Experimental Characterization of a Large Aperture Array Localization Technique using an SDR Testbench

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Overview

- Introduction
  - Source Localization
  - Antenna Array Testbed
  - Array Calibration
- Large Aperture Array Localization Procedure
- SDR Array Testbed Setup
- Array Synchronization
- Experimental Results
- Conclusions

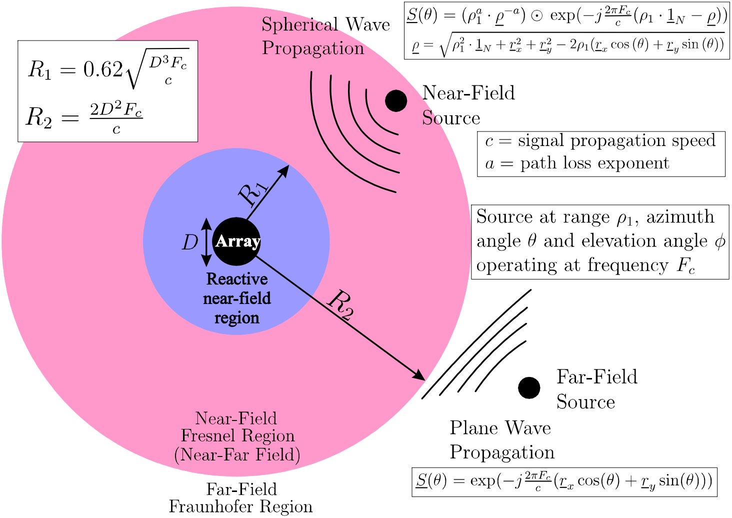
- Localization is crucial in many signal processing and communication technologies
  - Mobile Communications
  - Smart Antennas
  - Wireless Sensor Networks
  - MIMO Radar
- Main approaches to localization are
  - Range Based - Received Signal Strength (RSS), Time of Arrival (TOA), Time Difference of Arrival (TDOA)
  - Direction Based - Direction of Arrival (DOA)
- Here, an array based approach is used - exploit the range and directional information

- SDR peripherals allow rapid characterization of wireless algorithms
- Array testbed is made by combining USRP2 boards for
    - Direction Finding
    - Beamforming
    - MIMO and Mobile Communications
- Each board has one RF channel
- Channels must be synchronized in frequency and phase
- Uncertainties between RF channels imply calibration is required

- Uncertainties affect the detection, resolution and estimation performance of array signal processing algorithms
- They may include gain, phase, sensor location, mutual coupling etc...
- Array calibration attempts to estimate and compensate for the uncertainties
- The two main approaches are
  - Pilot Calibration - Observe the array response due to a source(s) with some known parameter(s) - typically direction
    - Find the array uncertainties explicitly by assuming source parameters are known
  - Self Calibration - Observe the array response due to a source(s) at unknown location(s)
    - Find array uncertainties and source parameters simultaneously by solving a highly non linear cost function
- An ad-hoc pilot calibration algorithm is employed in this work to combat gain and phase uncertainties

Large Aperture Array Localization Procedure

Concept of near-far and far field



- Receive L snapshots of data from $N = 4$ antennas when a single source is transmitting

$$\mathbb{X} = [\underline{x}(t_1), \underline{x}(t_2), \cdots \underline{x}(t_L)] \in \mathcal{C}^{N \times L}$$

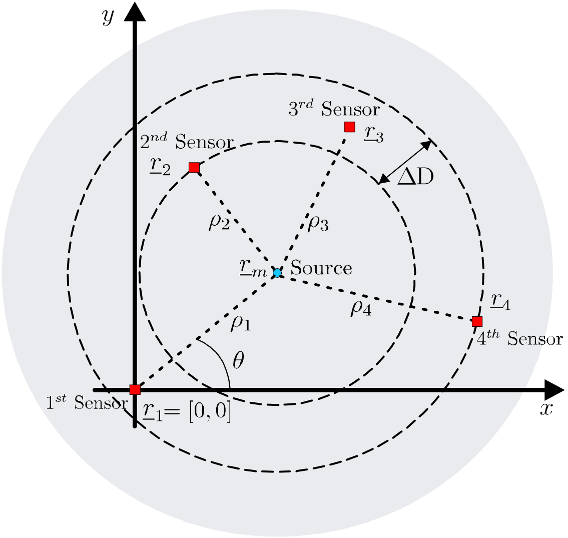
- Rotate the array reference point to be at each of the antenna locations and construct the covariance matrix in each case

$$\begin{aligned} \mathbb{R}_0 &= \frac{1}{L}\mathbb{X}_0\mathbb{X}_0^H \quad \mathbb{R}_1 = \frac{1}{L}\mathbb{X}_1\mathbb{X}_1^H \\ \mathbb{R}_2 &= \frac{1}{L}\mathbb{X}_2\mathbb{X}_2^H \quad \mathbb{R}_3 = \frac{1}{L}\mathbb{X}_3\mathbb{X}_3^H \end{aligned}$$

where

$$\mathbb{X}_i = \mathbb{X} \oslash (\underline{1}_N \cdot \mathrm{row}_i\,(\mathbb{X}))$$

- $\mathbb{X}_i$ describes the data $\mathbb{X}$ when the array reference point is at the i^{th} antenna and $\mathrm{row}_i\,(\mathbb{X})$ describes the i^{th} row of the matrix $\mathbb{X}$.



y
x
3^{rd} Sensor
$\underline{r}_3$
2^{nd} Sensor
$\underline{r}_2$
ΔD
ρ_2
ρ_3
$\underline{r}_m$ Source
$\underline{r}_4$
ρ_4
ρ_1
4^{th} Sensor
θ
1^{st} Sensor
$\underline{r}_1 = [0, 0]$

- Estimate signal eigenvalue λ_i of the i^{th} covariance matrix $\forall i = 0, 1, 2, 3$
  - Principle eigenvalue minus the average of the remaining eigenvalues
- Form ratios of signal eigenvalues with respect to antenna 0 (assuming with no loss of generality that this is the global reference antenna from which the source). These are the metrics used to find the location of the target. Note that a is the path loss exponent

$$
\begin{aligned}
\kappa_1 &= \sqrt[2a]{\frac{\lambda_1}{\lambda_0}} \\
\kappa_2 &= \sqrt[2a]{\frac{\lambda_2}{\lambda_0}} \\
\kappa_3 &= \sqrt[2a]{\frac{\lambda_3}{\lambda_0}}
\end{aligned}
$$

- Use the metrics κ_1, κ_2 and κ_3 to form three circular loci with center $\underline{r}_{c_i}$ and radius R_{c_i} for $\forall i = 1, 2, 3$

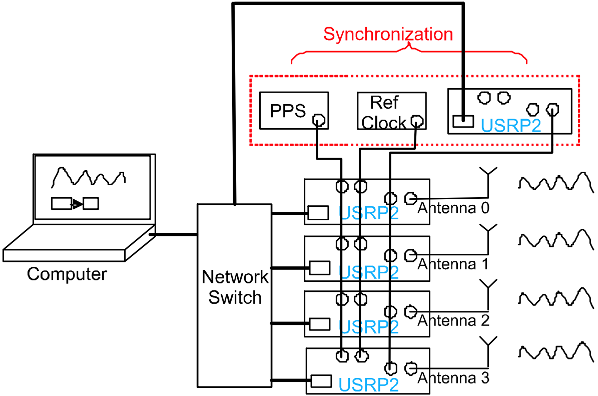
$$\begin{aligned} \underline{r}_{c_i} &= \frac{1}{1-\kappa_i^2} \cdot \underline{R}_i - \frac{\kappa_i^2}{1-\kappa_i^2} \cdot \underline{R}_0 \\ R_{c_i} &= \left| \frac{\kappa_1}{1-\kappa_i^2} \right| \cdot \|\underline{R}_0 - \underline{R}_i\| \end{aligned}$$

- Here, $\underline{R}_i$ is the location of the i^{th} antenna and $\underline{R}_0$ is the location of the global reference antenna. All are in meters and are assumed to be known.

Reference: Manikas, A.; Kamil, Y.I.; Karaminas, P.; , "Positioning in Wireless Sensor Networks Using Array Processing," Global Telecommunications Conference, 2008. IEEE GLOBECOM 2008. IEEE , vol., no., pp.1-5, Nov. 30 2008-Dec. 4 2008

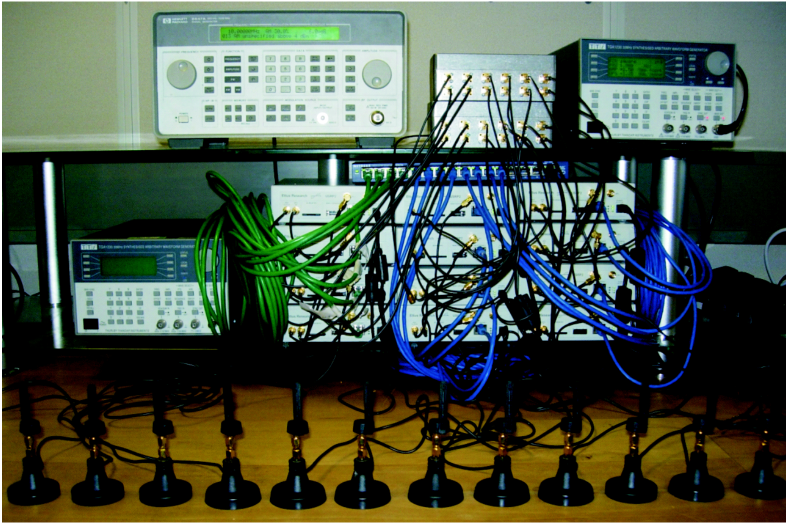
SDR Array Testbed Setup

System Setup



- Carrier frequency $F_c = 2.43GHz$
- $N = 4$ omnidirectional monopole antennas

SDR Array Testbed Setup
System Setup (Cont)



SDR Array Testbed Setup

System Setup (Cont)

- USRP2 boards convert signals from analog to digital
- Signal processing can all be done in software
- Boards must be fully synchronized to form an antenna array system
- However, each board has its own local oscillator (LO) and time reference
- Obtain frequency synchronization by using a 10MHz reference signal to drive the 100MHz system clock and a 1 PPS reference to fix the timing reference
- The 100MHz system clock drives the phase locked loop (PLL) controlling each LO

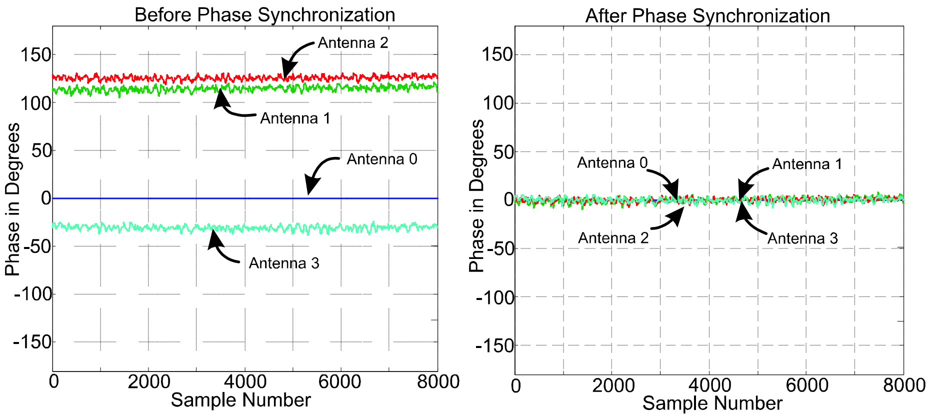
SDR Array Testbed Setup

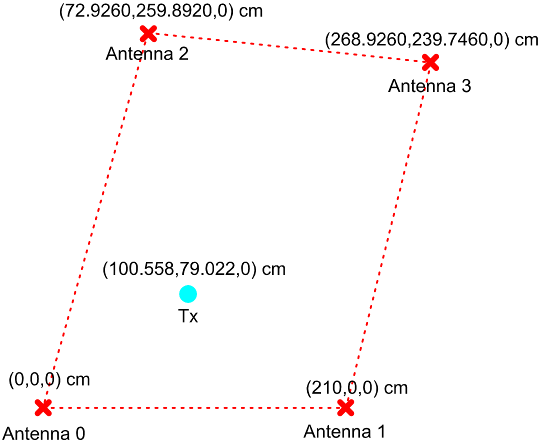
Phase Synchronization

- Providing a common reference signal to each board will not provide phase synchronization - not a true array system
- Phase ambiguity is caused by the division of the 100MHz clock by 16 to obtain the reference frequency of 6.25MHz which is used by the PLL
- Each time the boards are retuned, the phase between the LO's will take one of up to 16 possible values (4 possible values at 2.43GHz)
- Overcome by applying a common 2.43GHz carrier only tone to RF2 port of each board (zero phase)
- Isolate the tone from the over the air signal on RF1 and use to estimate the phase ambiguity
- Apply phase weightings to the received signal to align the phases

SDR Array Testbed Setup

Phase Synchronization - Example

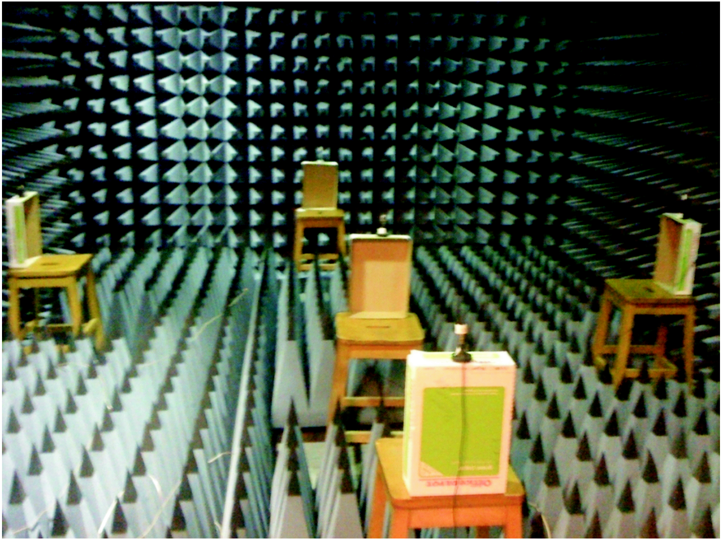


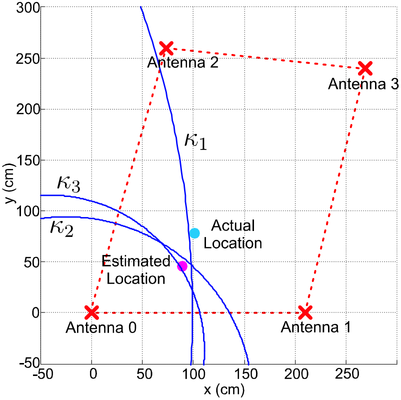


- Measurements are taken within an anechoic chamber

Experimental Results

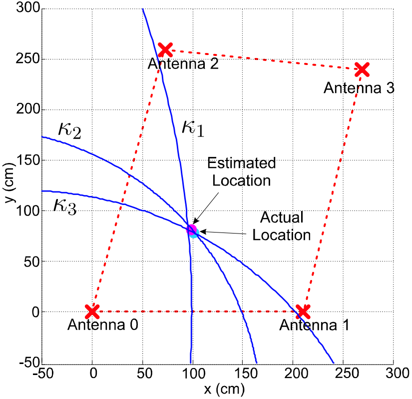
Experimental Setup (Cont)





Actual Location = [100.558, 79.022, 0] cm
Estimated Location = [88.2031, 46.1049, 0] cm
Error = 35.1593 cm

Practical Result



Actual Location = [100.558, 79.022, 0] cm
Estimated Location = [93.3221, 73.6362, 0] cm
Error = 9.0203 cm

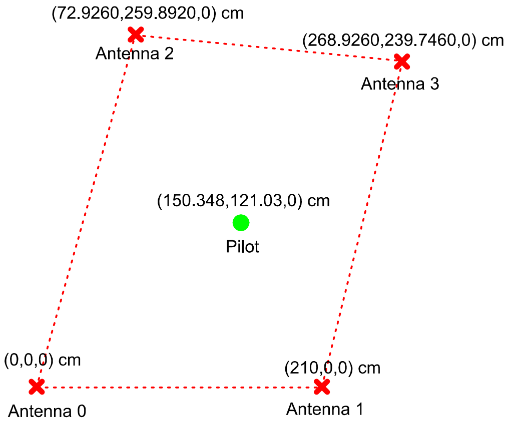
Simulated Result

- $L = 100$ snapshots and SNR=35.14dB

Experimental Results

Gain and Phase Pilot Calibration

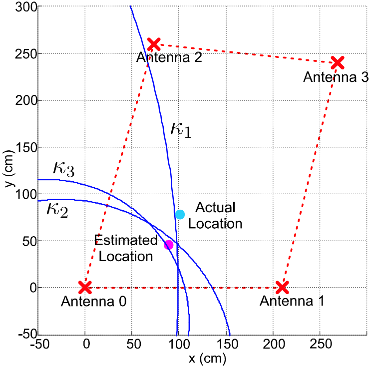
- Assume a pilot transmits from a known location
- Use the known array geometry to estimate gain and phase uncertainties



Experimental Results

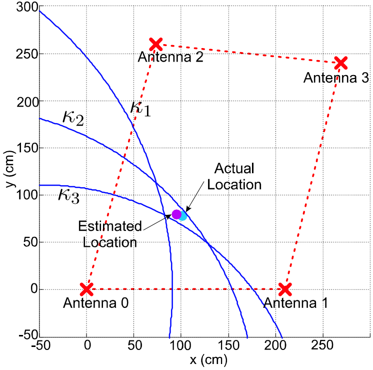
Practical Result Before and After Calibration

- Incorporating the estimated gain and phase of the array, the performance improves



Actual Location = [100.558, 79.022, 0] cm
Estimated Location = [88.2031, 46.1049, 0] cm
Error = 35.1593 cm

Practical Result Before Calibration



Actual Location = [100.558, 79.022, 0] cm
Estimated Location = [94.6336, 80.4734, 0] cm
Error = 6.0996 cm

Practical Result After Calibration

Conclusions

- A collection of individual USRP2 boards can be synchronized using a common clock reference, PPS and carrier signal to form an antenna array system
- Test bed is readily expandable, can work over a large range of frequencies and allows rapid characterizing of array processing algorithms in practical environments
- The performance of the large aperture localization algorithm after only basic calibration is comparable to simulation studies
- A more rigorous calibration procedure may yield even better results
- Next, the performance of the algorithm must be found when the test bed is placed outside the anechoic chamber