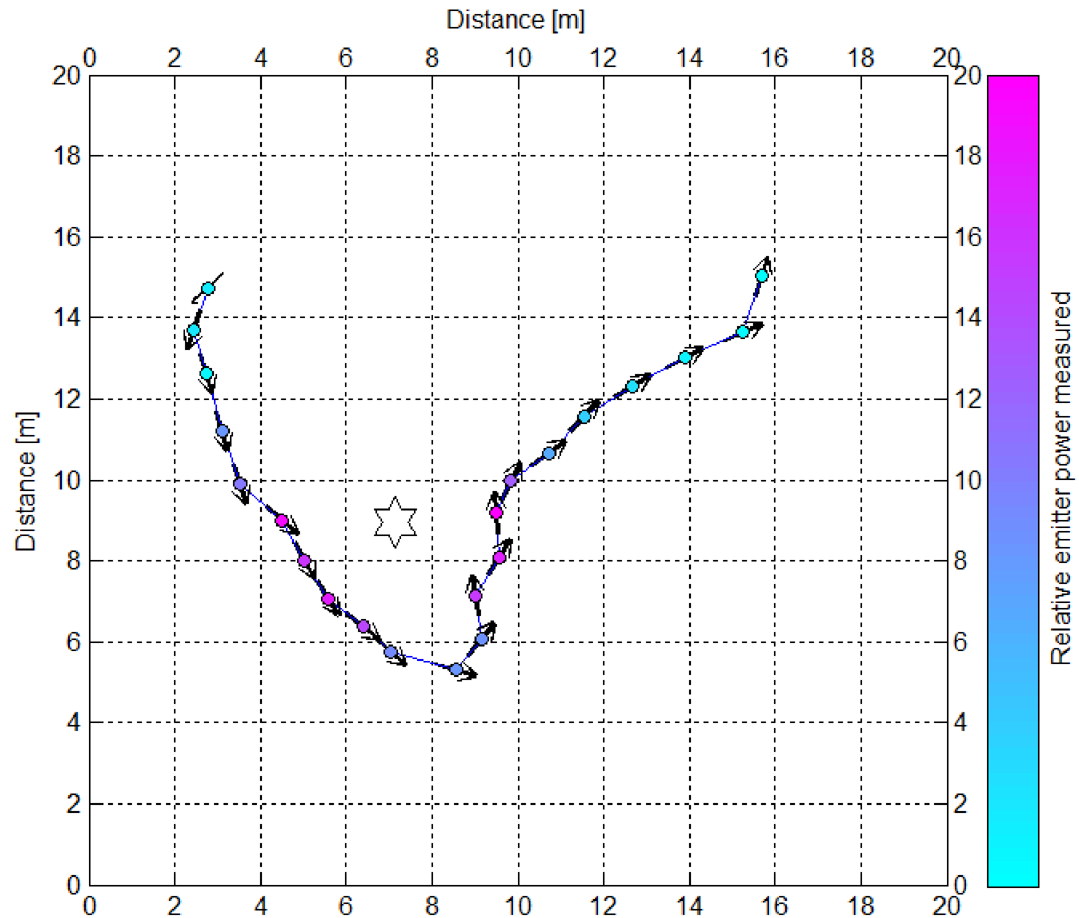
Measurements were acquired in November of 2014 and used to validate the algorithms for localizing a single emitter with RSS measurements from a mobile sensor using an omni-direction receiver.

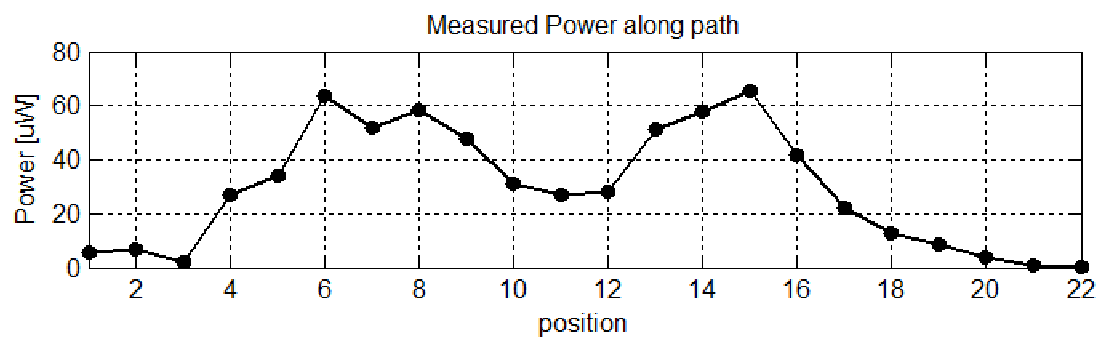
Measurements Nov 6, 2014



Measurements Acquired 11-10-2014

- Two sensors
  - transmitter stationary
  - Receiver traverses a random path
- Antennas are omni-directional
- Measurements collect the received signal strength
- No angle of arrival information





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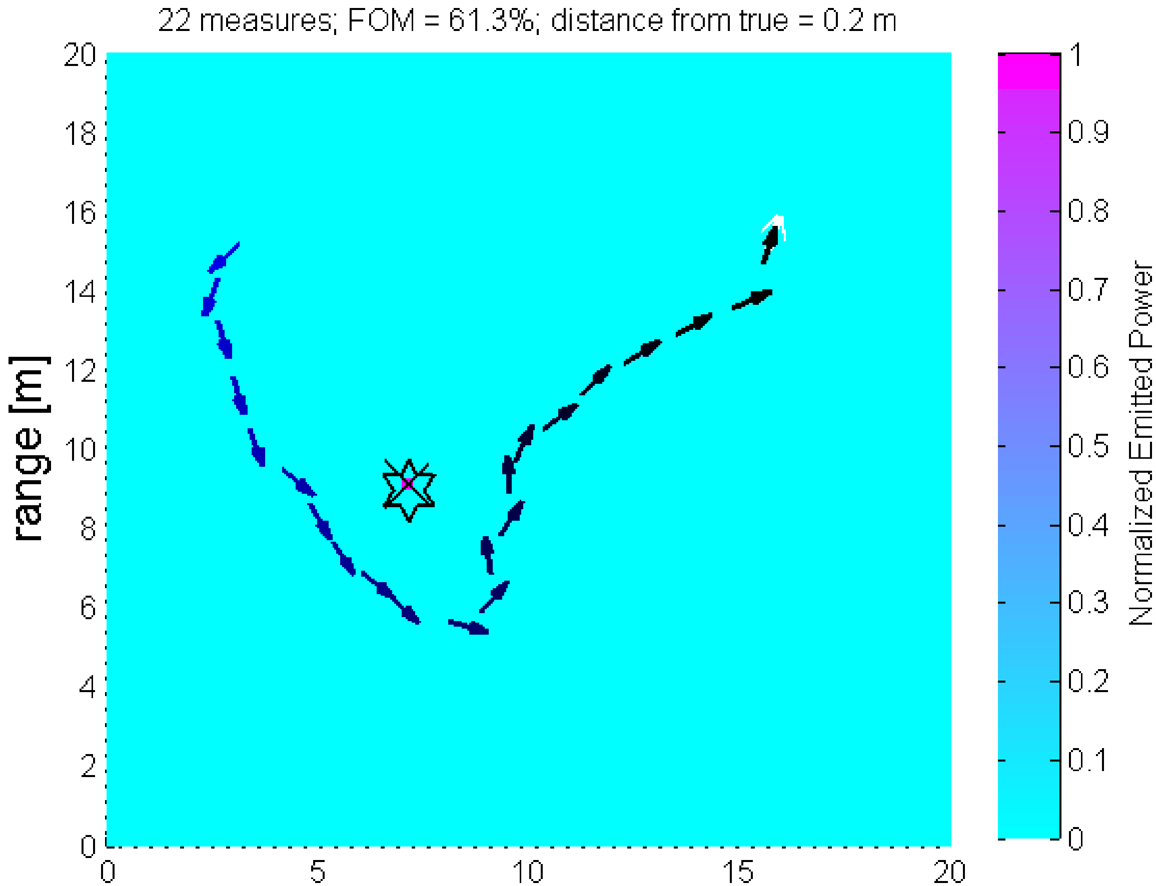
Localizing the emitter's source using measurements

- After 1 measurement the algorithm's prediction is quite a bit off
- After 14 measurements the algorithms is within a meter of the true location (FOM = 28.7%)
- After 18 measurements the algorithm is correctly predicting the location of the emitter and the predicted strength (FOM = 61.3%)



6. WHAT'S NEXT?

- *Identify multiple transmitters*
- *Using multiple receivers*
- *Optimal placement and optimal path*

Thank you

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