Localization in Sensor Networks

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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

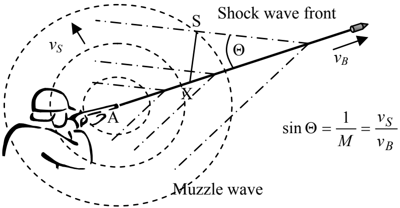

Figure 1: Acoustic events generated by a shot. The muzzle blast produces a spherical wave front, traveling at the speed of sound (v_S) from the muzzle (A) to the sensor (S). The shock wave is generated in every point of the trajectory of the supersonic projectile producing a cone-shaped wave front, assuming 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.

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 Nenning, GA

System Architecture

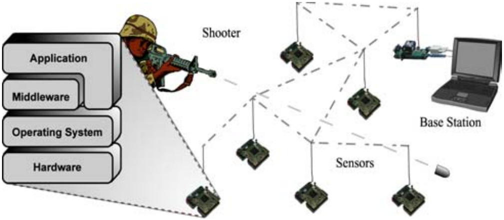

Figure 2: System Architecture

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

- $C_\tau(x, y, z, t) = count(|\ t_i(x, y, z, t) - t_i\ | \leq \tau)$

Search Algorithm

- General Bisection method
- Maximum 10^5 steps required

Setup

- 56 nodes
- 20 known shooter positions
- 171 shots

Figure 3: PinPtr: Field Setup

Shooter Localization Errors

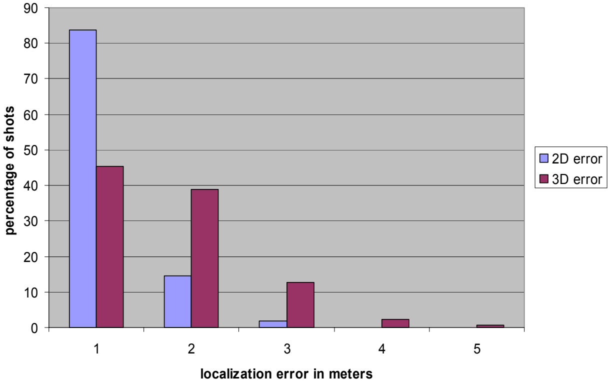

Figure 4: Localization Errors in 2D and 3D

Error Sources

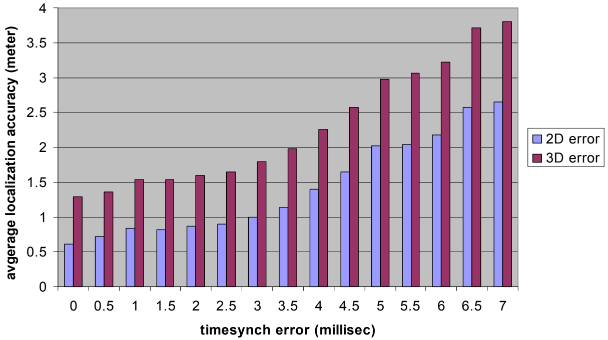

Figure 5: Localization accuarcy vs. time synch error

Sensor Density

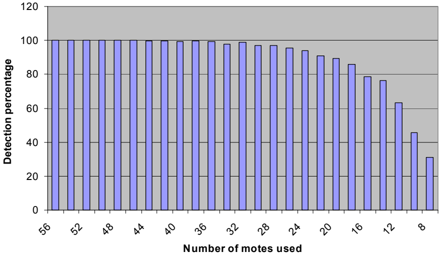

Figure 6: Detection rate vs. number of sensors used

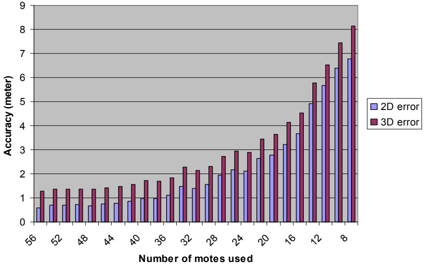

Figure 7: Localization accuarcy vs. number of sensor used

Sensor Fusion Accuracy

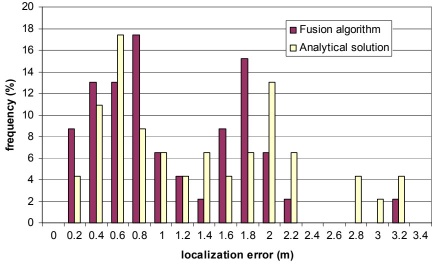

Figure 8: Error comparison with filtered readings

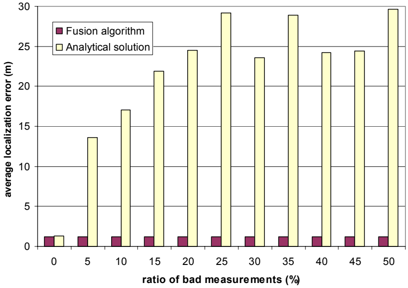

Figure 9: Error comparison with unfiltered readings

Remarks

- 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

Model

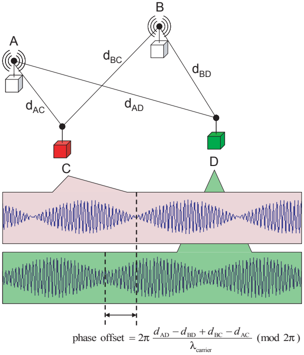

Figure 10: Radio Interferometric Ranging Technique

Filtered RSSI Signal

Theorem 1: *Let* $f_2 < f_1$ *be two close carrier frequencies with* $\delta = (f_1 - f_2)/2$, $\delta << f_2$, *and* $2\delta < f_{cut}$. *Furthermore, 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 frequncies $f_A > f_B$ such that $f_A - f_B < f_{cut}$, 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*

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

Relative Phase Offset

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

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

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

- $f_1(i) = f_1 + i.325Hz, i = -15, -14, ..., 15$
- f_2 constant
- Receiver analyzes $\mid f_1(i) - f_2 \mid$ which is the interference frequency
- Determine i for which the interference frequency is 0

Time Synchronization

- 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 exlusively on the obtained peak indexes
- Phase of the RSSI signal is estimated by the average phase of the filtered peaks

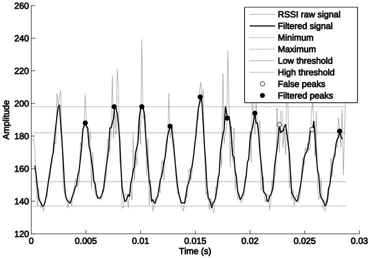

Figure 11: Peak detection and filtering

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
- $-2r \leq d_{ABCD} \leq 2r$

Range Accuracy

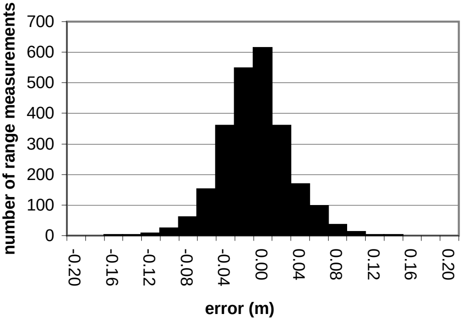

Figure 12: Central portion of the error distribution of the filtered ranges

Localization Accuracy

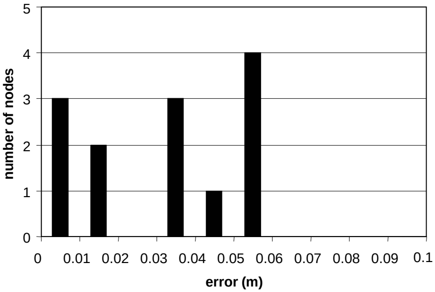

Figure 13: Error distribution of localization

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

Questions?