CS 455/655 --Mobile Sensor Networks
Lecture Notes 9: Sensor Localization (Multi-Lateration)

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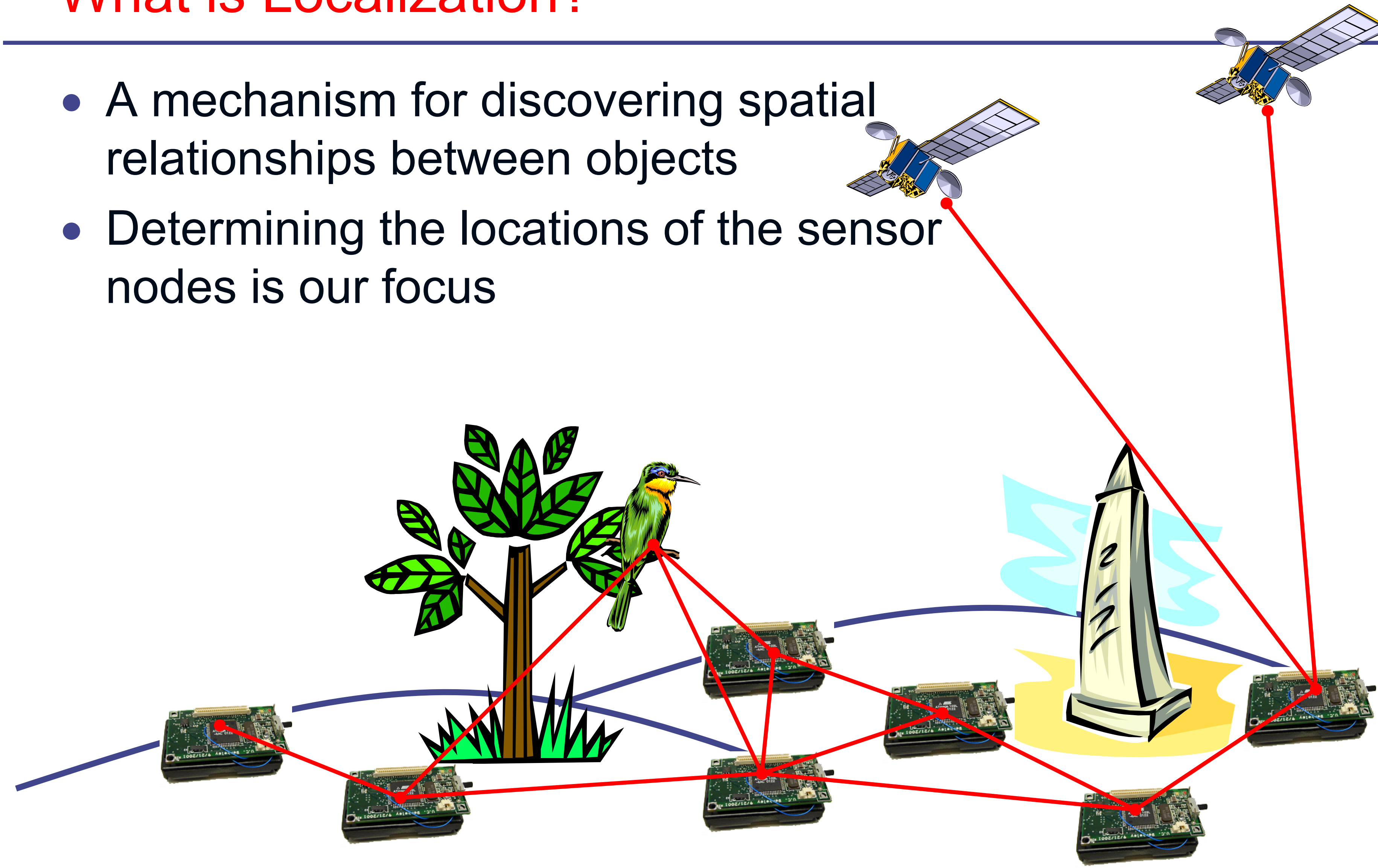
Outline

- Introduction
- Measuring technologies
- Tri/Multi-lateration Localization

What is Localization?

- A mechanism for discovering spatial relationships between objects
- Determining the locations of the sensor nodes is our focus



Sensor localization

- Determine ***physical position*** of sensor nodes
  - Coordinate system or reference
  - Absolute or relative coordinates
- Metrics
  - Accuracy (how close is an estimated position to the real position?)
  - Precision (for repeated position determinations, how often is a given accuracy achieved?)
  - Complexity
  - Energy consumption
  - …

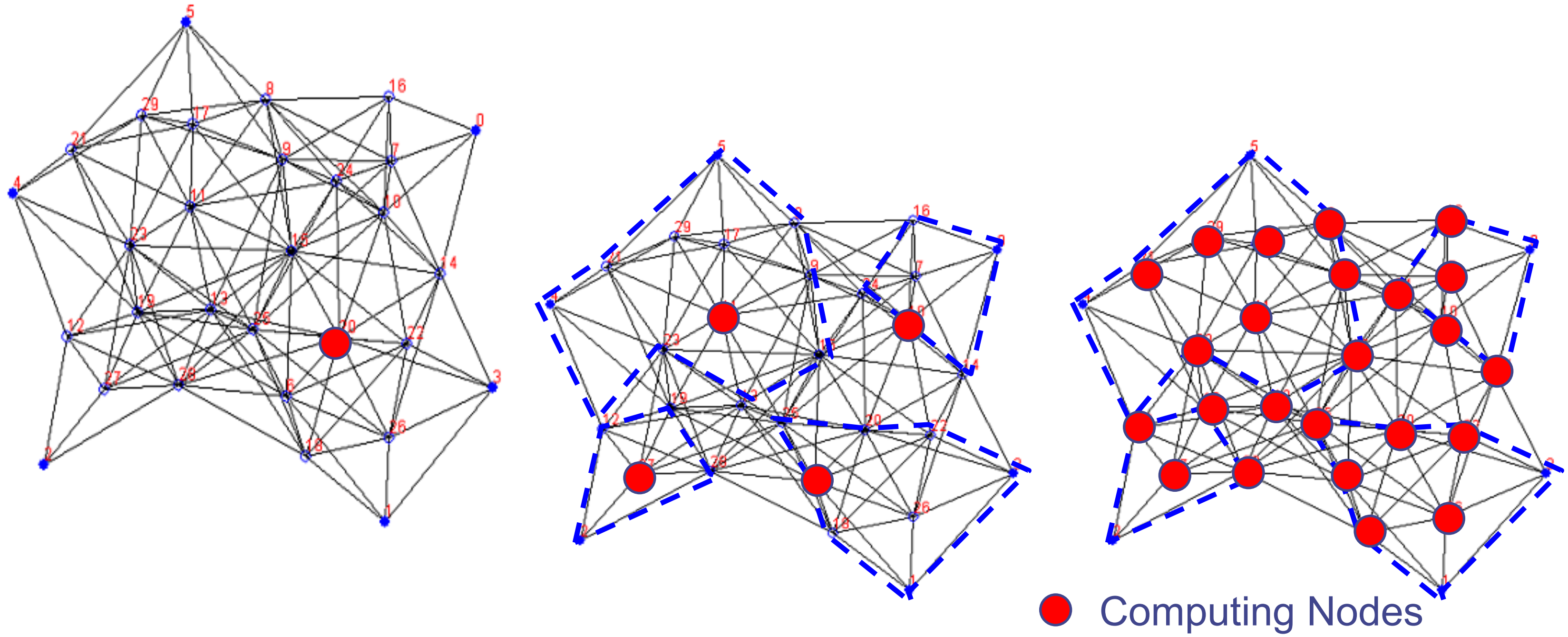
Why is localization important?

- Very fundamental component for many services
  - Sensor locations give raw sensor readings a physical context
    - Temperature readings $\Rightarrow$ temperature map
  - Context-aware computing– devices need to know where they are
  - Geographic routing & coverage problems
  - Tracking applications: people and asset tracking
  - Topology control
- GPS does not work everywhere, or too expensive to use GPS, or not accurate enough.

Challenges in sensor localization

- Localization captures multiple aspects of sensor networks:
  - **Physical layer imposes measurement challenges**
    - Multipath, shadowing, sensor imperfections, changes in propagation properties and more
  - **Extensive computation aspects**
    - Many formulations of localization problems, how do you solve the optimization problem?
    - How do you solve the problem in a distributed manner?
      - You may have to solve the problem on a memory constrained processor
  - **Networking and coordination issues**
    - Nodes have to collaborate and communicate to solve the problem
  - **System Integration issues**
    - How do you integrate location services with other applications?

Centralized or decentralized localization

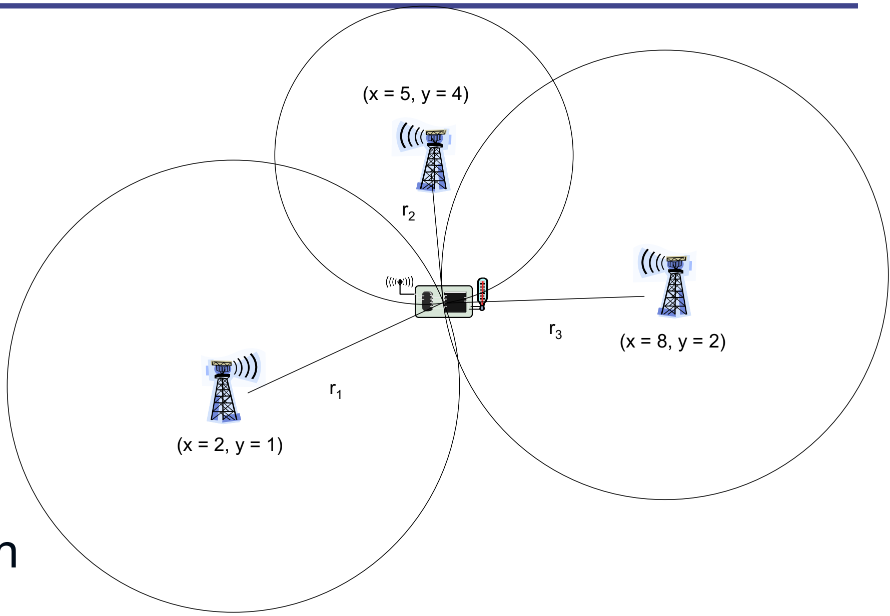


1. Centralized 2. Locally Centralized 3. (Fully) Distributed

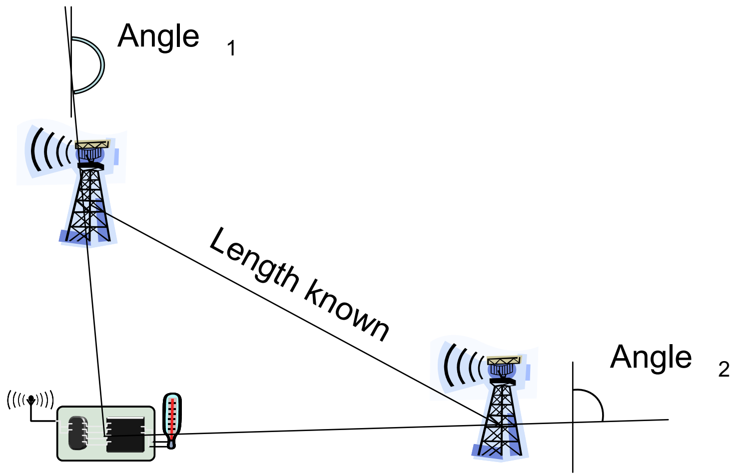
Decentralized algorithm can easily scale up

Main approaches

- Proximity
  - Exploit finite range of wireless communication
  - E.g.: infrared room number announcements



- (Tri-/Multi-)***lateration*** and ***angulation***
  - Use distance or angle estimates, simple geometry to compute position estimates



- Multidimensional Scaling

- Scene analysis
  - Radio environment has characteristic "signatures"
  - Can be measured beforehand, stored, compared with current situation

Estimating distances – RSSI

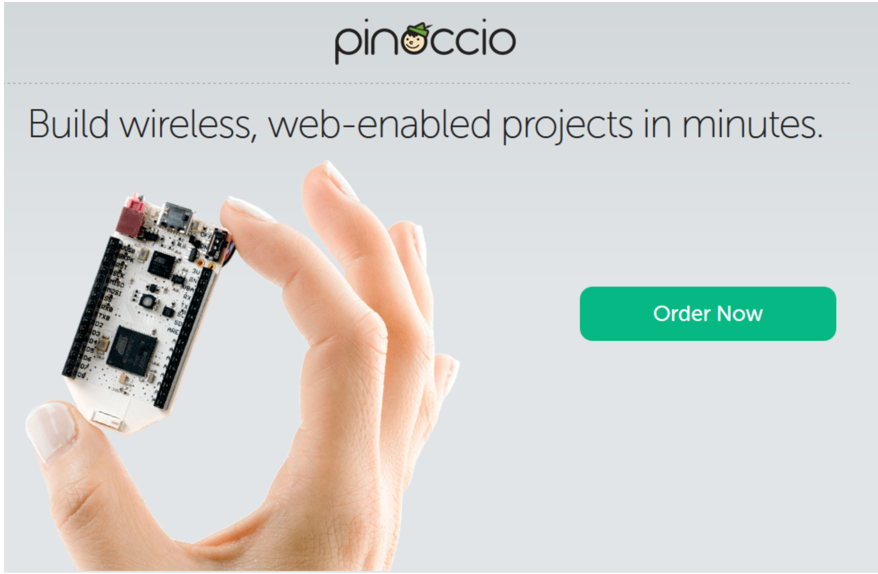
- Received Signal Strength Indicator
  - Send out signal of known strength, use received signal strength and path loss coefficient to estimate distance

$$P_{\text{recv}} = c\frac{P_{\text{tx}}}{d^{\alpha}} \Leftrightarrow d = \sqrt[\alpha]{\frac{cP_{\text{tx}}}{P_{\text{recv}}}}$$

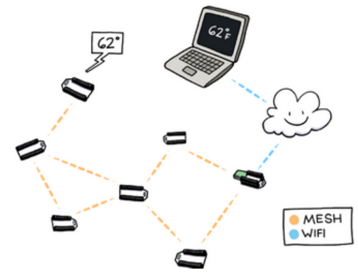
Where *Precv* is the received power, *c is* constant depending on a transceiver, *Ptx* transmitting power and *d* is the called distance-power gradient. There are tables defining gradient [1].

[1] Paolo Santi: *Topology Control in Wireless Ad Hoc and Sensor Networks*, ISBN-13: 978-0470094532, September, 2005.

Pinoccio Sensor using RSSI



https://pinocc.io/



Mesh networked, web-connected.

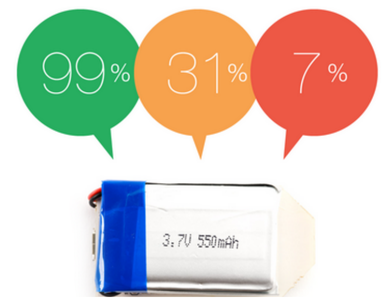
Field Scouts talk to each other using a mesh network (called a **Troop**), using an extremely low-power radio. This makes them ***14 times more efficient*** than standard WiFi devices. Slap a WiFi backpack on a Scout to make it the **Lead Scout**, and connect your entire Troop to the web!

Sending messages between Scouts (or out to the web) is super straightforward, and it all *just works*.

Learn how we mesh all the things.

Battery included, recharge circuit built-in.

Every Scout comes with its own (removable) rechargeable battery, making it *truly* wireless, straight out of the box. We've also gone ahead and built one of those pesky charging circuits right into the board, so you can monitor your power levels, and recharge your Scout using the USB connector, or a power source of your own (bust out those solar panels).



Experiments of RSSI, Zigbee

- Low-power RF modules MRF24J40 from Microchip with Zigbee support

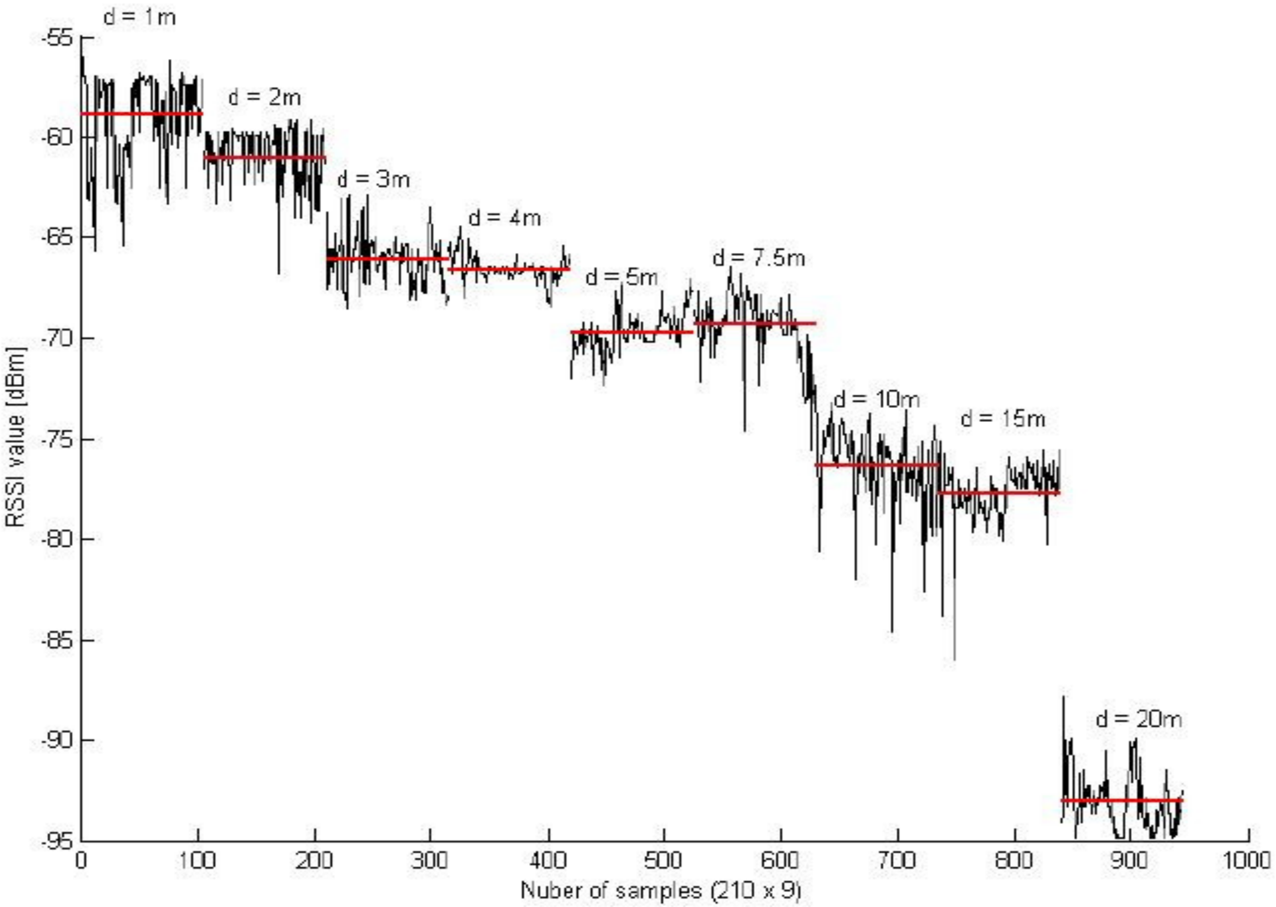


Fig. 3. Reading RSSI on MRF24J40.

Experiments of RSSI

- Low-power RF modules CC2420 from Texas Instruments with Zigbee support

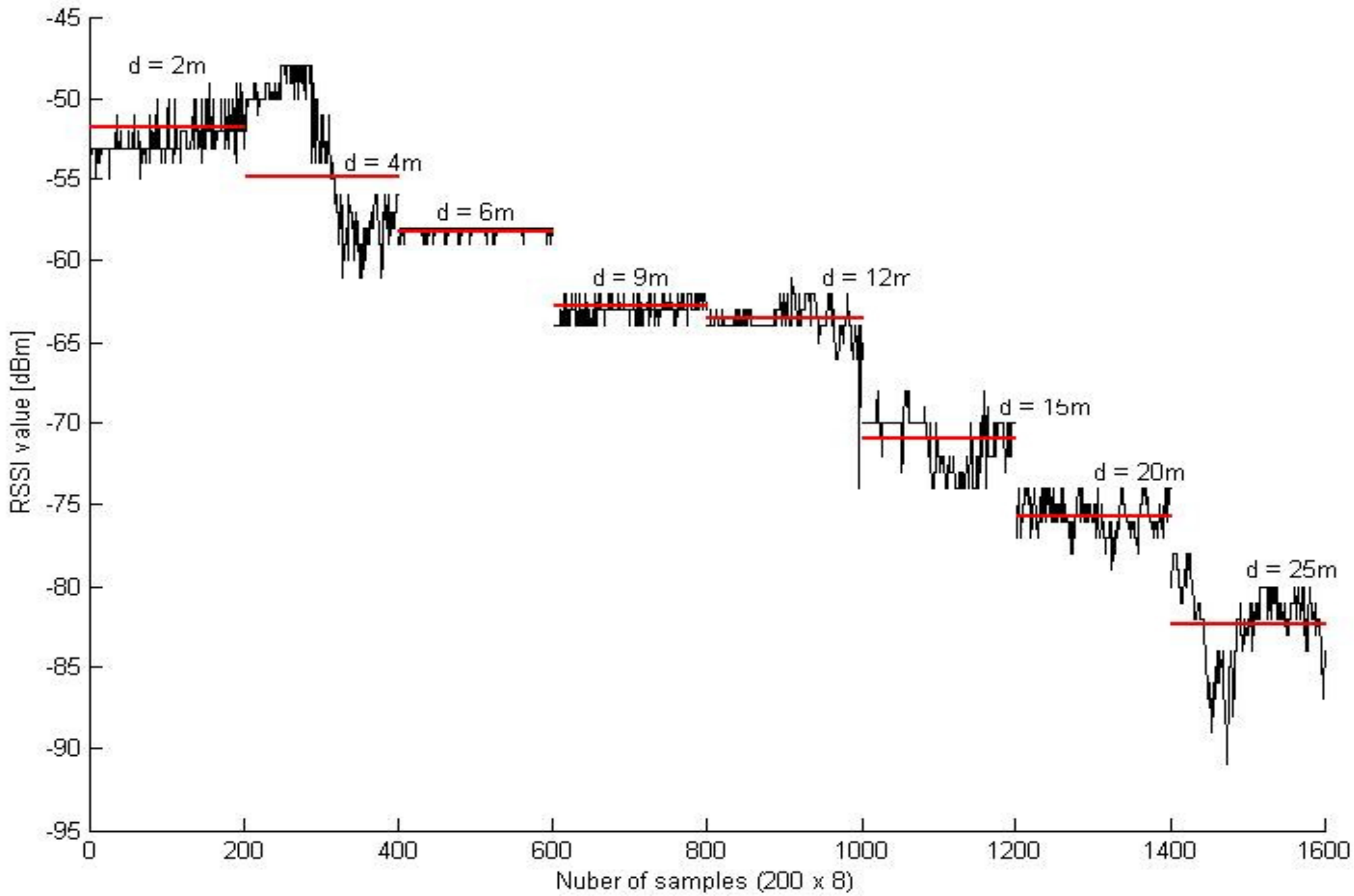
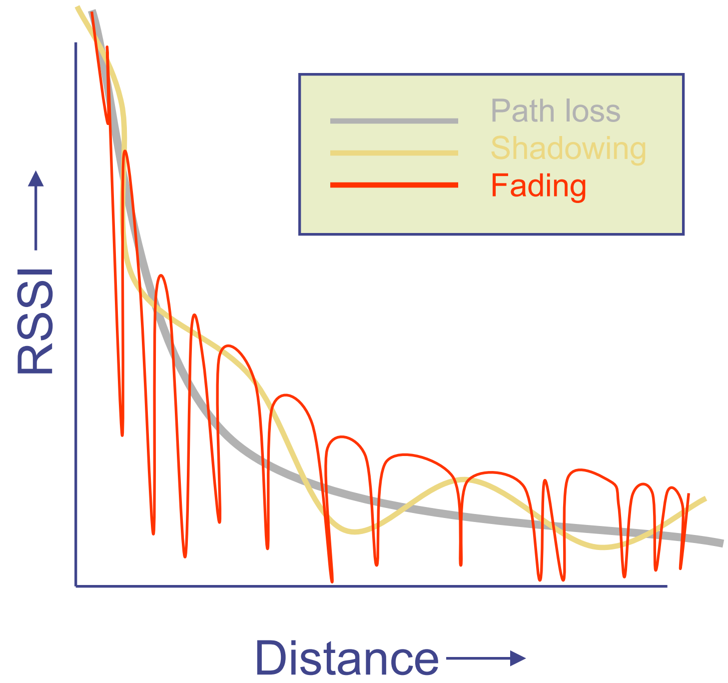


Fig. 4. Reading RSSI on CC2420

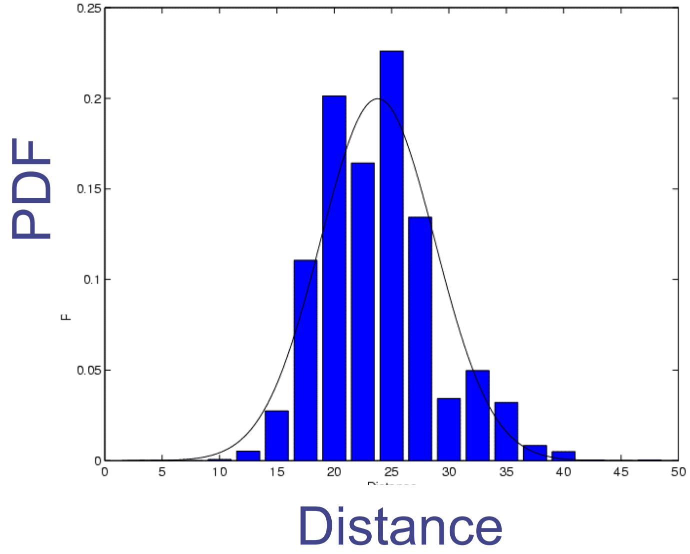
Problems with RSSI

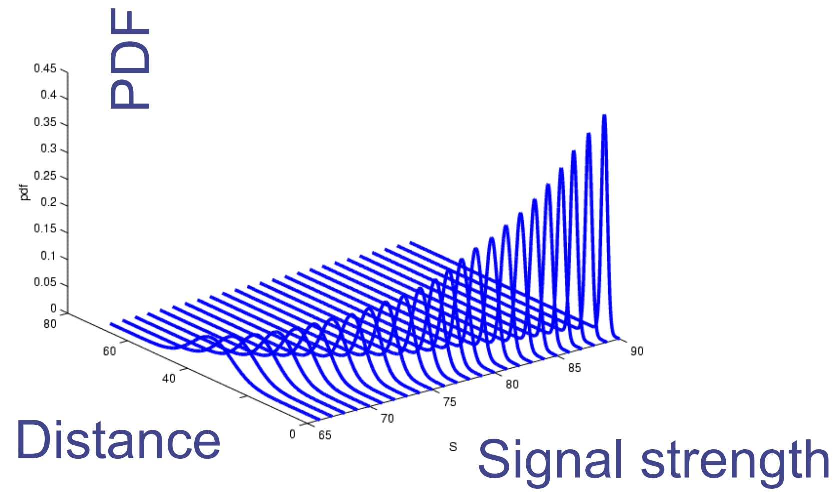
- RSSI is extremely problematic for fine-grained, ad-hoc applications
  - Path loss characteristics depend on environment
  - Shadowing depends on environment
  - Short-scale fading due to multipath adds random high frequency component with huge amplitude (30-60dB) – very bad indoors



Problems with RSSI

- Problem: Highly error-prone process – Shown: PDF for a fixed RSSI





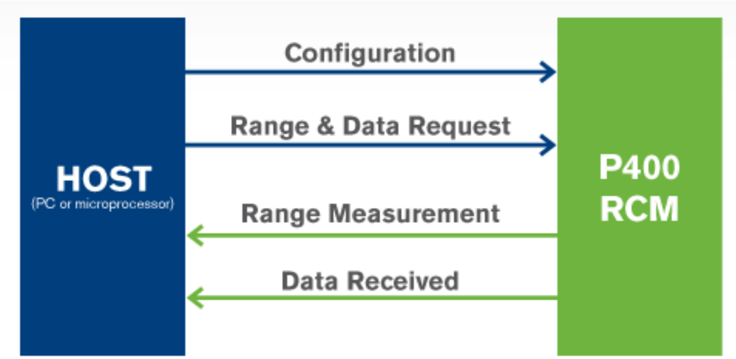
However, can still be useful:

Approximate localization of mobile nodes, proximity determination

“Signature” based method.

Estimating distances – ToA

- Time of arrival (ToA)
  - Use propagation speed and time of arrival to compute distance (D=V*t)
  - Measuring ToA requires fast, synchronized clocks to achieve high precision ($c \approx 1$ ft/ns)
- Ultra wide-band ranging for sensor nets?
  - Based on very short wideband pulses, achieve higher accuracy

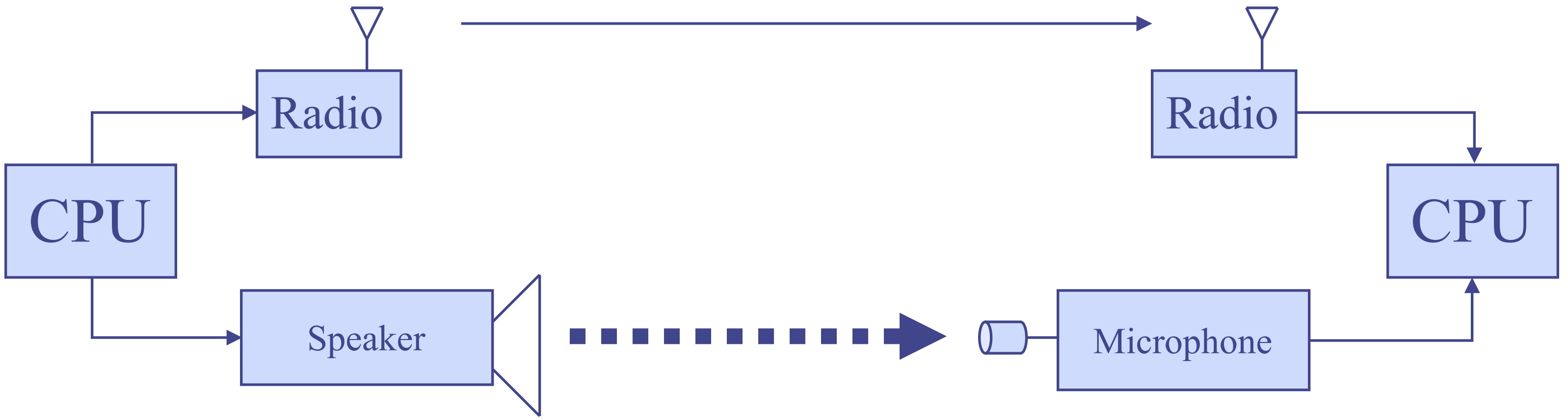


Estimating distances- TDoA

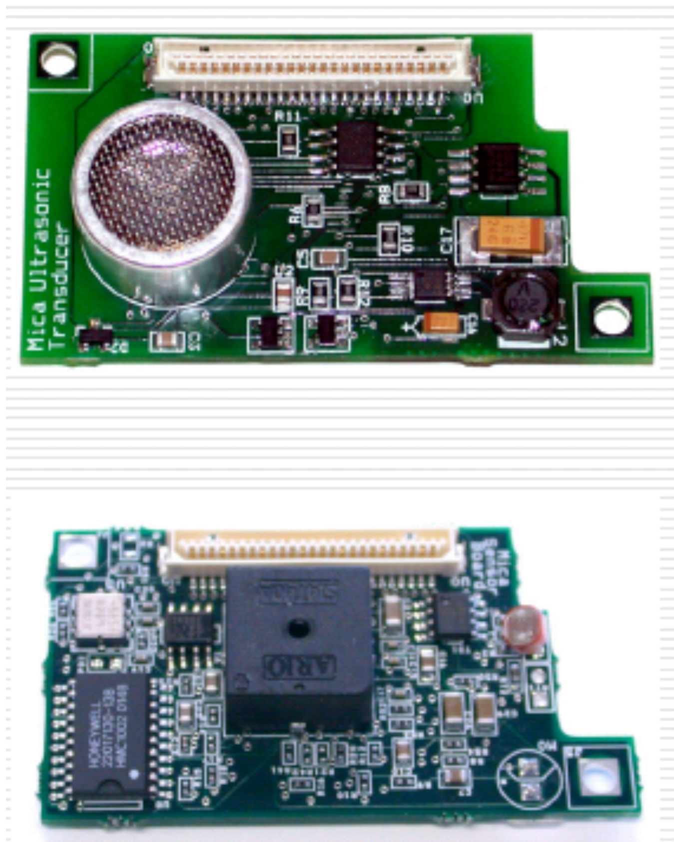
- Time Difference of Arrival (TDoA)
  - Use two different signals with different propagation speeds
  - Example: ultrasound and radio signal
    - Propagation time of radio negligible compared to ultrasound
  - Compute difference between arrival times to compute distance

TDoA illustration

- Radio channel is used to synchronize the sender and receiver
- Coded acoustic signal is emitted at the sender and detected at the emitter. TDoA determined by comparing arrival of RF and acoustic signals

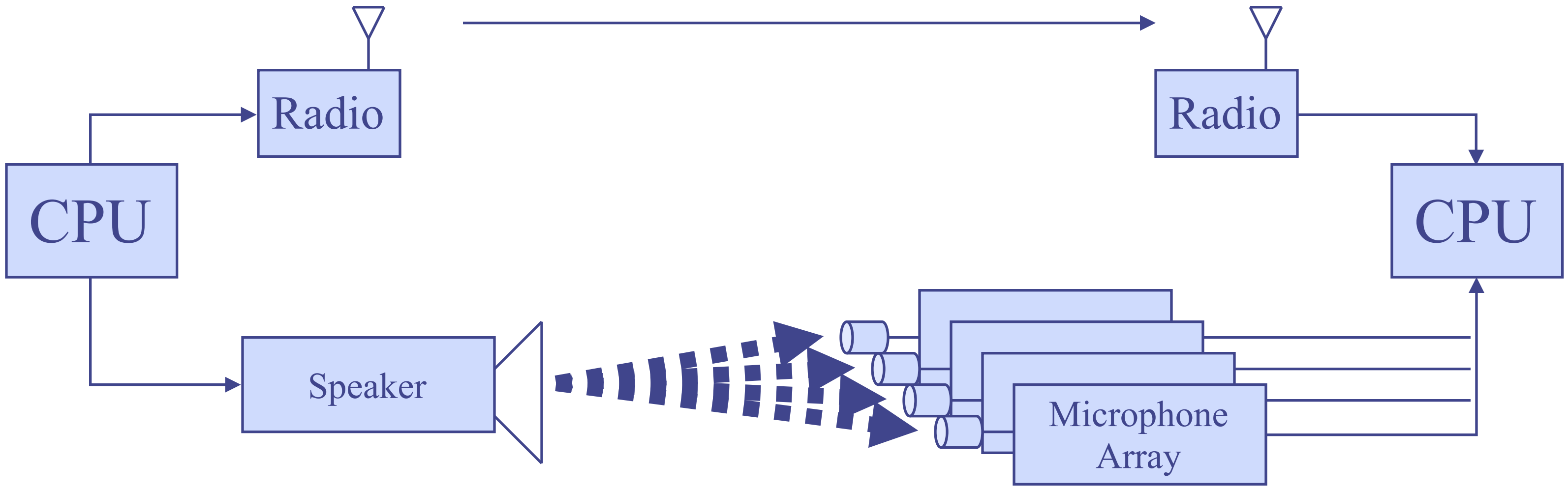


An example of TDoA implemetation

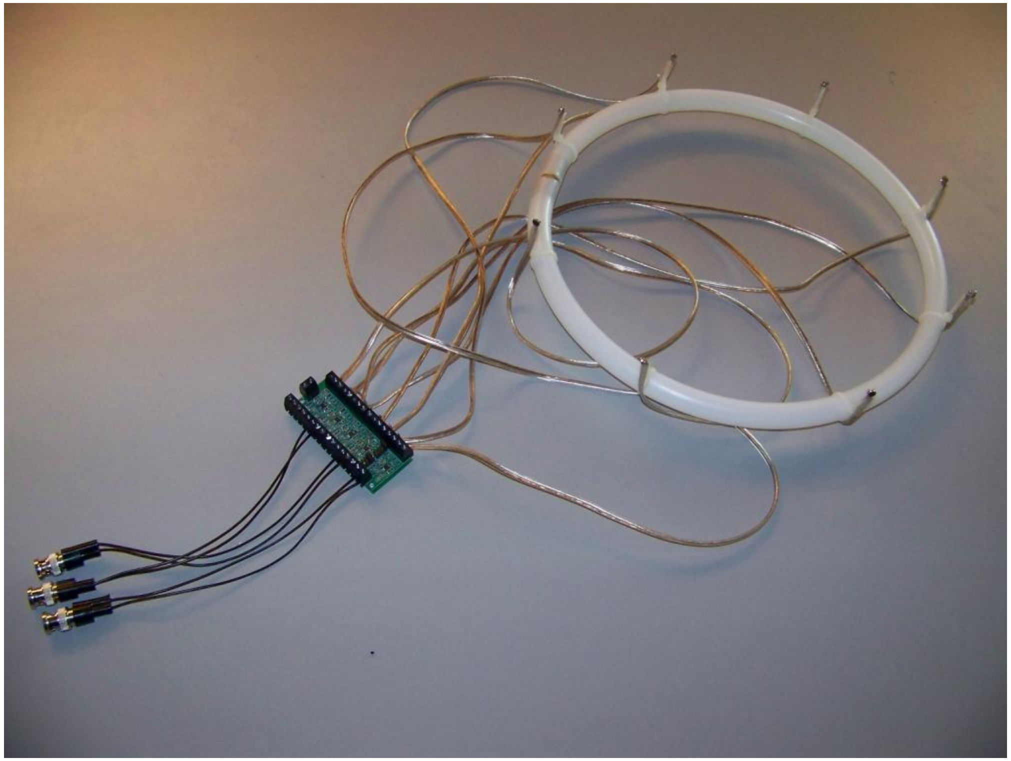


Estimating angles--AoA

- Angle-of-Arrival system with directional antenna
- Angle-of-Arrival system with multiple receiver channels
  - Time difference of arrivals at receiver used to estimate angle of arrival

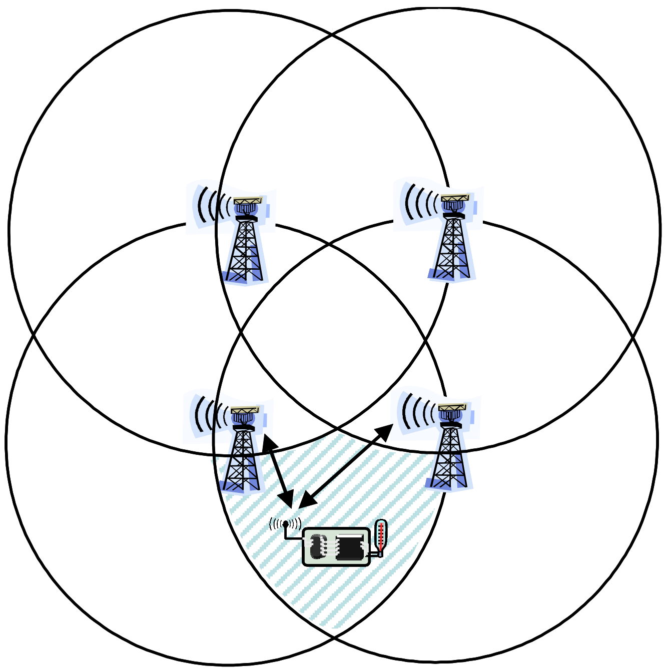


An example of microphone array

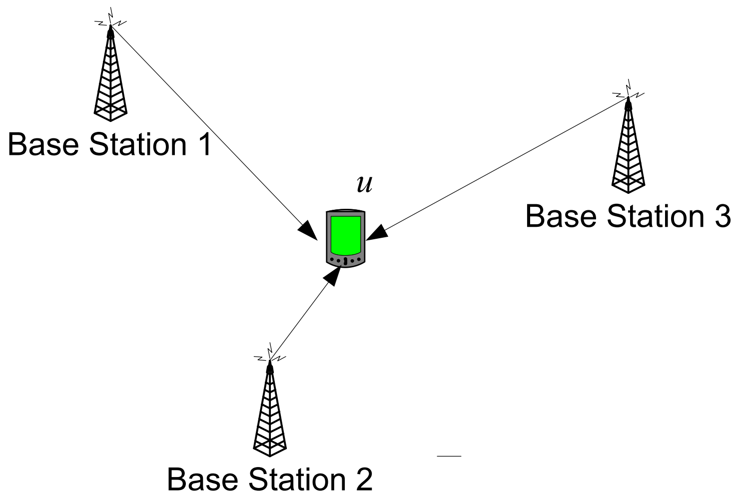


Single-hop localization – connectivity only

- ***Overlapping connectivity***: Position is estimated in the center of area where circles from which signal is heard/not heard overlap

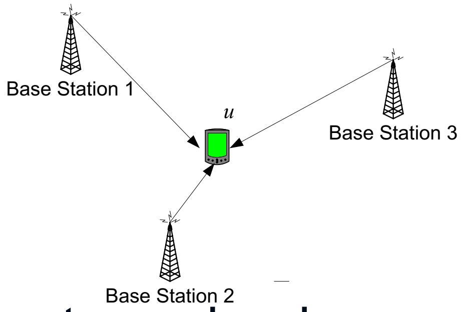


Single-hop localization- Tri/Multi-lateration



- Beacons (or base stations) advertise their coordinates & transmit a reference signal
- Node uses the three reference signal to ***estimate*** distances to each of the beacons (base stations)

Trilateration



- Assuming distances to three points with known location are exactly given
- Solve system of equations
  - (x_i, y_i) : coordinates of ***beacon point*** i, r_i distance to anchor i
  - (x_u, y_u) : unknown coordinates of node

$$(x_i - x_u)^2 + (y_i - y_u)^2 = r_i^2 \text{ for } i = 1, \ldots, 3$$

  - Some calculations:

$$(x_1 - x_u)^2 - (x_3 - x_u)^2 + (y_1 - y_u)^2 - (y_3 - y_u)^2 = r_1^2 - r_3^2$$
$$(x_2 - x_u)^2 - (x_2 - x_u)^2 + (y_2 - y_u)^2 - (y_2 - y_u)^2 = r_2^2 - r_3^2.$$

  - Rearranging terms gives a linear equation in (x_u, y_u)!

$$2(x_3 - x_1)x_u + 2(y_3 - y_1)y_u = (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2)$$
$$2(x_3 - x_2)x_u + 2(y_3 - y_2)y_u = (r_2^2 - r_2^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2)$$

Trilateration as matrix equation

- Rewriting as a matrix equation:

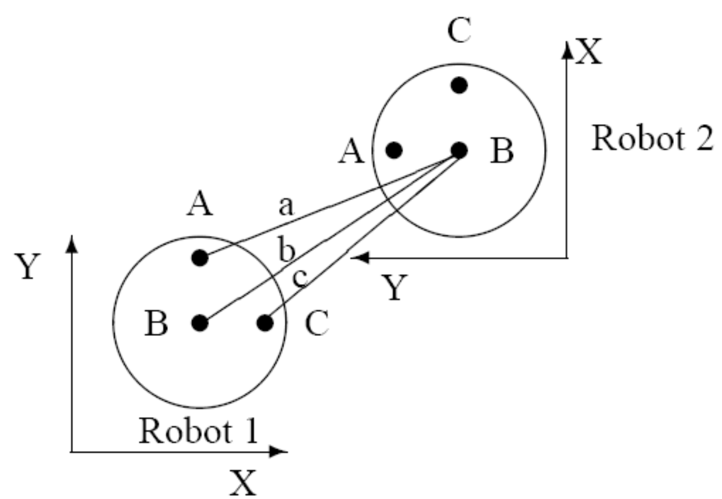
$$2\begin{bmatrix} x_3 - x_1 & y_3 - y_1 \\ x_3 - x_2 & y_3 - y_2 \end{bmatrix} \begin{bmatrix} x_u \\ y_u \end{bmatrix} = \begin{bmatrix} (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2) \\ (r_2^2 - r_2^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2) \end{bmatrix}$$

- Example: $(x_1, y_1) = (2,1)$, $(x_2, y_2) = (5,4)$, $(x_3, y_3) = (8,2)$,
  $r_1 = 3.16$, $r_2 = 2$, $r_3 = 3$

$$2\begin{bmatrix} 6 & 1 \\ 3 & -2 \end{bmatrix} \begin{bmatrix} x_u \\ y_u \end{bmatrix} = \begin{bmatrix} 64 \\ 22 \end{bmatrix}$$

$(x_u, y_u) = (5,2)$

Trilateration Localization for Multi-Robot Team



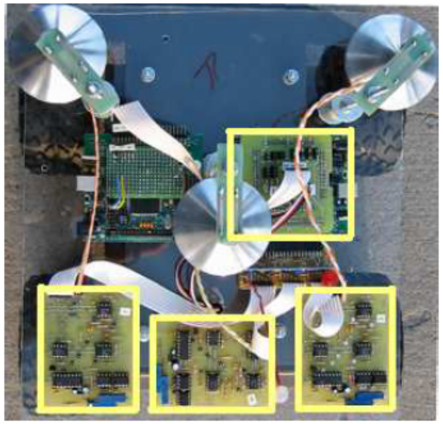


Fig. 1. Three base points in an XY coordinate system pattern.

$$(x_{2B} - x_{1A})^2 + (y_{2B} - y_{1A})^2 = a^2$$
$$(x_{2B} - x_{1B})^2 + (y_{2B} - y_{1B})^2 = b^2$$
$$(x_{2B} - x_{1C})^2 + (y_{2B} - y_{1C})^2 = c^2$$

$$x_{2B} = \frac{b^2 - c^2 + d^2}{2d} \qquad y_{2B} = \frac{b^2 - a^2 + d^2}{2d}$$

Paul M. Maxim, Suranga Hettiarachchi, William M. Spears, Diana F. Spears,
Jerry Hamann, Tom Kunkel, and Caleb Speiser. **Trilateration Localization for Multi-Robot Teams (Available at: http://homepages.ius.edu/suhettia/papers/icinco.pdf)**

Trilateration Localization for Multi-Robot Team

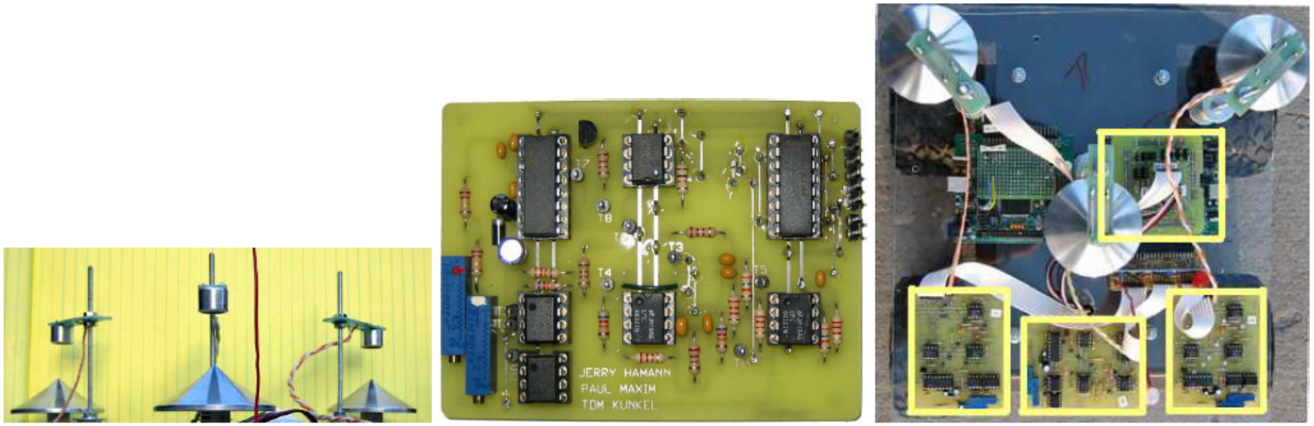
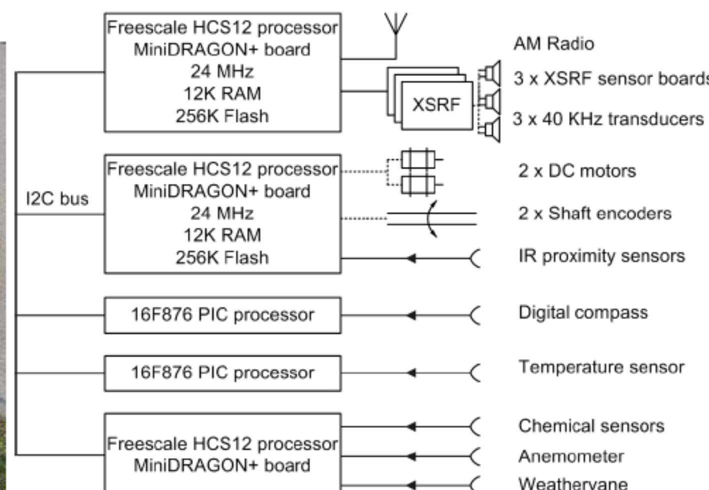


Fig. 2. The acoustic transducers and parabolic cones (left). The XSRF acoustic sensor printed circuit board (middle), and the completed trilateration module (top-down view, right).



Multilateration with distance errors

- What if only distance estimation $r_i^0 = r_i + \varepsilon_i$ available?
- Use multiple anchors, overdetermined system of equations

$$2\begin{bmatrix} x_n - x_1 & y_n - y_1 \\ \vdots & \vdots \\ x_n - x_{n-1} & y_n - y_{n-1} \end{bmatrix} \begin{bmatrix} x_u \\ y_u \end{bmatrix} = \begin{bmatrix} (r_1^2 - r_n^2) - (x_1^2 - x_n^2) - (y_1^2 - y_n^2) \\ \vdots \\ (r_{n-1}^2 - r_n^2) - (x_{n-1}^2 - x_n^2) - (y_{n-1}^2 - y_n^2) \end{bmatrix}$$

- Use (x_u, y_u) that minimize mean square error, i.e, $||\mathbf{Ax} - \mathbf{b}||_2$

Minimize mean square error

- Look at square of the of Euclidean norm expression (note that $\|\mathbf{v}\|_2^2 = \mathbf{v}^\mathrm{T}\mathbf{v}$ for all vectors v)

$$||\mathbf{A}\mathbf{x} - \mathbf{b}||_2^2 = (\mathbf{A}\mathbf{x} - \mathbf{b})^\mathrm{T}(\mathbf{A}\mathbf{x} - \mathbf{b}) = \mathbf{x}^\mathrm{T}\mathbf{A}^\mathrm{T}\mathbf{A}\mathbf{x} - 2\mathbf{x}^\mathrm{T}\mathbf{A}^\mathrm{T}\mathbf{b} + \mathbf{b}^\mathrm{T}\mathbf{b}$$

- Look at derivative with respect to x, set it equal to 0:

$$2\mathbf{A}^\mathrm{T}\mathbf{A}\mathbf{x} - 2\mathbf{A}^\mathrm{T}\mathbf{b} = 0 \Leftrightarrow \mathbf{A}^\mathrm{T}\mathbf{A}\mathbf{x} = \mathbf{A}^\mathrm{T}\mathbf{b}$$

  - Has unique solution (if A has full rank), which gives desired minimal mean square error

Summary

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