Heterogeneous Sensor Webs for Target Tracking in Urban Terrain

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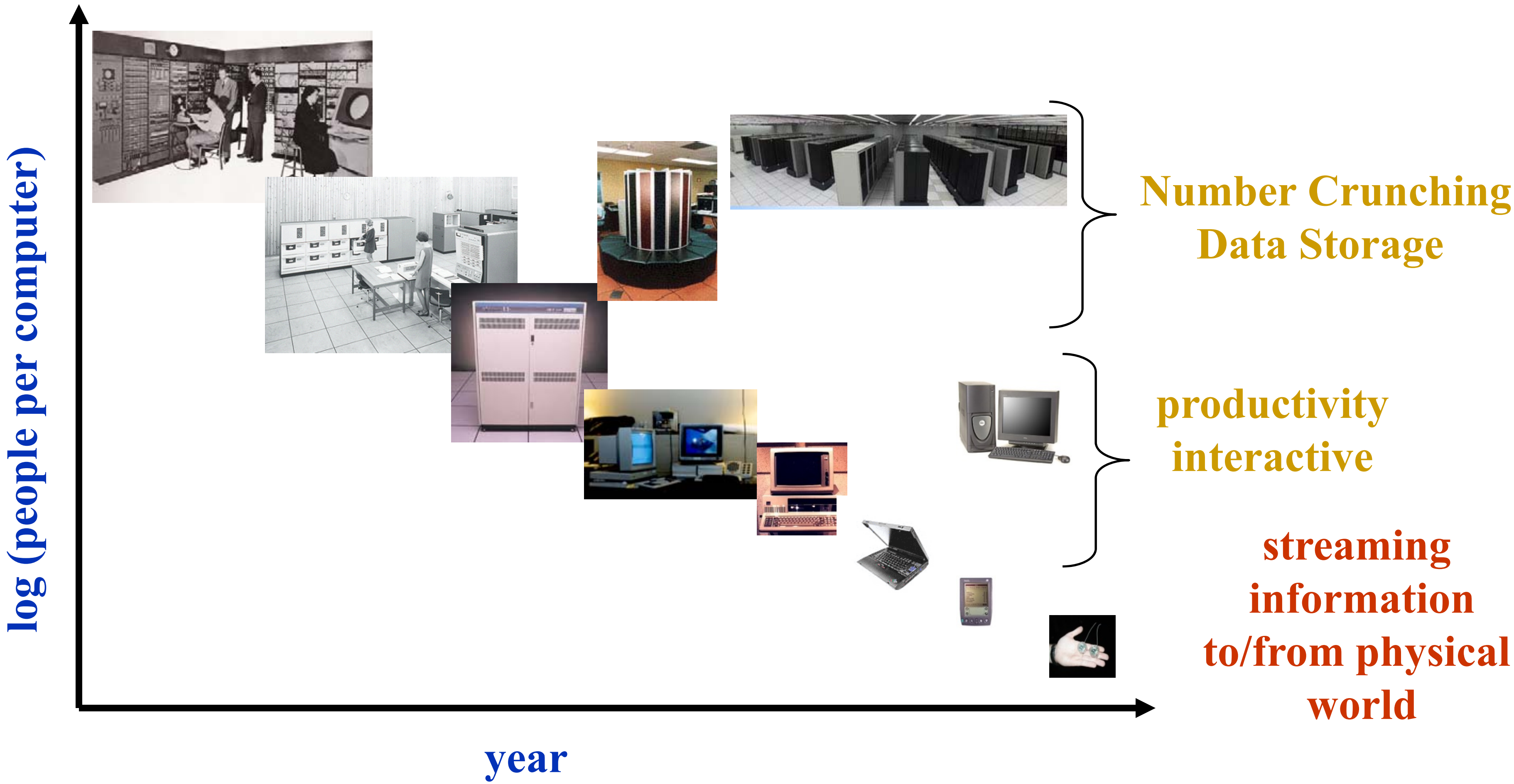
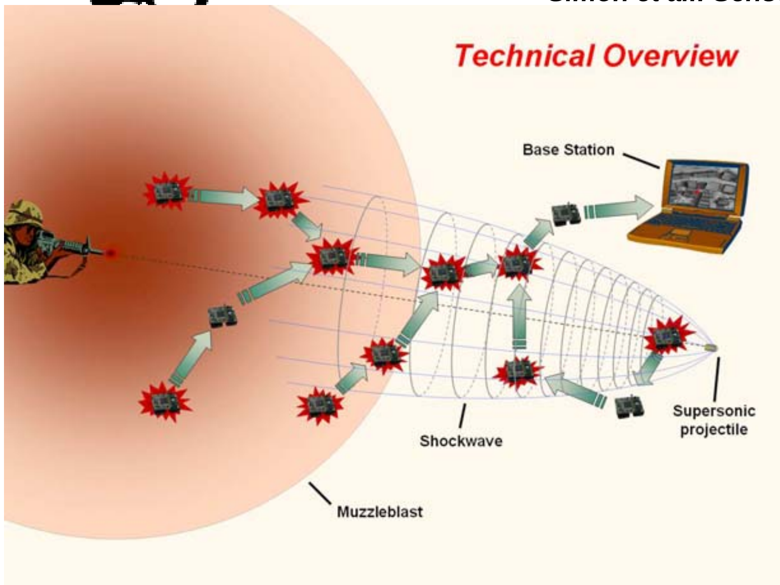
Bell's Law:
New computer class per 10 years

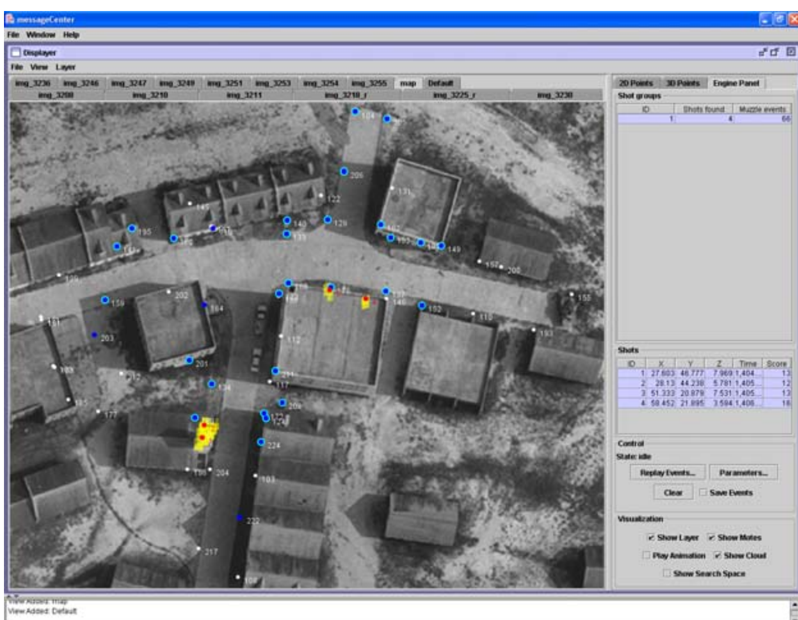


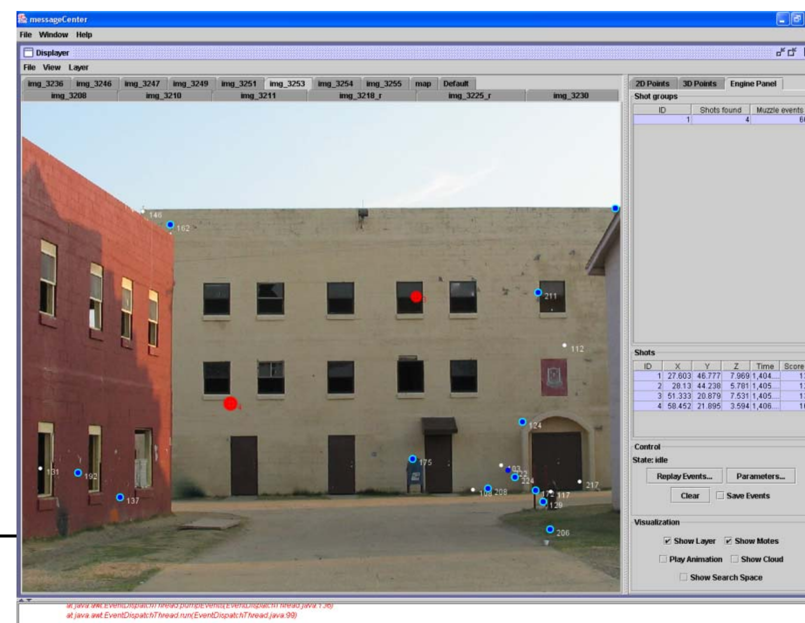
Shooter Localization

Ledeczi et al.: Multiple Simultaneous Acoustic Source Localization in Urban Terrain;
Simon et al.: Sensor Network-Based Countersniper System



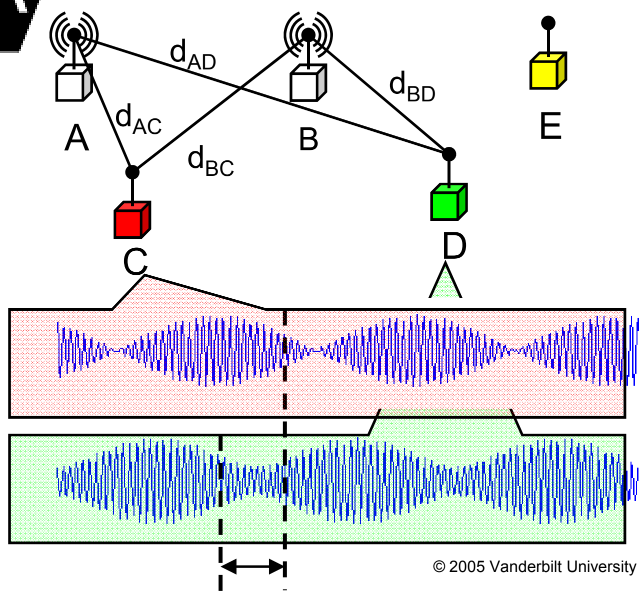
- Mica2 network and cheap acoustic sensors are used to accurately locate enemy shooters in urban terrain
- Performance:
  - Average 3D accuracy: ~1 meter
  - Latency: <2 seconds
  - Multipath elimination w/unique sensor fusion
  - Multiple simultaneous shot resolution
  - Long range shots: 1 degree accuracy in both azimuth and elevation, 5% accuracy in range
- Challenges:
  - Severely resource constrained nodes
  - Very limited communication bandwidth
  - Significant multipath effects in urban environment





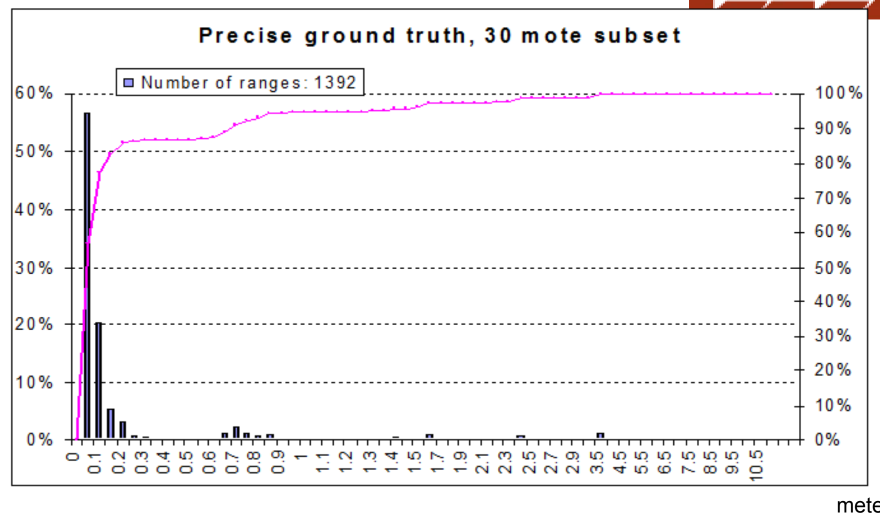
Sensor Localization w/ Radio Interferometry

Maroti, Kusy, Ledeczi et al.: Radio Interferometric Positioning

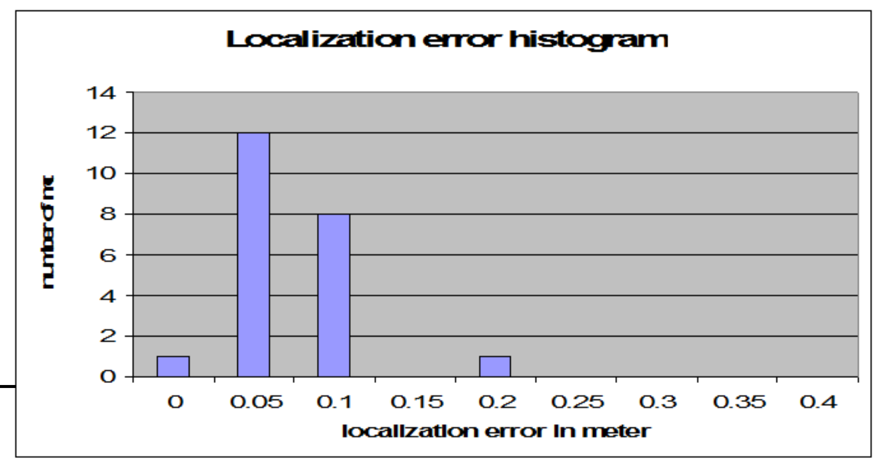


- COTS radio chip (CC1000 on MICA2)
  - transmit frequency: 400-460 MHz
  - wave length: 65 cm < λ < 75 cm
  - adjustable in 64 Hz steps
- Two senders (A and B) transmit simultaneously
  - frequency separation: 100-800 Hz
- Several receivers (C, D and E) measure interference
  - sample radio signal strength at 8.9 kHz
  - beat frequency: 100-800 Hz
  - use time synchronization with 1 μs precision to correlate phase offsets
  - result is $(d_{AD}-d_{BD}+d_{BC}-d_{AC})$ modulo λ
    - d_{XY} is distance between X and Y
    - λ is wave length of carrier frequency
- Perform multiple measurements with different frequencies

Ranging accuracy



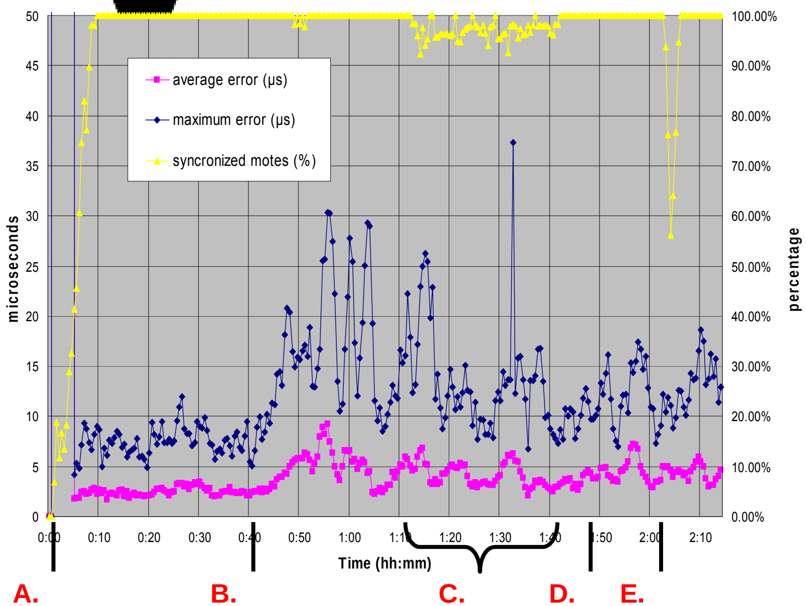
- 5x6 randomized grid (36x45m)
- Ground truth has ~5cm error
- 68% of measured ranges has <10cm error, 87% are within lambda
- Genetic Algorithm based localization:
  - 3 dead nodes, 1 did not converge, 4 anchors
  - Mean error: 7cm

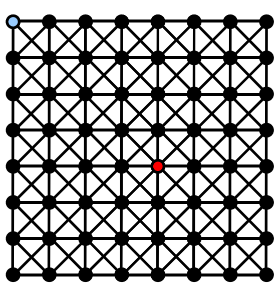


Time Synchronization

Maroti, Kusy, Simon, Ledeczi : The Flooding Time Synchronization Protocol

FTSP experiment





- first root
- second root

A. All motes are turned on
B. The first leader is turned off
C. Randomly selected motes were reset every 30 seconds
D. Half of the motes were switched off
E. All motes were switched back on

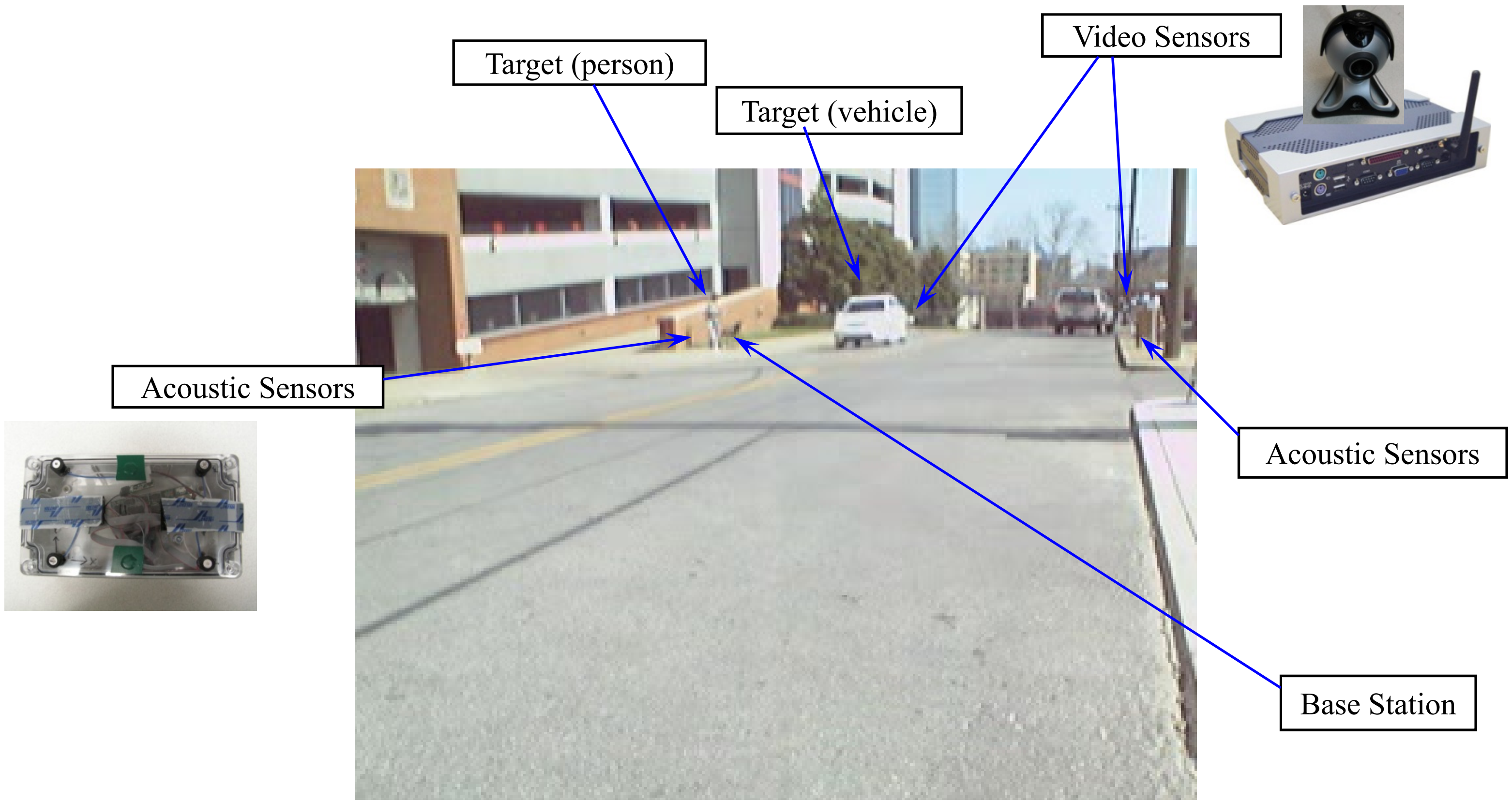
FTSP: Flooding Time Sync Protocol

- Uses the TimeStamping module:
  - Time synchronization primitive: establishing time reference points between a sender and receiver(s) using a single radio message
  - Sender obtains timestamp when the message was actually sent in its own local time
  - The message can contain the local time of the sender at the time of transmission (or the elapsed time since an event)
  - Receiver obtains timestamp when the message was received in its own local time
  - Integrated in the MAC layer
  - 1.2 µs precision
- Periodic resynchronization (e.g. one msg per 30s per node)
- Skew compensation w/ linear regression
- Robust: Handles topology changes, node/link failures
- Accuracy: 1-2 microseconds per hop using 1MHz clock.

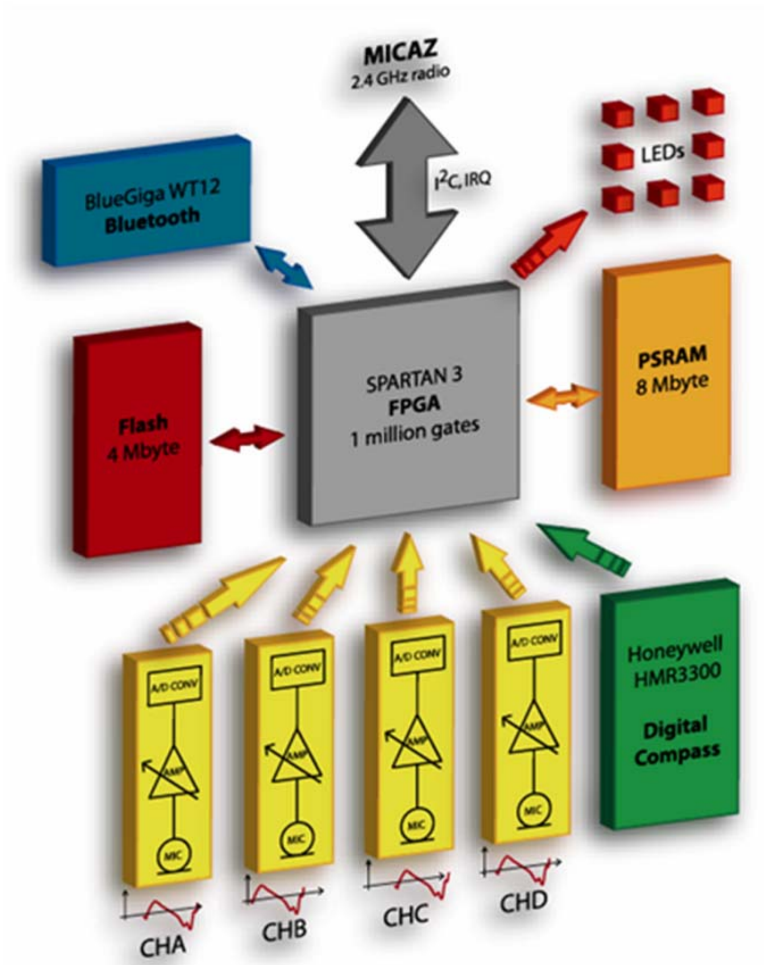
RITS: Routing Integrated Time Sync

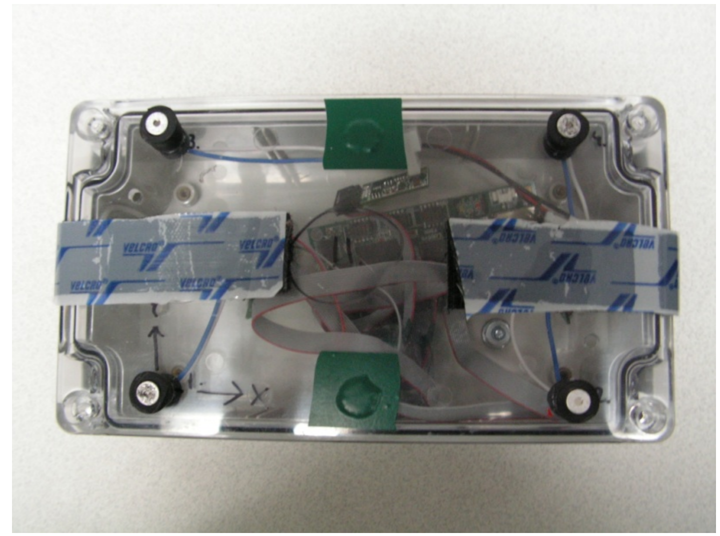
- No continuous (re)synchronization needed
- No extra messages
- Stealthy operation
- Uses the TimeStamping module
- No clock skew estimation
- Precision depends on the hop count of the route and on the total routing time, but it is comperable to that of FTSP

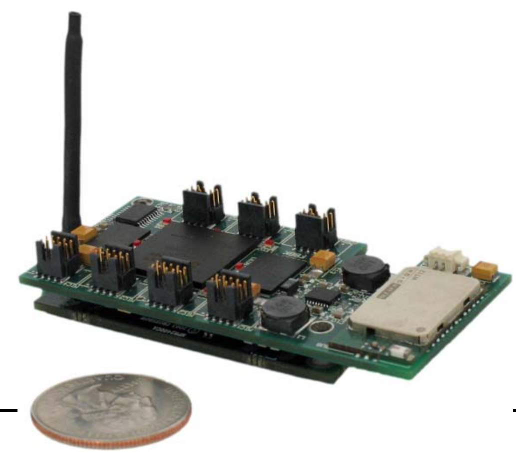
Target Tracking in Urban Terrain Using HSNs



Audio Sensor Node

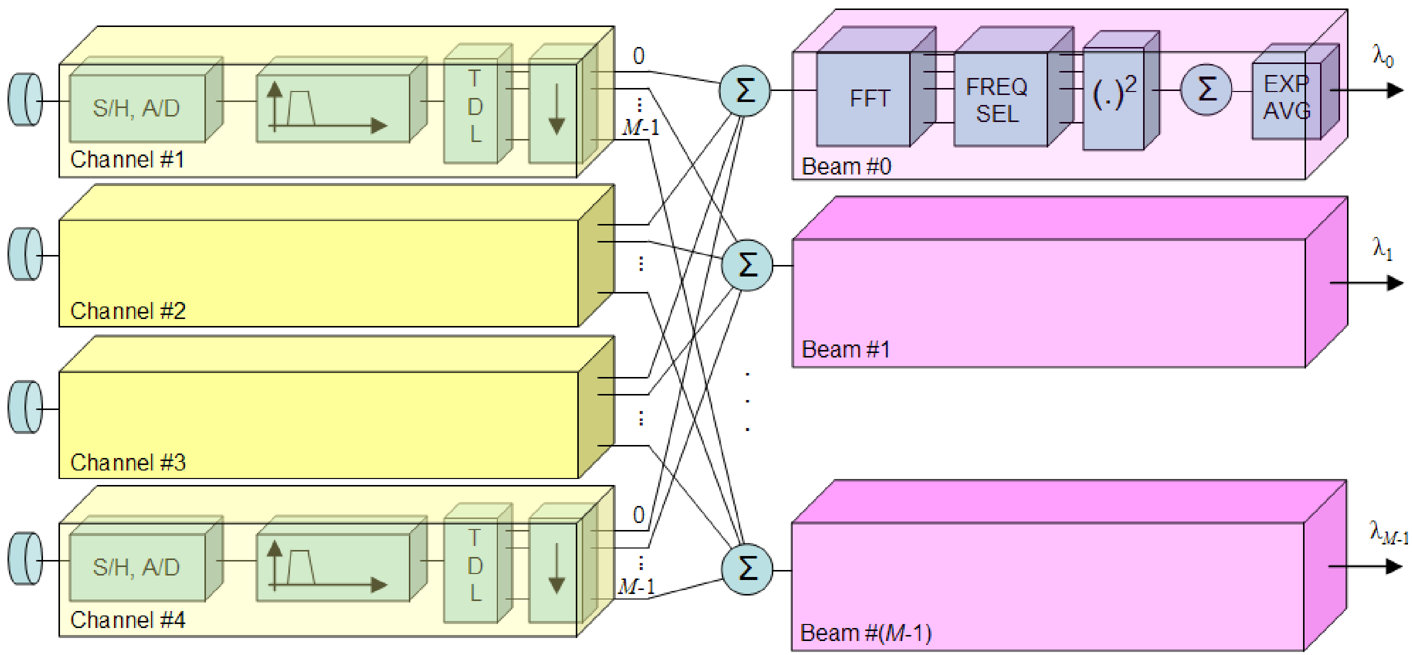






Audio Sensing

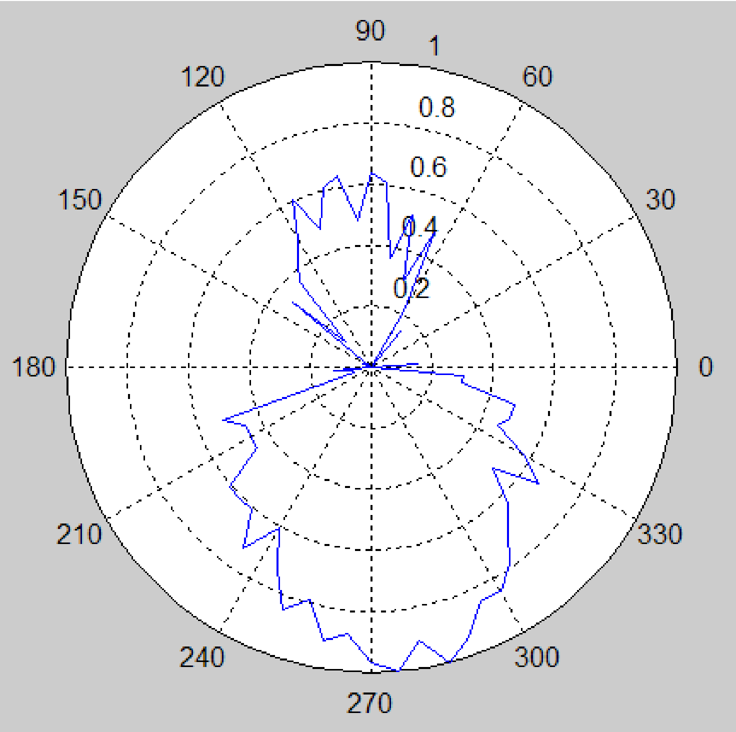
- Acoustic Beamforming



FPGA Implementation

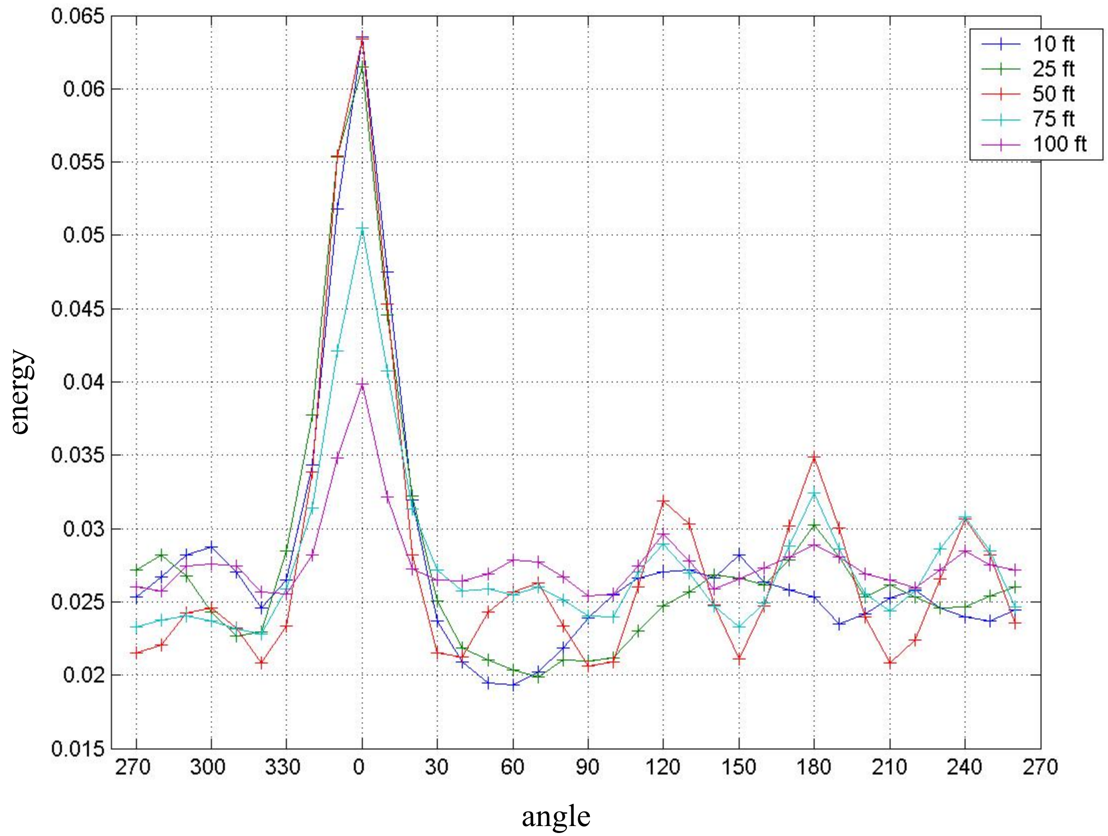
FPGA resources used	
Block RAMs	41%
Slices	43%

Current usage	
FPGA	105 mA
Mote	20 mA
Total	125 mA



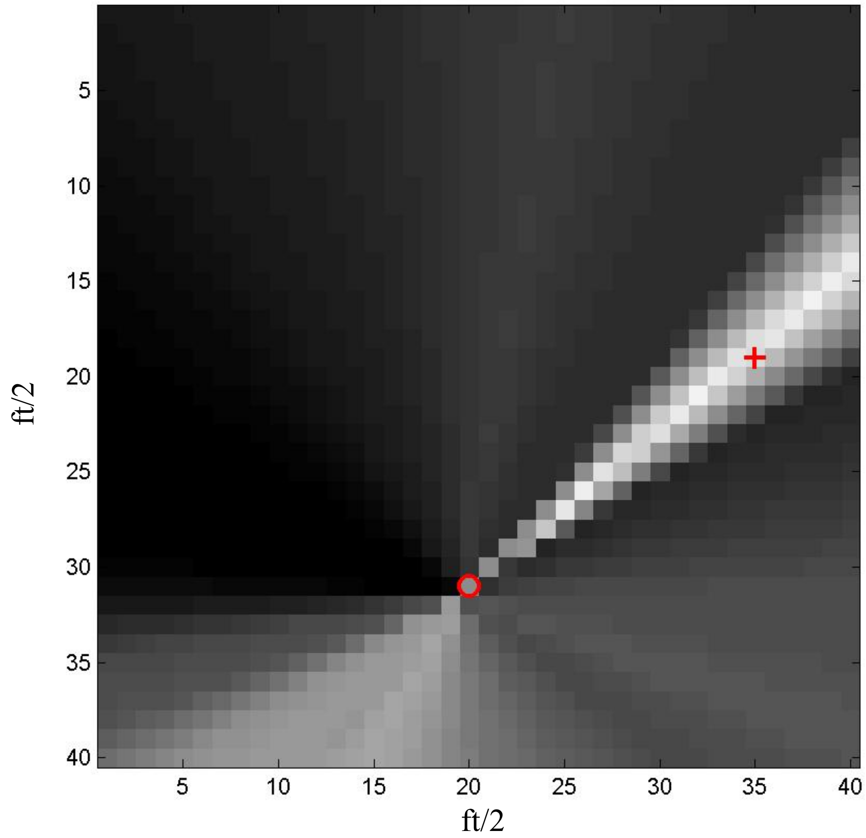
DOA Measurements

Average normalized energy for 100 experiments



Audio Sensor Model

- Audio detection function

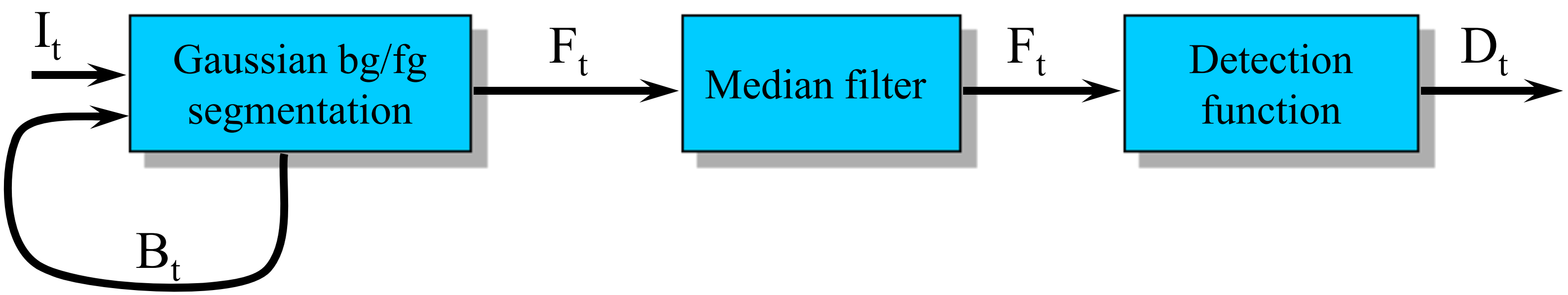


Video Sensor Node

- 533Mhz CPU
- 128MB RAM
- 3 UBS, 2 Serial, 1 parallel port
- 802.11b wireless adapter
- QuickCam Pro
  - up to 640x480 and 30 fps

- Algorithms implemented using OpenCV (Intel)
  - 320x240 resolution
  - 4 fps
  - Timestamped video capture

Video Sensing



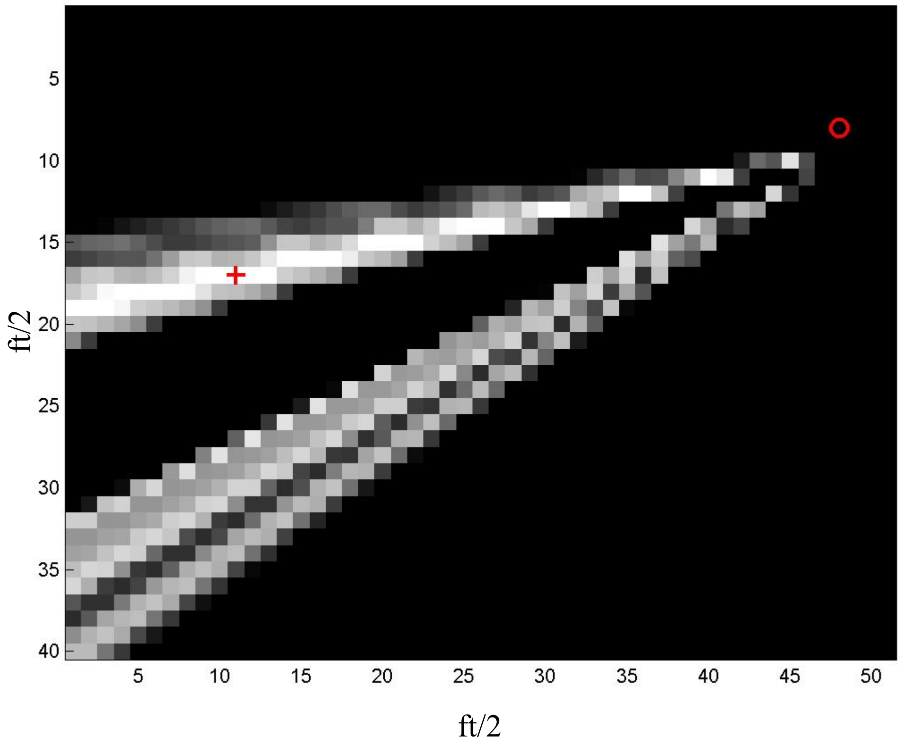
- Object detection
  - Moving object in FOV
- Adaptive background mixture model for real-time tracking with shadow detection
  - Each background pixel is modeled a mixture of Gaussians

*With the assistance of Parvez Ahammad (UCB)

Video Sensor Model

- Video detection function

$$\Lambda_j = \frac{1}{H} \cdot \sum_{k=1}^{H} F(j,k) : j = 1,2,...,W$$



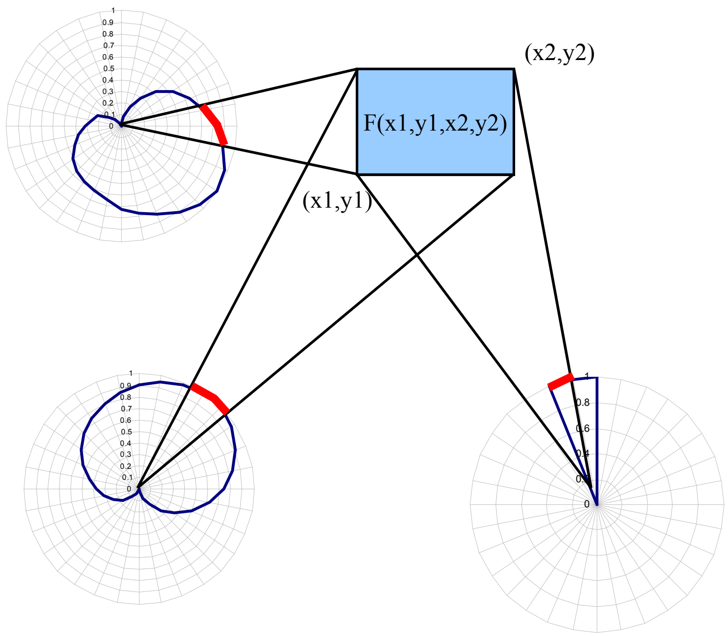
Audio Video Sensor Fusion

- Detection function
  - Acoustic sensors

$$\Xi(\varphi) = \omega\Lambda_{j-1} + (1-\omega)\Lambda_j,\ \mathrm{j}: \varphi_{j-1} \le \varphi < \varphi_j$$

  - Video sensors

$$\Xi(\varphi) = \begin{cases} \omega\Lambda_{j-1} + (1-\omega)\Lambda_j & \text{if } (\theta_0 \le \varphi < \theta_1)\ \&\ (\varphi_{\mathrm{j}-1} \le \varphi < \varphi_j) \\ 0 & \textit{otherwise} \end{cases}$$



- Consistency function
  - Largest detection value (sensor k , region i)

$$\Xi_{\max}^{(k,i)} = \max_{\varphi_A^{(i,k)} < \varphi < \varphi_B^{(i,k)}} \Xi^{(k)}(\varphi)$$

  - Consistency value

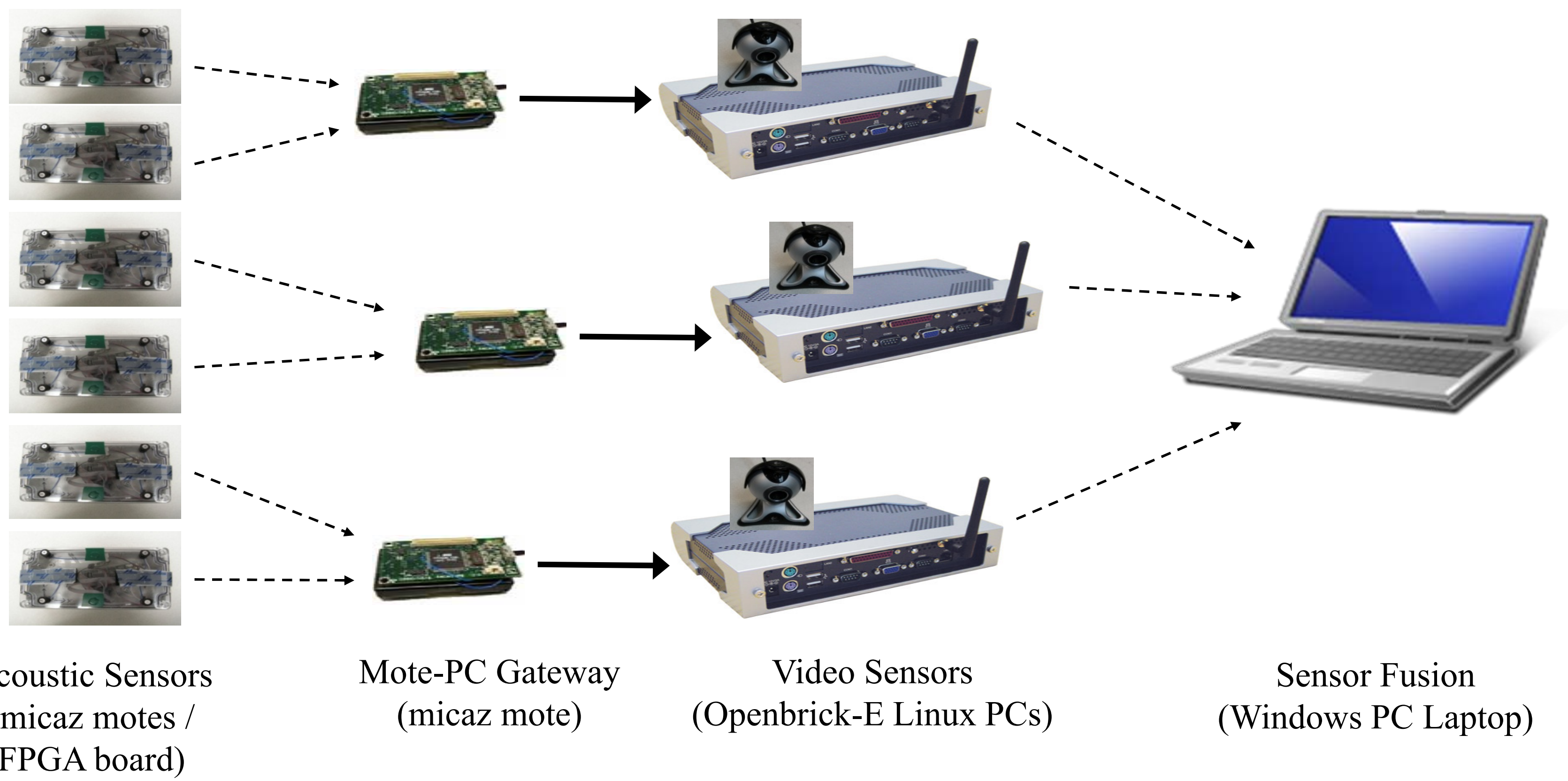
$$C_i = \sum_{k=1}^{K} w^{(k,i)} \Xi_{\max}^{(k,i)}$$

Sequential Bayesian Filtering

$$p(x^{(t+1)} \mid z^{(t+1)}) \propto p(z^{(t+1)} \mid x^{(t+1)}) \cdot \int p(x^{(t+1)} \mid x^{(t)}) \cdot p(x^{(t)} \mid z^{(t)}) dx^{(t)}$$

- Nonparametric representation for probability distributions
  - Discrete grids in two-dimensional plane
- Motion model
  - Target speed and heading are uniform in $[0, v_{max}]$ and $[0, 2\pi)$ resp.
- The consistency function is used as the likelihood of the observations given the target location

HSN Time Synchronization

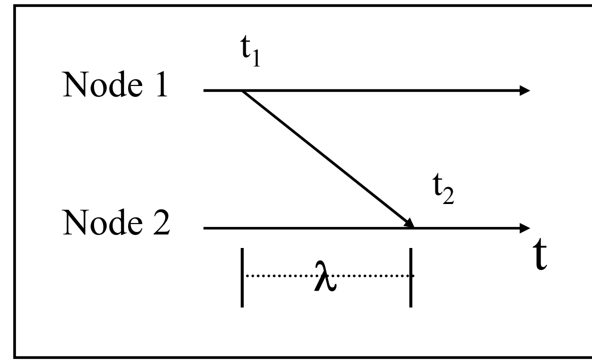


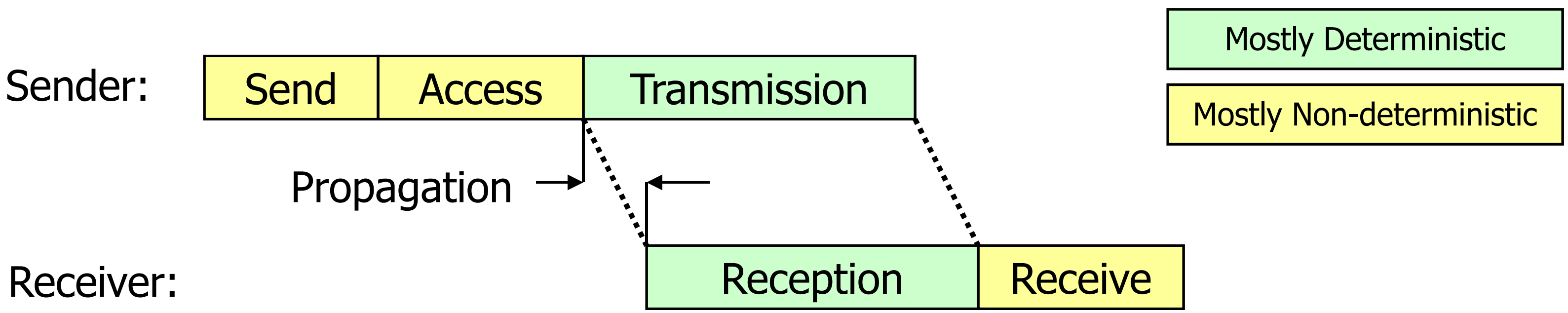
Problem: Observation timestamps must use a common timescale

Synchronization Error

- Node 1 sends synchronization timestamp to Node 2
- Message delay is λ
  - Deterministic components
  - Non-deterministic components

  - Critical Path over wireless network (critical paths are different for different network media):



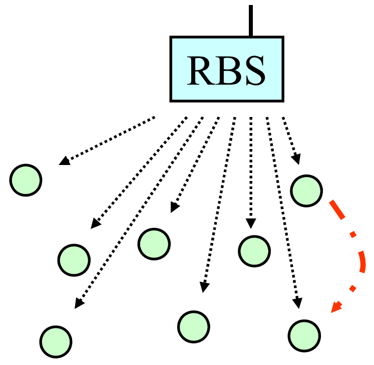


- Unless this delay is accounted for, there will be synchronization error

Synchronization Protocols

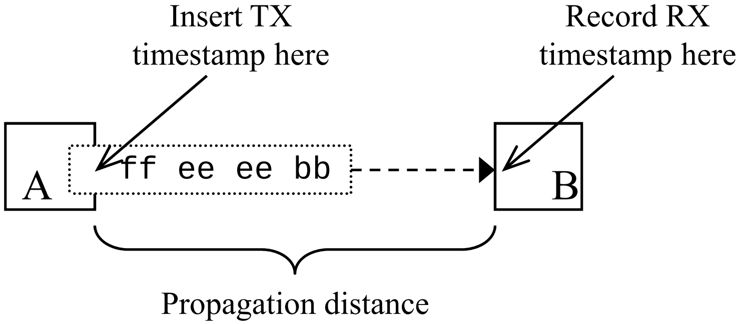
- Reference Broadcast Synchronization (RBS)
  - Nodes synchronize to the arrival of a reference beacon
  - Exchange arrival timestamps with each other
  - Eliminates sender-side message delay
  - Microsecond accuracy

  - Used in PC network



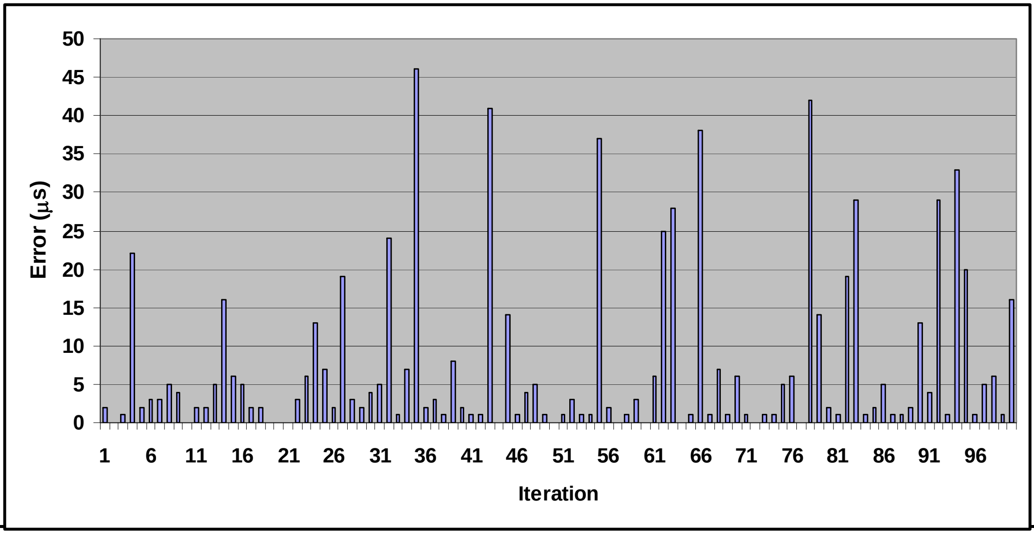
- Routing-Integrated Time Synchronization (RITS)
  - Sender node inserts timestamp into message as message is transmitting
  - Receiver node takes timestamp as message is incoming
  - Delay is mostly deterministic
  - Microsecond accuracy

  - Used in Mote network and Mote-PC connection



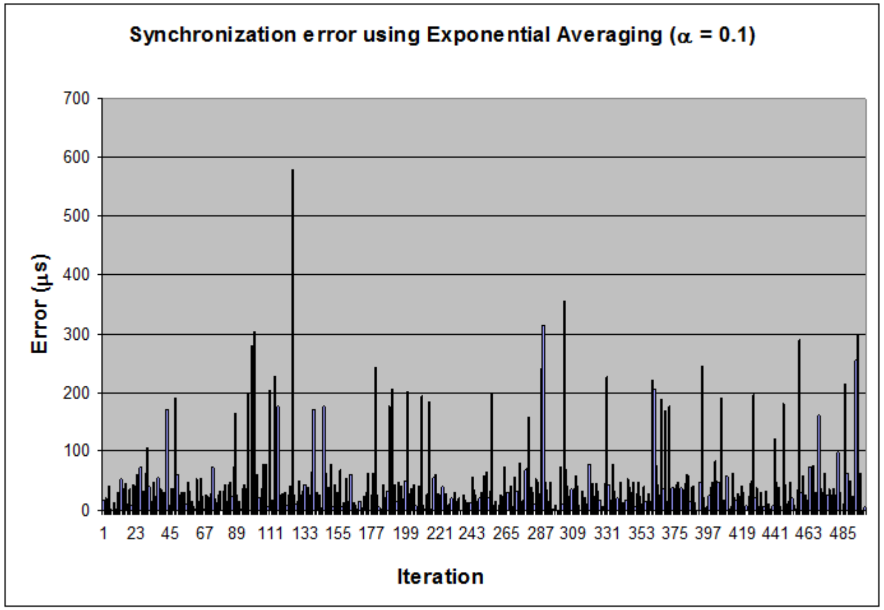
Mote-PC Synchronization Results

- Evaluated by connecting GPIO pins on each device to an oscilloscope
  - Upon timestamping, each device sets GPIO pins high, and signals are captured on oscilloscope
  - Capture times are then compared
- Average error: 7.32 μs, maximum error: 46 μs
  - Attributed to jitter, both from UART and CPU
  - Similar results obtained in presence of network congestion

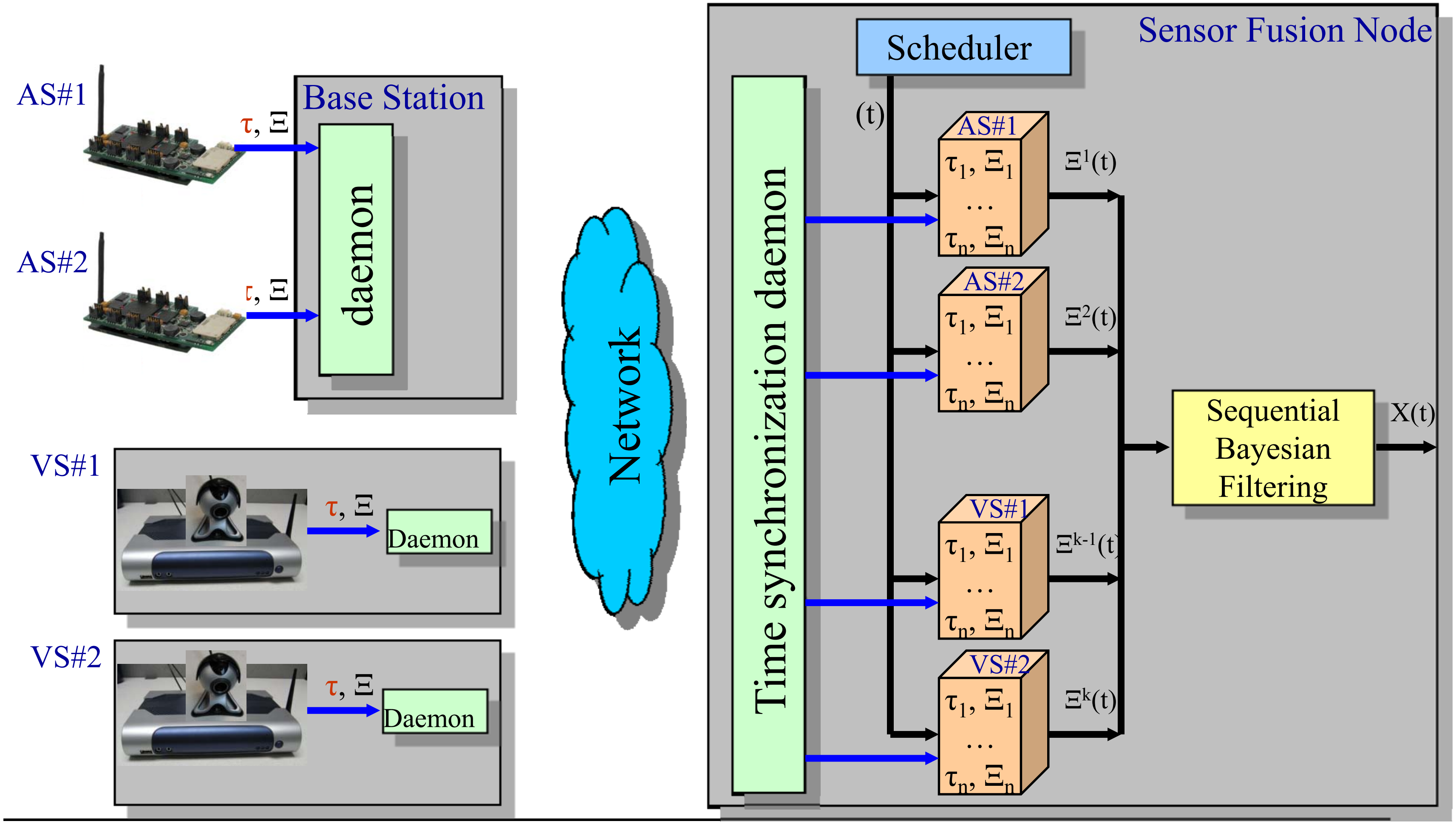


HSN Synchronization Results

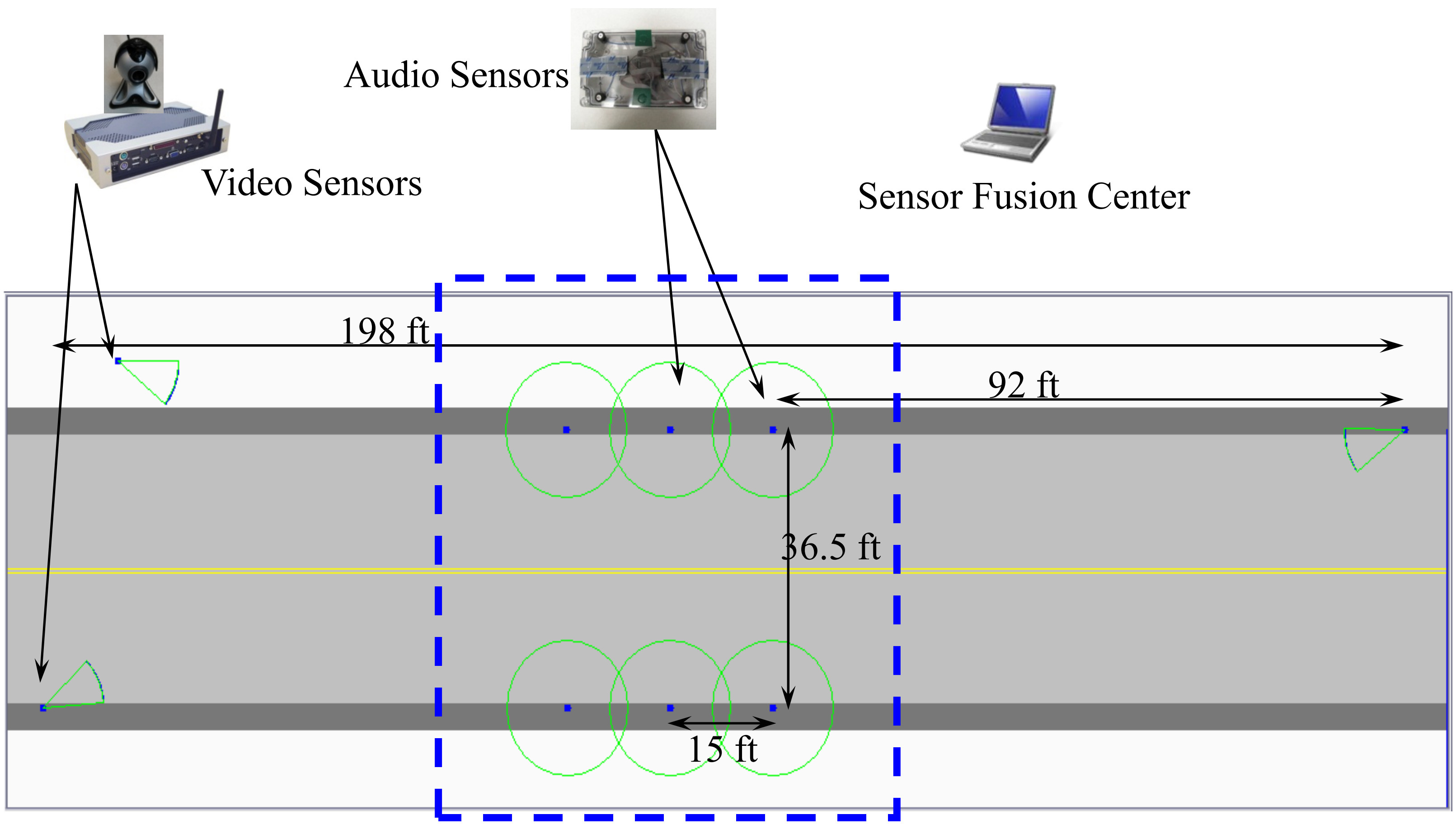
- Synchronization over entire HSN using RITS and RBS
  - Exponential Averaging
    - Average = 41.80 μs
    - Maximum = 579 μs
    - Median = 24 μs
  - Linear Regression
    - Average = 43.81 μs
    - Maximum = 450 μs
    - Median = 27.5 μs
  - No Clock Skew Compensation
    - Average = 60.53 μs
    - Maximum = 343 μs
    - Median = 38 μs



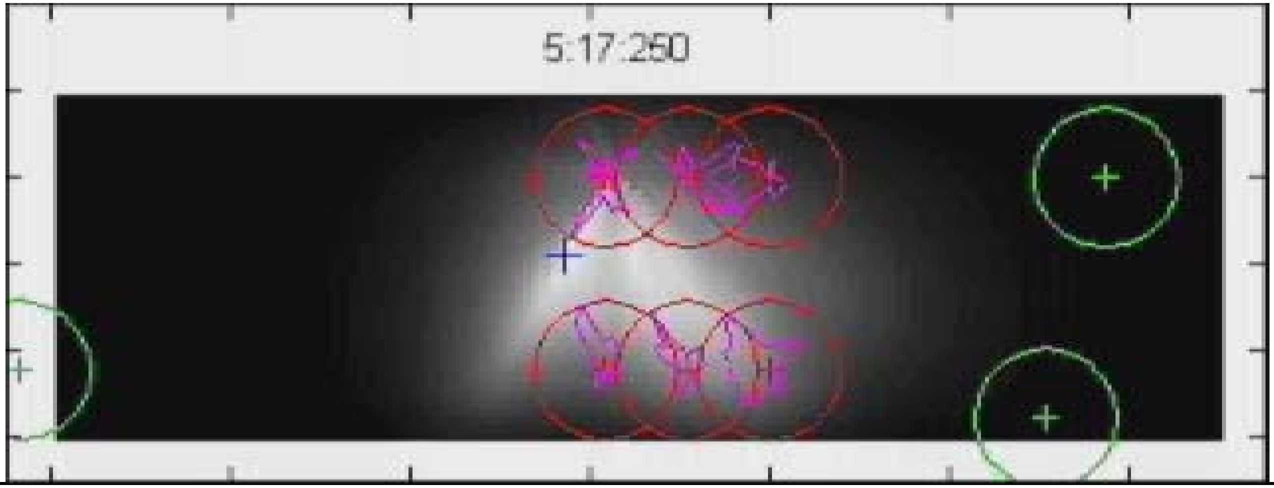
System Architecture



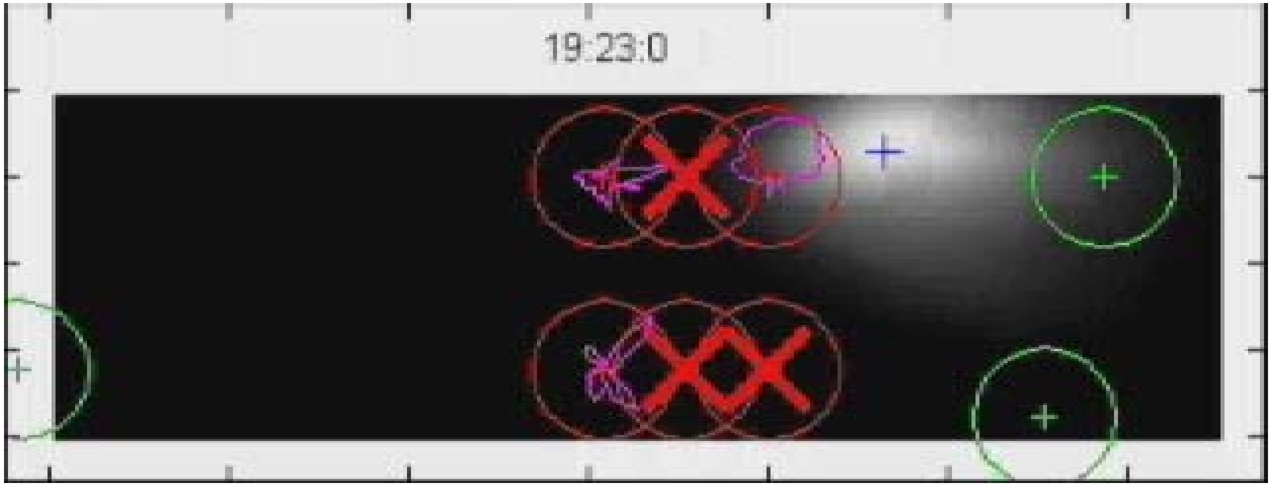
Experimental Setup



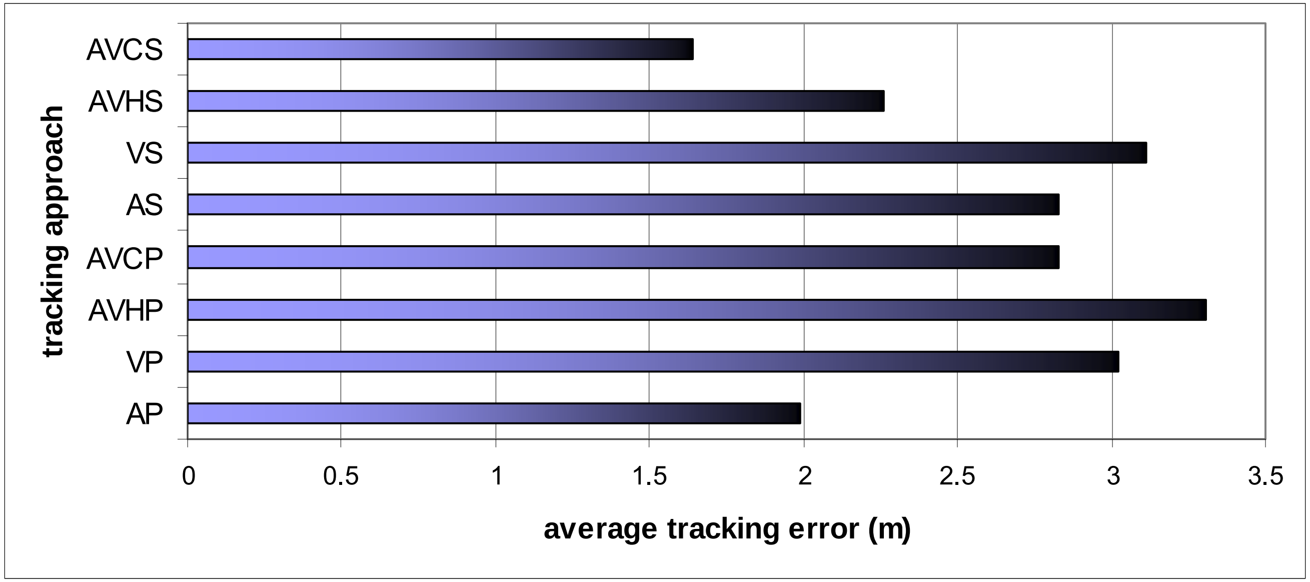
Tracking Experiment #1

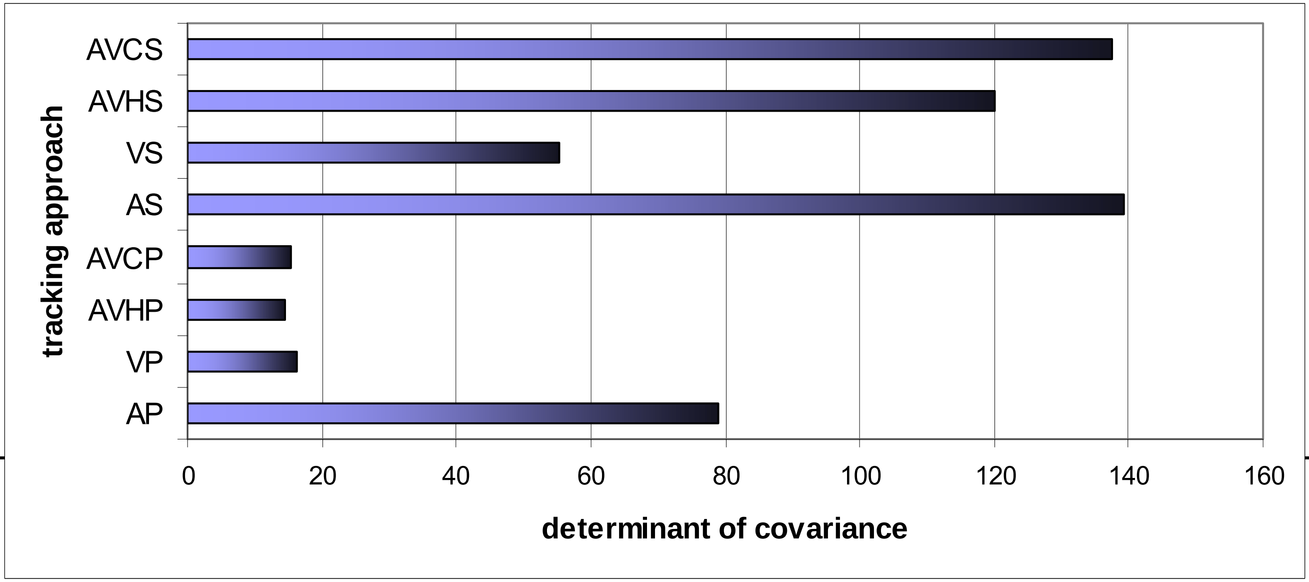


Tracking Experiment #2

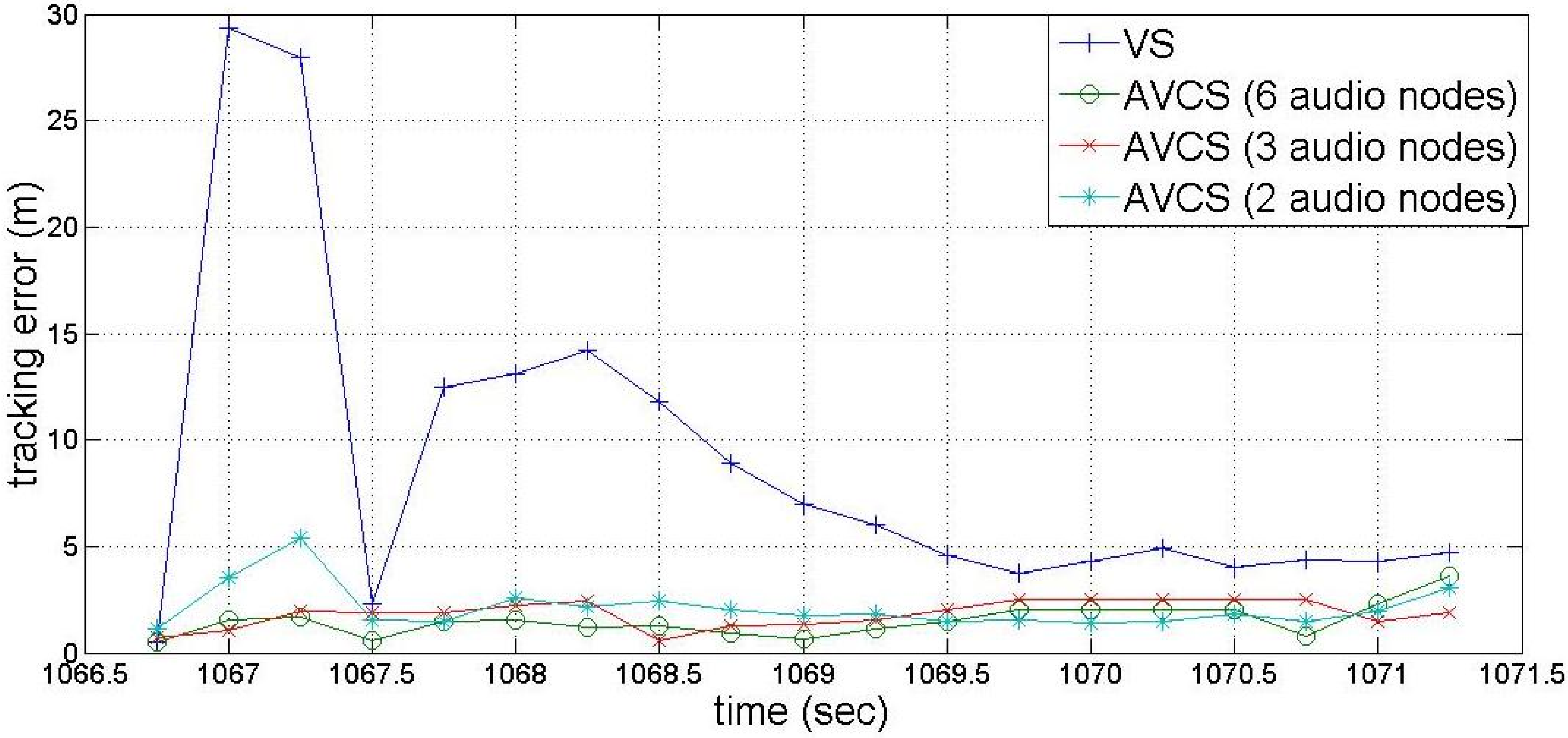


Evaluation Results

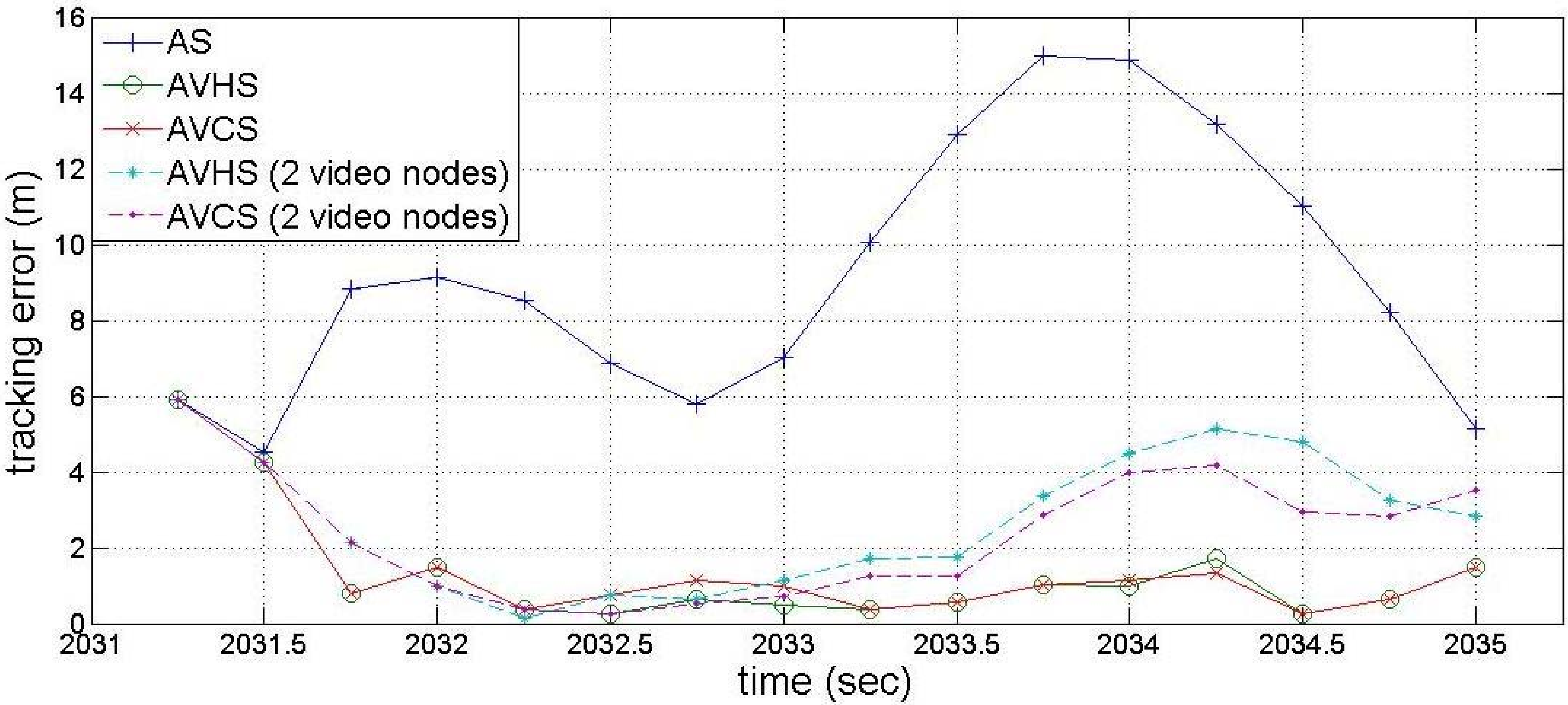




Audio Assisting Poor Video



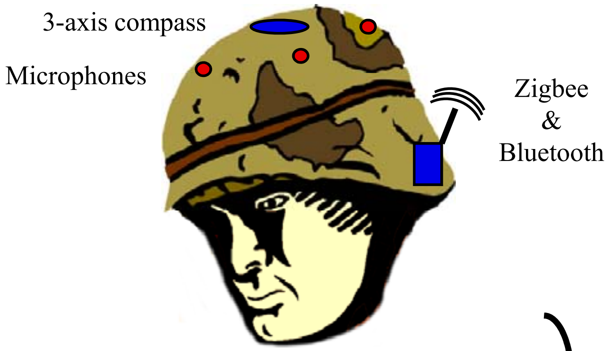
Video Assisting Poor Audio



Mobile Sensor Nodes

- While traditional, statically deployed sensor networks have their merits, the future lies in *people- and vehicle-mounted sensors:*
- *→ MOBILITY*

- Localization and tracking of the mobile sensor nodes is a challenge
- GPS is not available on every platform all the time:
  - cost, size, power limitations
  - accuracy
  - GPS-denied environments



Vanderbilt Assist

Boomerang by BBN

RedOwl by BU

Mobile countersniper systems

Tracking Moving Nodes

- Radio-interferometric range, or *q-range* q_{ABCD} involves four nodes A, B, C and D:

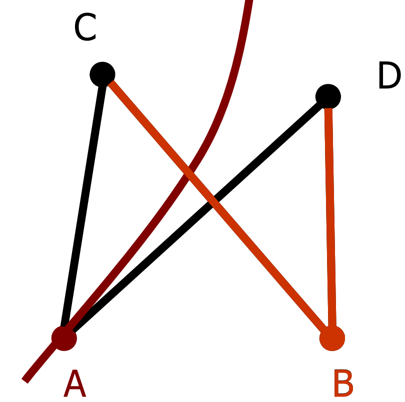
$$q_{ABCD}=d_{AD}-d_{BD}+d_{BC}-d_{AC}$$

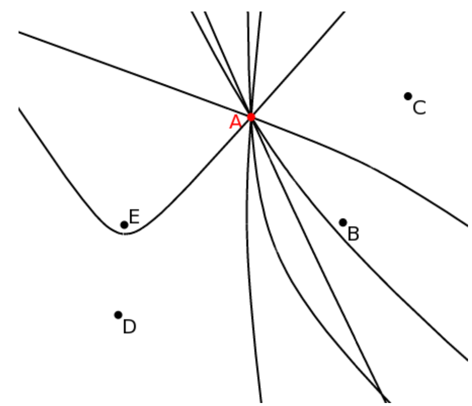
- In tracking, one of the four nodes (e.g. A) is unknown, thus we define the *t-range* that relates three nodes as follows:

$$t_{ACD} = d_{AD}-d_{AC} = q_{ABCD}+d_{BD}-d_{BC}$$

where q_{ABCD} can be measured, d_{BD} and d_{BC} are given

- The t-range defines a hyperbola in 2D (hyperboloid in 3D)
- For example, 12 infrastructure nodes yield 11*(10)/2 = 55 different hyperbolae from a single measurement (transmission) round



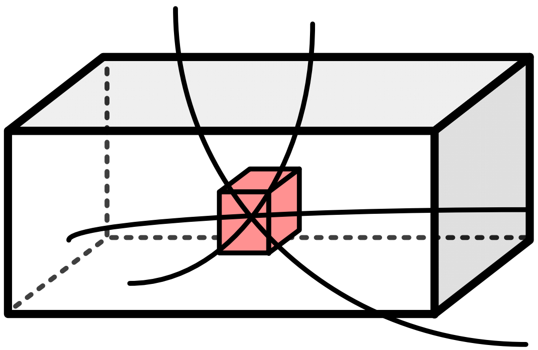


transmitter A at intersection of 6 hyperb. defined by receivers B,C,D,E

Calculating Locations in Tracking

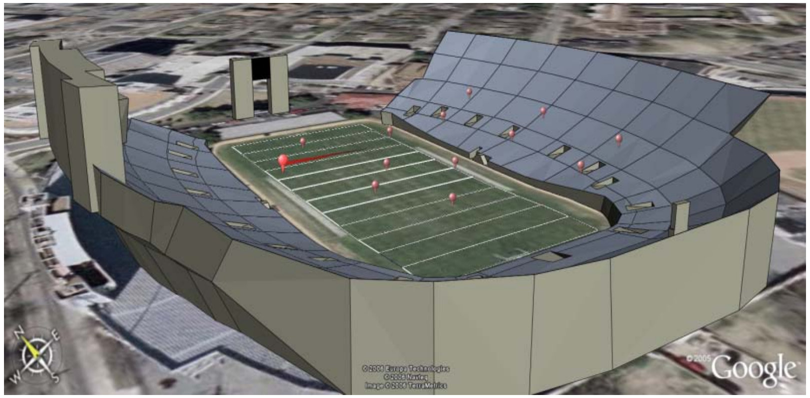
Location estimation

- node location is found at the intersection of hyperbolae



- hyperbolae intersect at a single point
- except for the measurement error
- search for a region which gets intersected by many hyperbolae

Evaluation



Test at the football stadium

- Vanderbilt football stadium
- 12 infrastructure nodes
- 80 x 90 m area
- 0.6m avg and 1.5m max 2D error
- 3 sec update rate

Implementation

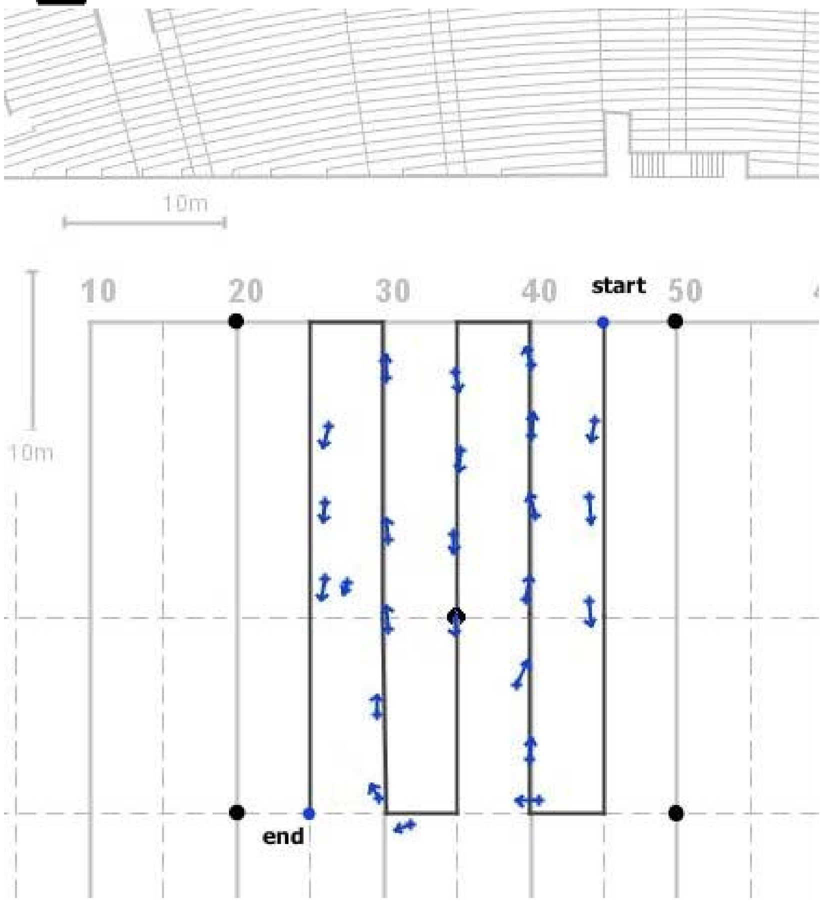
Infrastructure and target nodes

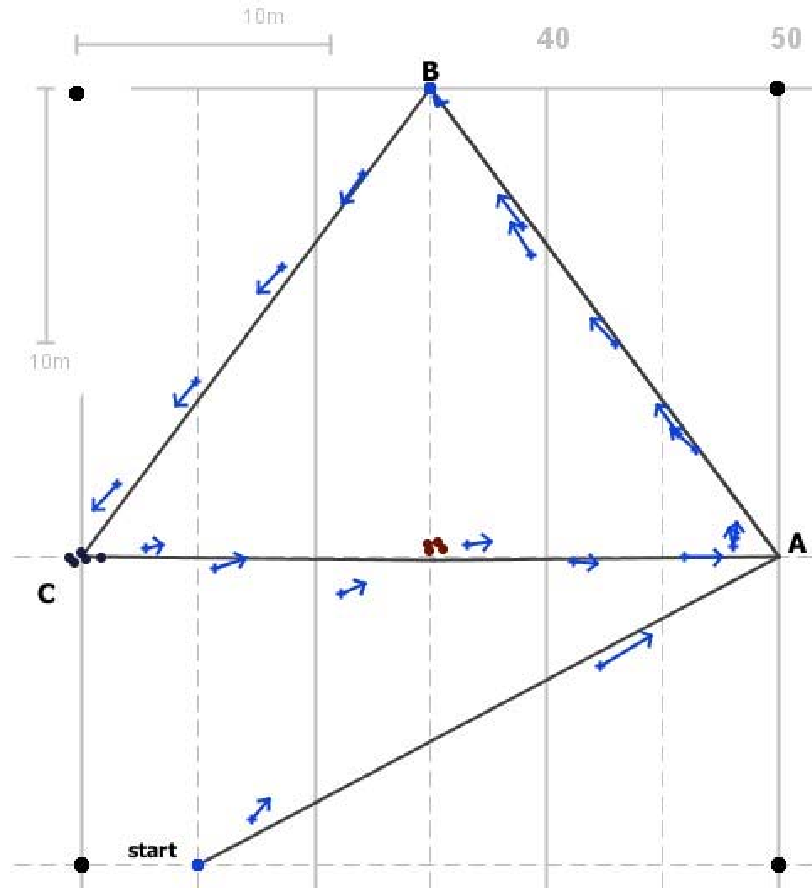
- Berkeley Motes (mica2/XSM from Crossbow)
- 7.2MHz microcontroller
- 4kB RAM
- low-power radio transciever (CC1000 from Chipcon/TI)
- TinyOS operating system

Hardware requirements

- Option to transmit unmodulated sine wave
- Ability to tune the radio frequency in <100Hz increments
- Sample ADC at 17kHz
- Time synchronization

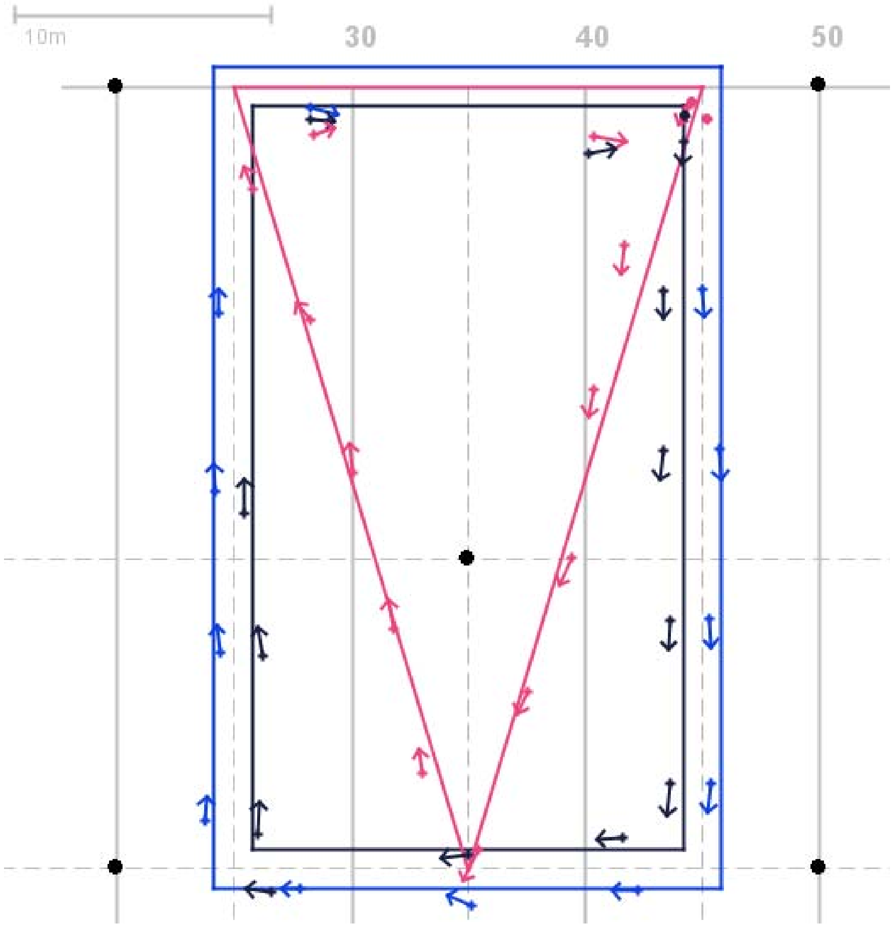
Tracking a Single Target

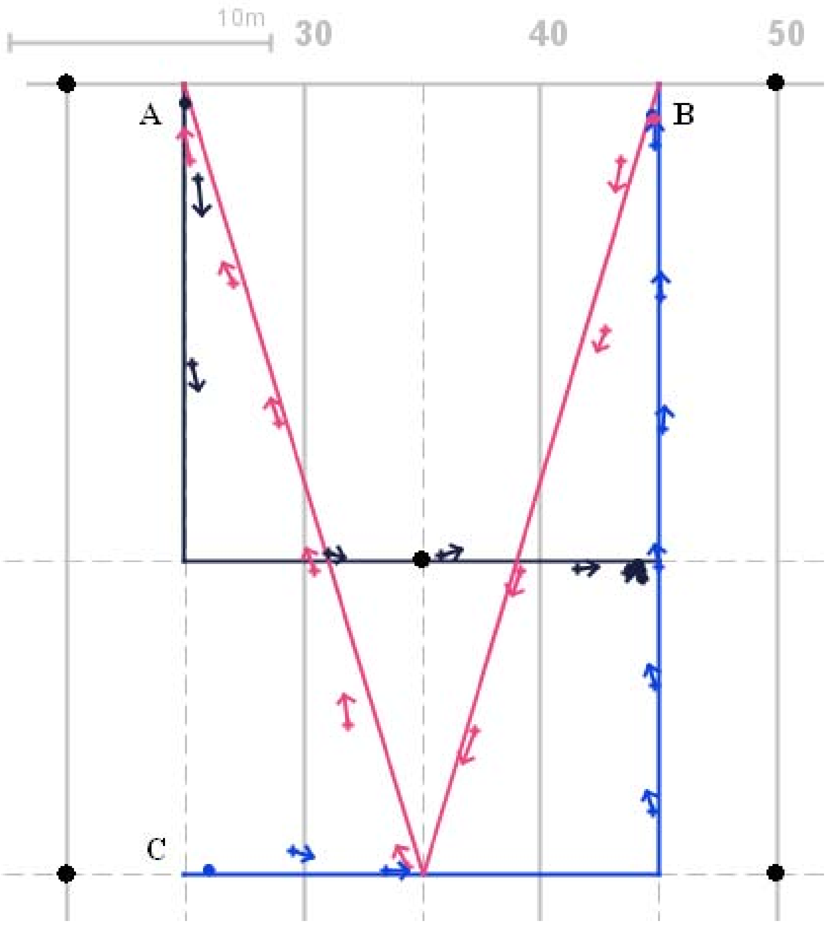




Mean position error:	0.9m	1.6m
Mean speed error:	0.2m/s	0.2m/s
Mean angle error:	11.6°	13.3°

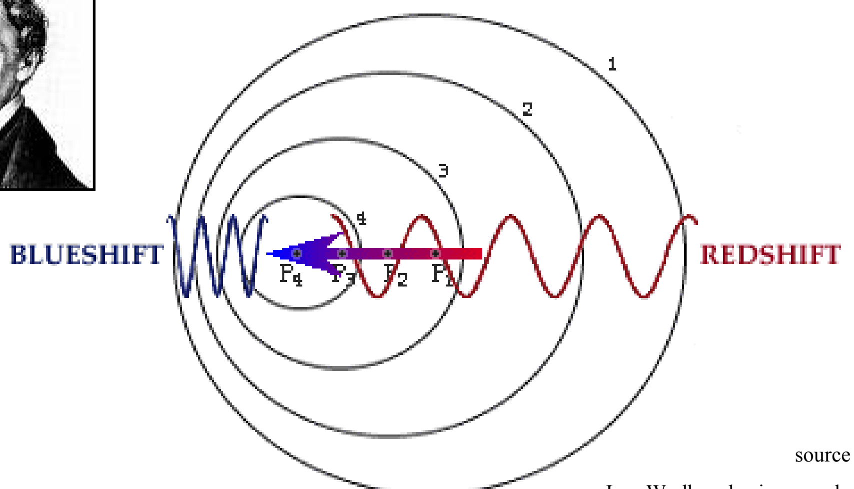
Tracking Multiple Targets





Doppler Effect

- Assume a mobile source transmits a signal with frequency f, and f' is the frequency of received signal



source
Jose Wudka, physics.ucr.edu

$$f' = f + \Delta_f$$

$$\Delta_f = -v / \lambda_f$$

v is relative speed of source and receiver

λ_f is wavelength of the transmitted signal

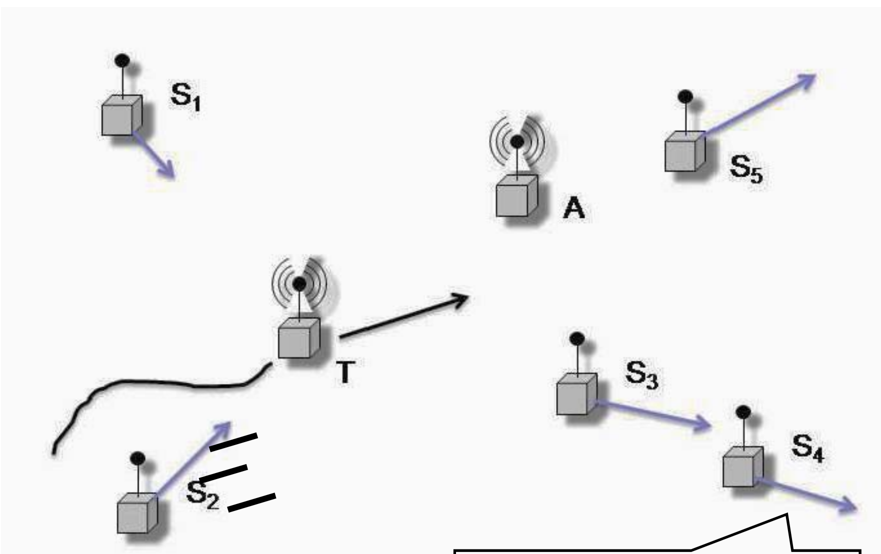
Can we Measure Doppler Shifts?

	Typ. freq	Dopp. Shift (@ 1 m/s)
Acoustic signals	1-5 kHz	3-15 Hz
Radio signals (mica2)	433 MHz	1.3 Hz
Radio signals (telos)	2.4 GHz	8 Hz

If we can utilize radio signals, no extra HW is required

Formalization

We want to calculate both location and velocity of node T from the measured Doppler shifts.



$$f_4 = f_T - f_A + \Delta f_4$$
$$= f_T - f_A + v_4/\lambda_T$$

Unknowns:

- Location, velocity of T, and $f_T - f_A$

$\mathbf{x}=(x,y,v_x,v_y,f\hat{})$

Knowns (constraints):

- Locations (x_i,y_i) of nodes S_i
- Doppler shifted frequencies f_i

$\mathbf{c}=(f_1,\ldots,f_n)$

Function H(**x**)=**c**:

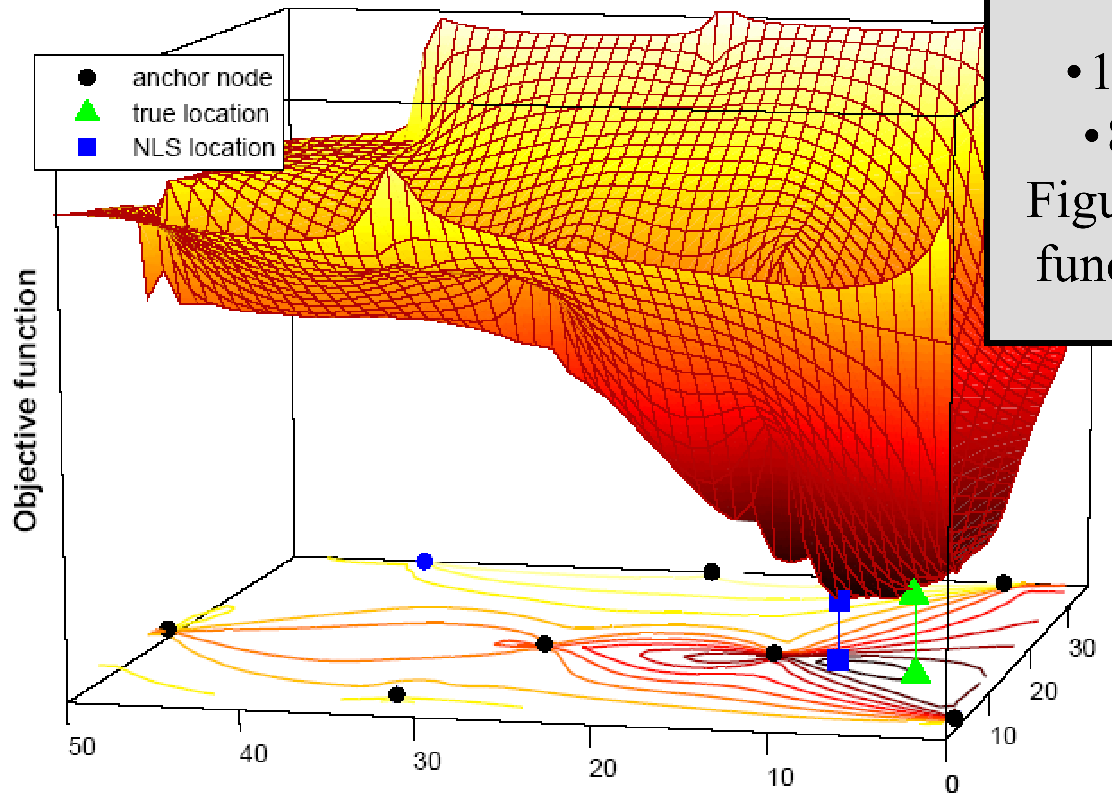
$$H_i(\mathbf{x}) = \hat{f} - \frac{1}{\lambda_t}\frac{v_x(x_i - x) + v_y(y_i - y)}{\sqrt{(x_i - x)^2 + (y_i - y)^2}}$$

Non-linear system of equations!

Tracking as Optimization Problem

Non-linear Least Squares (NLS)

- Minimize objective function ||H(**x**) – **c**||
- What's the effect of measurement errors?



Experiment:

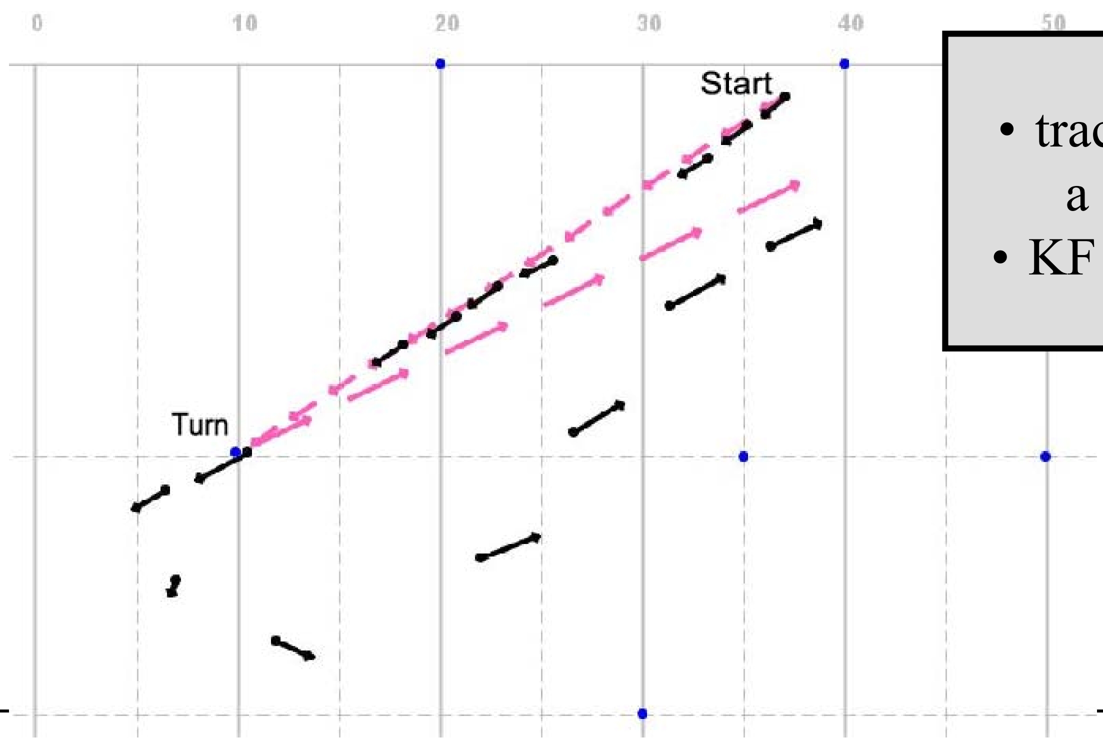
- 1 mobile transmitter
- 8 nodes measure f_i

Figure shows objective function for fixed (x,y) coordinates

Improving Accuracy

State Estimation: Kalman Filter

- Measurement error is Gaussian
- Model dynamics of the tracked node (constant speed)
- Accuracy improves, but maneuvers are a problem



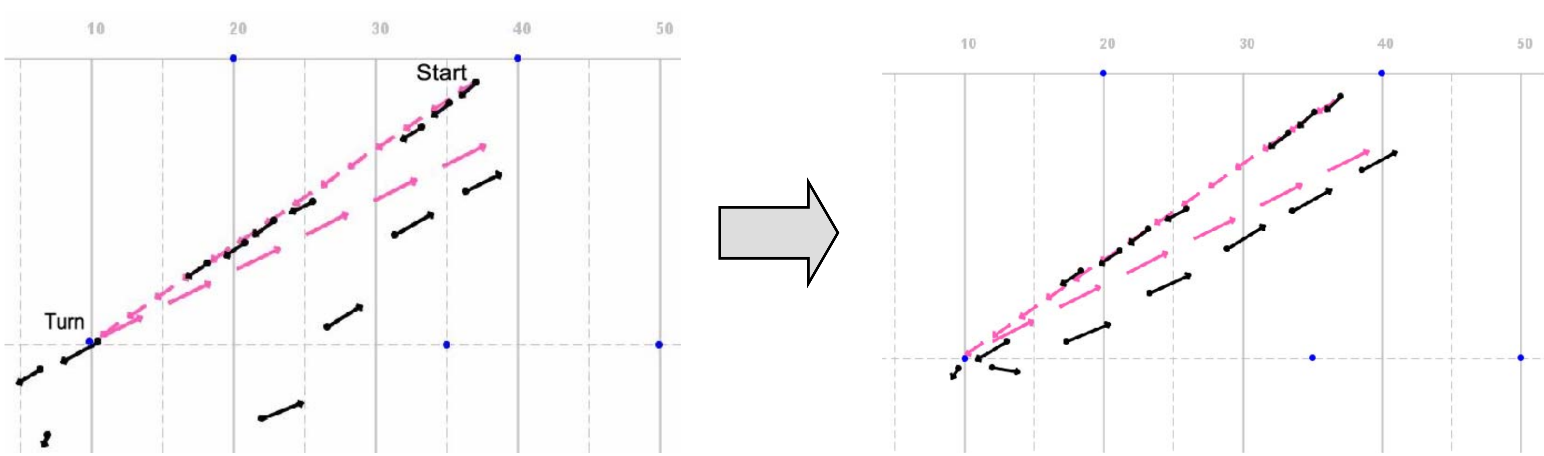
Experiment:

- tracked node moves on a line and then turns
- KF requires 6 rounds to converge back.

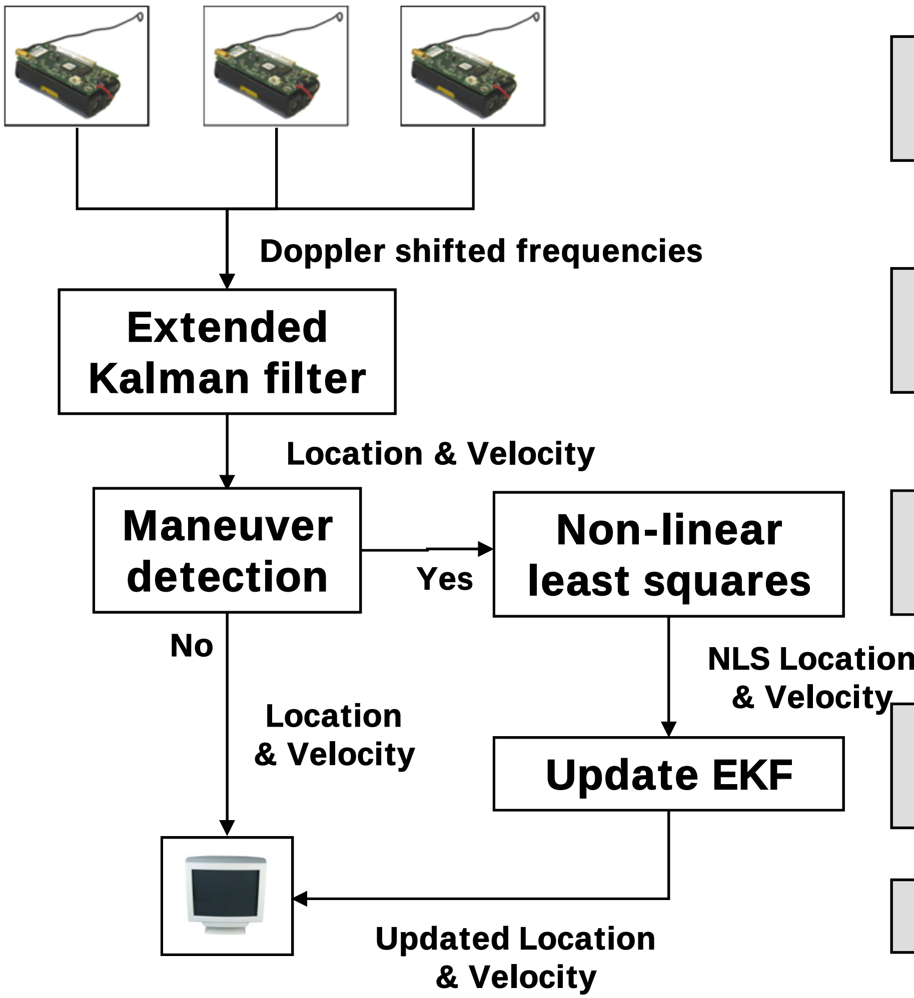
Resolving EKF Problems

Combine Least Squares and Kalman Filter

- Run standard KF algorithm
- Detect maneuvers of the tracked node
- Update KF state with NLS solution



Tracking Algorithm



Infrastructure nodes record Doppler shifted beat frequency.

Calculate location and velocity using Kalman filter.

Run a simple maneuver detection algorithm.

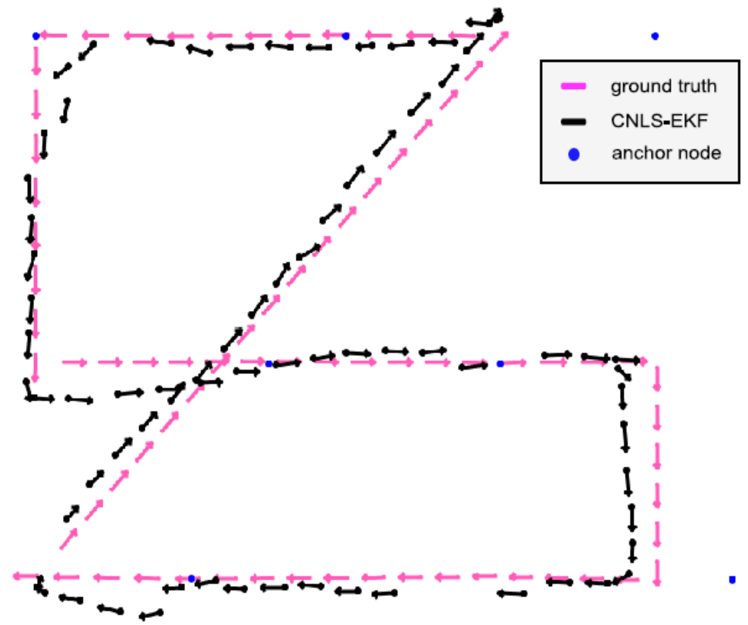
If maneuver is detected, calculate NLS solution and update EKF state.

Show location on the screen.

Experimental Evaluation

Vanderbilt football stadium

- 50 x 30 m area
- 9 infrastructure XSM nodes
- 1 XSM mote tracked
- position fix in 1.5 seconds



Non-maneuvering case

Mean Errors:	Location	Speed	Heading
EKF algorithm	1.5 m	0.14 m/s	7.2°
CNLS-EKF algorithm	1.3 m	0.13 m/s	6.9°
Improvement over EKF	10%	1.7%	4.4%

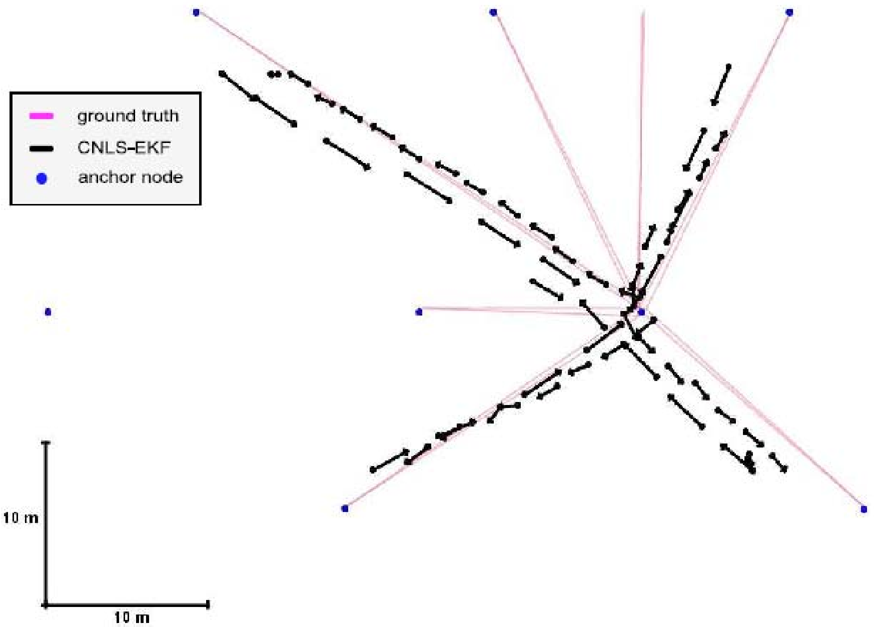
Experimental Evaluation

Vanderbilt football stadium

- 50 x 30 m area
- 9 infrastructure XSM nodes
- 1 XSM mote tracked
- position fix in 1.5 seconds

Maneuvering case

Mean Errors:	Location	Speed	Heading
EKF algorithm	4.3 m	0.42 m/s	17.7°
CNLS-EKF algorithm	2.2 m	0.35 m/s	17.5°
Improvement over EKF	48.7%	16.3%	0.4%



Only some of the tracks are shown for clarity.

Future Work

- Multiple target tracking
- Inference of high level behaviors

- Inexpensive legged robotic vehicles with self-localization capabilities

- Indoor localization