Localization in Sensor Networks

Rahul Jain

ETH Zürich

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 Localization

- Active Localization
  - System sends signals to localize target
  - eg. Radar (non-cooperative), GPS (cooperative)
- Passive Localization
  - System deduces location from observation of signals that are already present
  - eg. Signals normally emitted by the target (eg. birdcalls)
Motivation

- Many applications of WSN require the knowledge of where the individual nodes are located
- Motivating examples: Countersniper systems, Animal Tracking and Logistics
- We now look at an example of countersniper systems
Problem and Challenges

- To locate snipers in an urban environment
- Challenges of an urban terrain
  - Multipath effects
  - Poor coverage due to shading effect of buildings
- Limitations of existing systems
  - Require direct line of sight
  - Rely on muzzle flash that can be suppressed
  - Centralized, thus not robust to sensor failure
- Cost effectiveness
Solution

- Use an ad-hoc wireless sensor network-based system
- Utilize many cheap sensors for
  - good coverage of direct signal
  - tolerance to failures
- Detect via acoustic signals like muzzle blasts and shockwaves
Acoustic Signals

Figure 1: Acoustic events generated by a shot. The muzzle blast produces a spherical wave front, traveling at the speed of sound ($v_S$) from the muzzle ($A$) to the sensor ($S$). The shock wave is generated in every point of the trajectory of the supersonic projectile producing a cone-shaped wave front, assuming the speed of the projectile is constant $v_B$. The shockwave reaching sensor $S$ was generated in point $X$. The angle of the shockwave cone is determined by the Mach number ($M$) of the projectile.

$$\sin \Theta = \frac{1}{M} = \frac{v_S}{v_B}$$
PinPtr

- Ad-hoc wireless network of inexpensive sensors
- Sensors can
  - detect muzzle blasts and acoustic shockwaves
  - measure their time of arrival (TOA)
- Message routing service delivers TOA to a base station
- User Interface through base stations or PDAs
- System field tested at the US Army McKenna MOUT (Military Operations in Urban Terrain) facility at Fort Benning, GA
System Architecture

Figure 2: System Architecture
Middleware Services

- **Time Synchronization**
  - Flooding Time Synchronization Protocol
  - All nodes synchronized with a root node

- **Message Routing**
  - Gradient-based best effort converge-cast protocol
  - All data routed to a root node

- **Sensor Localization**
  - Estimate the sensor position using shots
  - Current implementation places sensors by hand
Sensor Fusion

Consistency Function

\[ C_\tau(x, y, z, t) = \text{count}(\mid t_i(x, y, z, t) - t_i \mid \leq \tau) \]

Search Algorithm

- General Bisection method
- Maximum $10^5$ steps required
Setup

- 56 nodes
- 20 known shooter positions
- 171 shots

Figure 3: PinPtr: Field Setup
The shooter localization error of the system is shown in Figure 6, where the 3D error is the total localization error, while in the 2D error the elevation information is omitted. The system accuracy is remarkably good in 2D. The average 2D error was 0.6m, 83% of shots had less than one meter, and 98% had less than 2 meters of error.

The elevation detection was not as accurate because the sensors were mostly positioned on the ground, approximately in a plane. There were only a few sensors located on rooftops or window ledges. This lack of variation in sensor node elevation resulted in the 3D accuracy being worse than the 2D accuracy. It is expected that this could be significantly improved by locating a larger fraction of the sensor nodes in elevated positions. As Figure 6 shows, 46% of the shots had less than 1m, and 84% of shots had less than 2m position error in 3D. The average 3D error was 1.3m.

6.1 Error sources

The sensor fusion algorithm uses TOA measurements recorded by different sensors at different locations. Hence, two potential sources of measurement error are imperfect time synchronization and inaccurate sensor locations. The data gathered at the field trials enabled us to experiment with the effect these have on the overall system accuracy. The effects of time synchronization error are summarized in Figure 7. For each simulated time synchronization error value of $T$, the detection time for each sensor was modified by $t$ where $-T/2 < t < T/2$ using uniform random distribution. Then the sensor fusion algorithm estimated the shooter position. Each shot was used ten times; therefore, each data point in the diagram represents 1710 experiments.

The results in Figure 7 clearly show that the time synchronization accuracy of FTSP is much better than what is needed by this system.
Localization in Sensor Networks

Error Sources

Figure 5: Localization accuracy vs. time synch error

![Graph showing the relationship between timesync error and average localization accuracy](image)

**Figure 5:** Localization accuracy vs. time synch error
Figure 6: Detection rate vs. number of sensors used

Figure 7: Localization accuracy vs. number of sensors used
Sensor Fusion Accuracy

**Figure 8:** Error comparison with filtered readings

**Figure 9:** Error comparison with unfiltered readings
Deployment of sensors in an urban environment is not trivial
No power management
Can not detect multiple shots
Silencers?
Radio Interferometry

- Pair of nodes emitting radio waves simultaneously at slightly different frequencies
- Carrier frequency of the composite signal is between the two frequencies
- Neighbouring nodes can measure the energy of the envelope signal as the signal strength
Localizations in Sensor Networks

In the subsequent section we provide the theoretical background behind ranging. To obtain the signal power:

\[ (\sin(2\pi f t))^2 \approx 2f \sin^2(\pi f t) \]

We model the radio RSSI circuitry in the following way.

\[ \text{IF}(t) = a \cos(\pi f t + \phi) \]

Assume that a node receives the radio signal

\[ \delta(t) = e^{-\delta t} \sin(\pi f t + \phi) \]

Phase ambiguities and localize the participating nodes.

\[ \frac{\text{phase offset}}{\text{carrier}} = \frac{d_{AB} - d_{CD} + d_{AC} - d_{BD}}{\lambda_{carrier}} \]

where

\[ \lambda_{carrier} \]

Figure 10: Radio Interferometric Ranging Technique
Filtered RSSI Signal

Theorem 1: Let $f_2 < f_1$ be two close carrier frequencies with
\[ \delta = (f_1 - f_2)/2, \delta \ll f_2, \text{ and } 2\delta < f_{\text{cut}}. \]\nFurthermore, assume that a node receives the radio signal

\[ s(t) = a_1 \cos(2\pi f_1 t + \varphi_1) + a_2 \cos(2\pi f_2 t + \varphi_2) + n(t), \]

where $n(t)$ is the Gaussian noise. Then the filtered RSSI signal $r(t)$ is periodic with fundamental frequency $f_1 - f_2$ and absolute phase offset $\varphi_1 - \varphi_2$. 
Relative Phase Offset

Theorem 2: Assume that the two nodes A and B transmit pure sine waves at two close frequencies $f_A > f_B$ such that $f_A - f_B < f_{\text{cut}}$, and two other nodes C and D measure the filtered RSSI signal. Then the relative phase offset of $r_C(t)$ and $r_D(t)$ is

$$2\pi \left( \frac{d_{AD} - d_{AC}}{c/f_A} + \frac{d_{BC} - d_{BD}}{c/f_B} \right) \pmod{2\pi}$$
Relative Phase Offset

Theorem 3: Assume that the two nodes A and B transmit pure sine waves at two close frequencies $f_A > f_B$, and two other nodes C and D measure the filtered RSSI signal. If $f_A - f_B < 2\text{kHz}$, and $d_{AC}, d_{AD}, d_{BC}, d_{BD} \leq 1\text{km}$, then the relative phase offset of $r_C(t)$ and $r_D(t)$ is

$$2\pi\left(\frac{d_{AD} - d_{BD} + d_{BC} - d_{AC}}{c/f}\right) \pmod{2\pi}$$

where $f = (f_A + f_B)/2$. 

Scheduling

- At most \( n(n - 3)/2 \) choices for the independent interference measurements
- In the current implementation, the base station selects all possible pairs of transmitters while all other nodes within their range act as receivers
Tuning

- \( f_1(i) = f_1 + i \times 0.325\, \text{Hz}, i = -15, -14, \ldots, 15 \)
- \( f_2 \) constant
- Receiver analyzes \( |f_1(i) - f_2| \) which is the interference frequency
- Determine \( i \) for which the interference frequency is 0
Nodes need to synchronize and measure absolute phase offsets relative to a common time instant for calculating the relative phase offset.

The master broadcasts a radio message identifying the other sensor node, type of measurement, transmit power and the time to start the measurement.
Frequency and Phase Estimation

- Peak detection performed on line in the ADC
- Post processing works exclusively on the obtained peak indexes
- Phase of the RSSI signal is estimated by the average phase of the filtered peaks

![Figure 11: Peak detection and filtering](image)

The phase of the RSSI signal is estimated by the average phase of the filtered peaks.
Localization

- Generate an initial population of populationSize random solutions
- Select subpopulationSize solutions randomly from the population
- Evaluate each solution in the selected subset using the error function
- Sort the subset according to error
- Remove the worst 20% of the individuals in the sub-set, then generate new individuals by selecting random parents from the best 20% and applying genetic operators on the parents
- Go to step (2)
Error Sources

- Carrier frequency inaccuracy
- Carrier frequency drift and phase noise
- Multipath effects
- Time synchronization error
Effective Range

- Interferometric Radio Range \((r)\) is twice the range of digital communication
- \(-2r \leq d_{ABCD} \leq 2r\)
The algorithm measuring the interference signal frequency and phase also determines the average amplitude of the signal. After filtering, approximately 1000 measurements remained with 28% of them shifted by integer multiples of 10.

Filtering stages:
1. Remove ranges with SNR less than a certain threshold.
2. Discard frequency estimates with amplitude less than a specified fraction of the A/D range.
3. Remove frequency estimates with large error, as they are likely to have bad phase estimates.

The filtering process improves the ratio of good to bad measurements, with an approximate 50% improvement illustrated on Figure 9.

Figure 10 shows the central portion of the error distribution of all the ranges. Figure 11 displays the error distribution of localization utilizing only 20% of the raw ranging data. The average accuracy was 3 cm, with the largest error approximately 6 cm. The results are shown in Figure 12 with the three anchor nodes depicted by large circles.

Figure 12: Central portion of the error distribution of the filtered ranges.
The interference signal is measured by all the nodes in the network. After filtering, approximately 1000 measurements remained with 28% of them shifted by integer multiples of 10 degrees. This filtering improved the accuracy of the localization, which is illustrated in Figure 9.

The genetic optimization procedure ran for 2 minutes. The results are shown in Figure 11. The average accuracy was 3 cm, while the largest error was approximately 6 cm. The results are shown in Figure 11 with the three anchor nodes depicted by large circles. The genetic optimization procedure ran for 2 minutes. The results are shown in Figure 11. The average accuracy was 3 cm, while the largest error was approximately 6 cm. The results are shown in Figure 11 with the three anchor nodes depicted by large circles.

The genetic optimization procedure ran for 2 minutes. The results are shown in Figure 11. The average accuracy was 3 cm, while the largest error was approximately 6 cm. The results are shown in Figure 11 with the three anchor nodes depicted by large circles.

The localization accuracy as a function of the number of nodes is shown in Figure 13. The error distribution of localization is shown in Figure 10 with the three anchor nodes depicted by large circles. The error distribution of the resulting localization is shown in Figure 12 with the three anchor nodes depicted by large circles. The results are shown in Figure 11. The average accuracy was 3 cm, while the largest error was approximately 6 cm. The results are shown in Figure 11 with the three anchor nodes depicted by large circles. The results are shown in Figure 11 with the three anchor nodes depicted by large circles. The results are shown in Figure 11 with the three anchor nodes depicted by large circles.
Latency

- In a 16 node network, there are approx. 32000 measurements carried out.
- This entire process takes about 80 minutes.
- If we use one-fifth of the transmitter pairs, we reduce the time to 20 minutes.
- For small scale networks, the entire process can be completed in under 5 minutes.
Remarks

- High accuracy and long range
- Supports 3D localization
- Does not require extra hardware or calibration
- High Latency
- Applications?
Questions