Wireless Sensor Network based Shooter Localization

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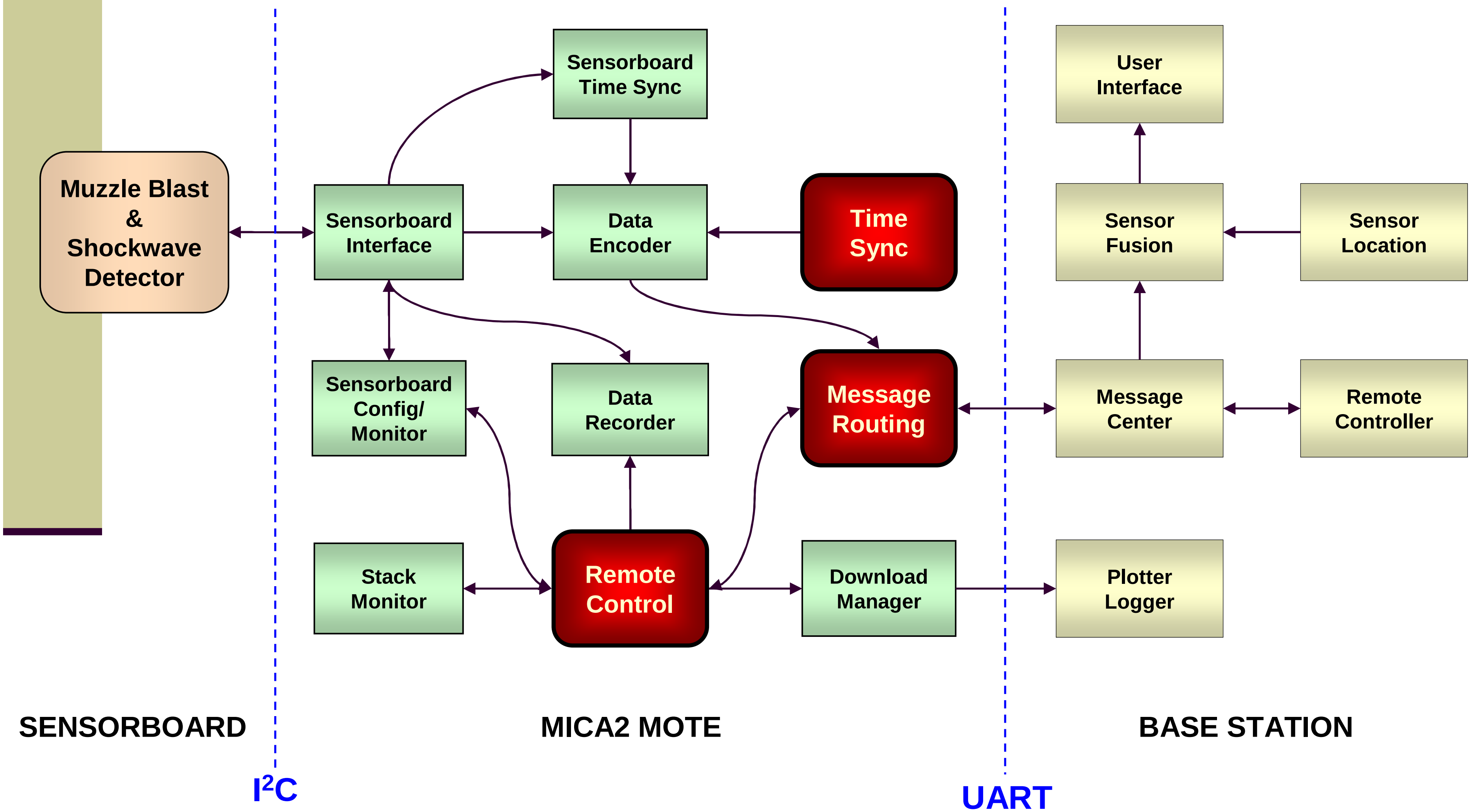
Overview

- CONOPS Support: Fast and accurate enemy shooter localization is key in reducing friendly casualties and neutralizing enemy combatants
- Different approach compared to other acoustic shooter localization systems (e.g., BulletEars, Pilar, Ferret, Boomerang)
- Ad-hoc wireless network of cheap acoustic sensors is used to accurately locate enemy shooters in urban environment
- Challenges
  - Severely resource constrained nodes and communication bandwidth
  - Extreme multipath effects in urban environment
  - Simultaneous shot resolution
- Performance
  - Average accuracy: 1 meter
  - Latency: 2 seconds
  - Simultaneous shot resolution: 6 shots per second

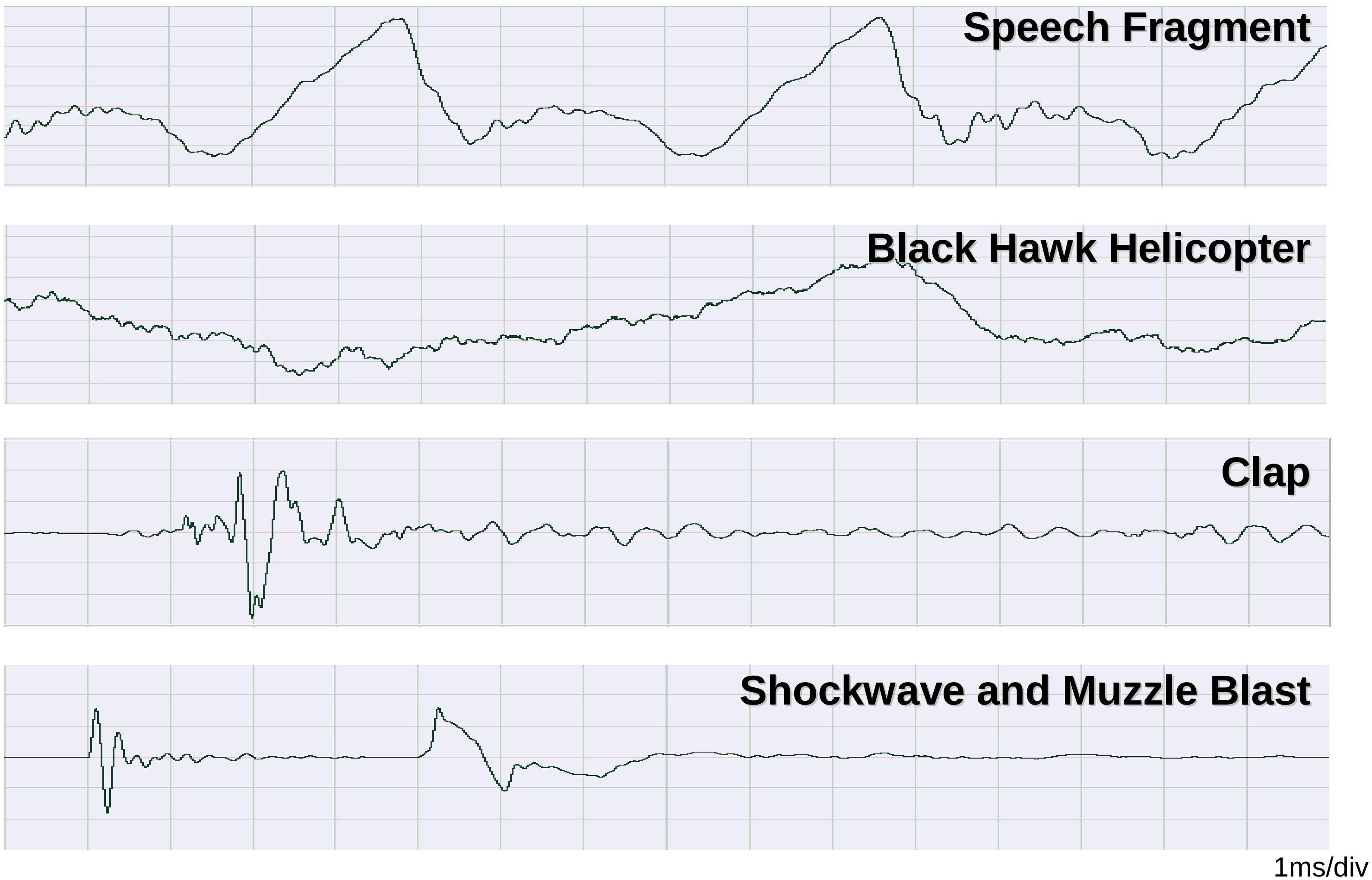
Technical Approach

- Detect TOA of acoustic shockwave and muzzle blast
- MICA2 mote (UC Berkeley and Crossbow)
- Acoustic sensor board (Vanderbilt):
  - Three acoustic channels (only one is used)
  - High-speed AD converters
  - FPGA for signal processing: shockwave and muzzle blast detection on board
- Timestamp of shockwave and/or muzzle blast is sent to mote
- Motes route time of arrival data to base station
- Base station fuses data, estimates shooter position and displays result

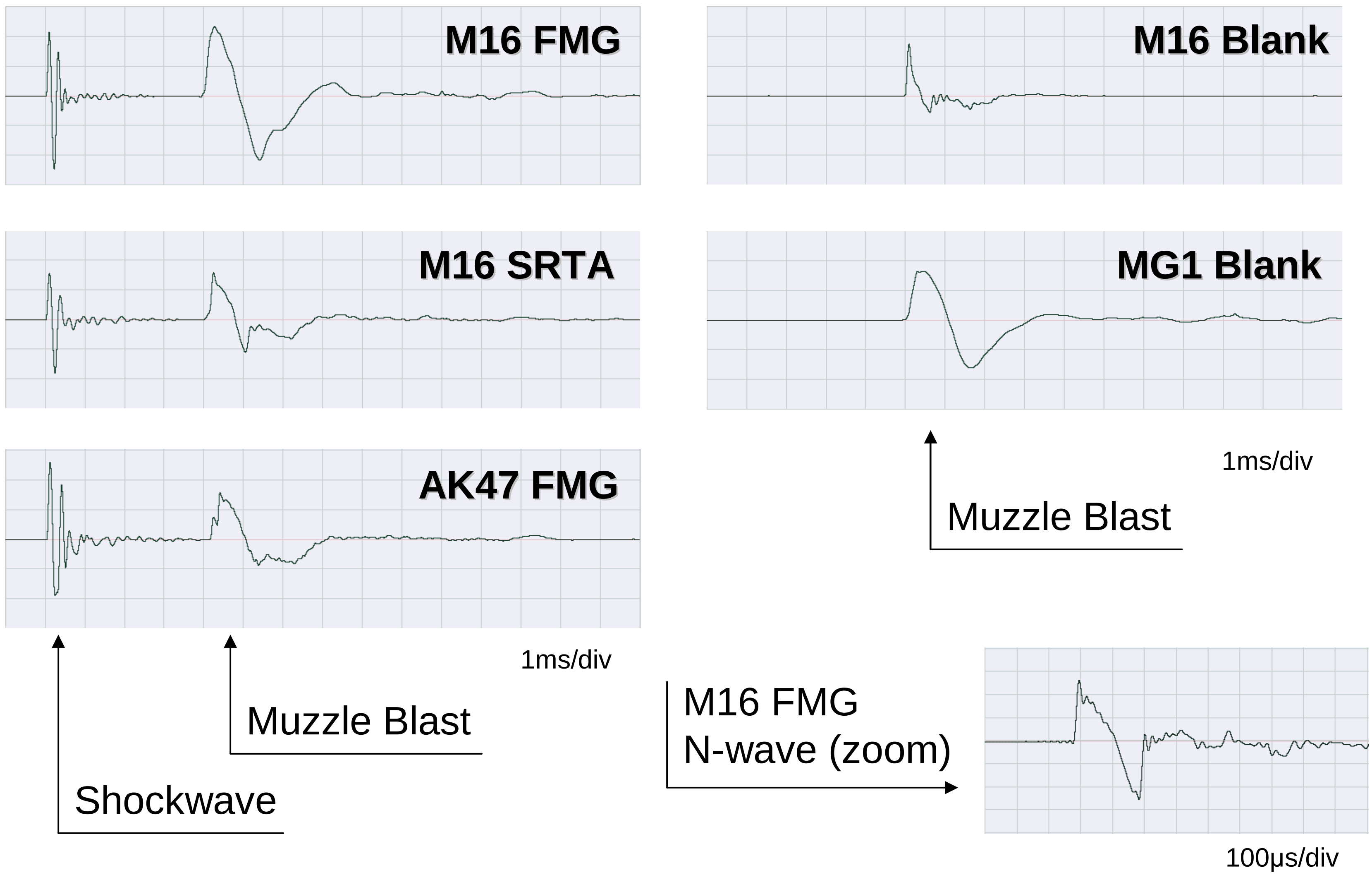
Technical Approach: System Architecture



Acoustic Sensor Board: False Alarm Rejection

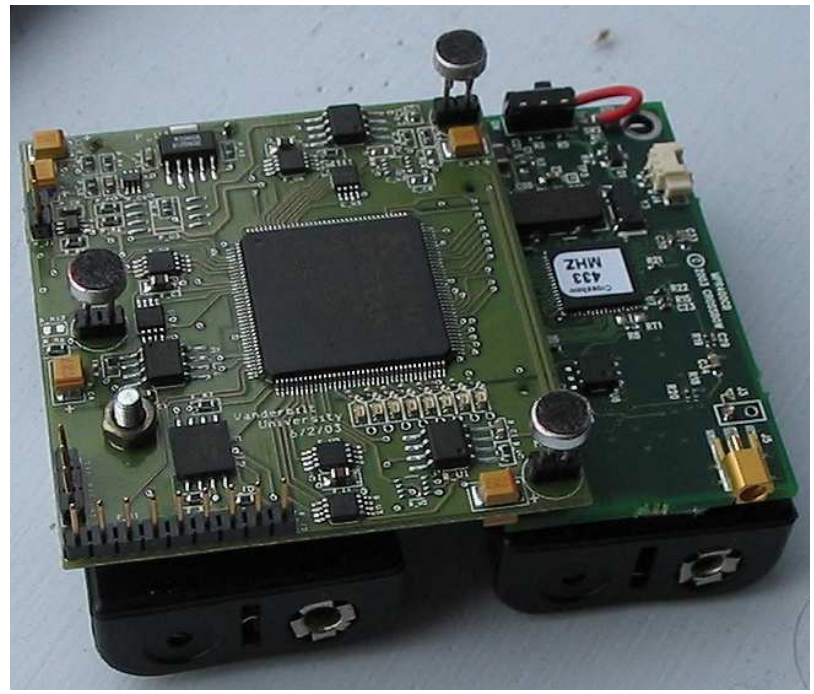


Acoustic Sensor Board: Different Weapon Types



Acoustic Sensor Board

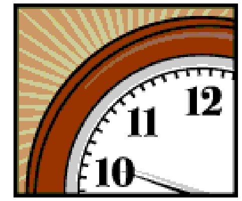
- Xilinx Spartan-II FPGA
- Three acoustic channels
  - Only one is used in shooter localization
  - Selection of the microphone
  - Max 1 MHz sampling rate, 12-bit ADC
- ZC encoding
  - Feature extraction
  - Data compression



MICA2 hardware

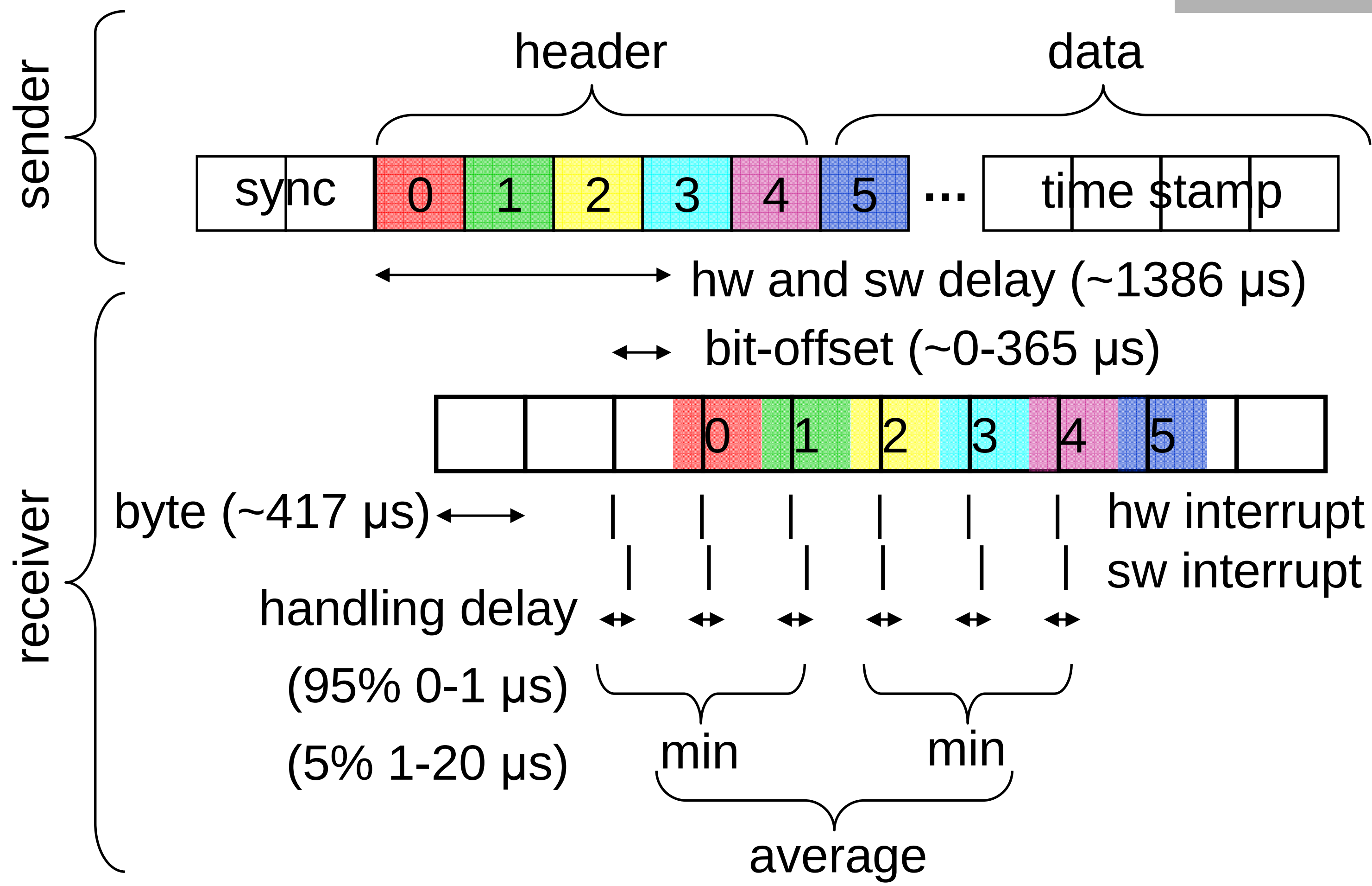
- 8 MHz, 8-bit microcontroller
- 4 KB of RAM, 128 KB of ROM
- Wireless communication
  - Packet is 29 bytes data, 7 bytes header
  - 30 packets per second under no collisions
  - 30-100 feet range
- Power management
  - 2-3 days of continuously operation on two AA batteries
  - 2-3 of months when sleeping
- Various sensors and actuators boards
- Cost: $150 from XBow

Middleware Services: Time Synchronization



- Requirement
  - sound travels one foot per millisecond
  - time synch error in the whole network should be less than 1 millisecond (less than 1 ft error)
- Algorithm
  - selected leader broadcasts its time
  - receivers maintain a table of global-local time pairs
  - receivers calculate clock offset and skew using linear regression
  - receivers rebroadcast the global time
- Performance:
  - ±1.5 μsec per hop error
  - Low overhead: one timesynch round per minute (i.e., one message per minute per mote)

Time Synchronization Primitive: Time Stamping of Radio Messages

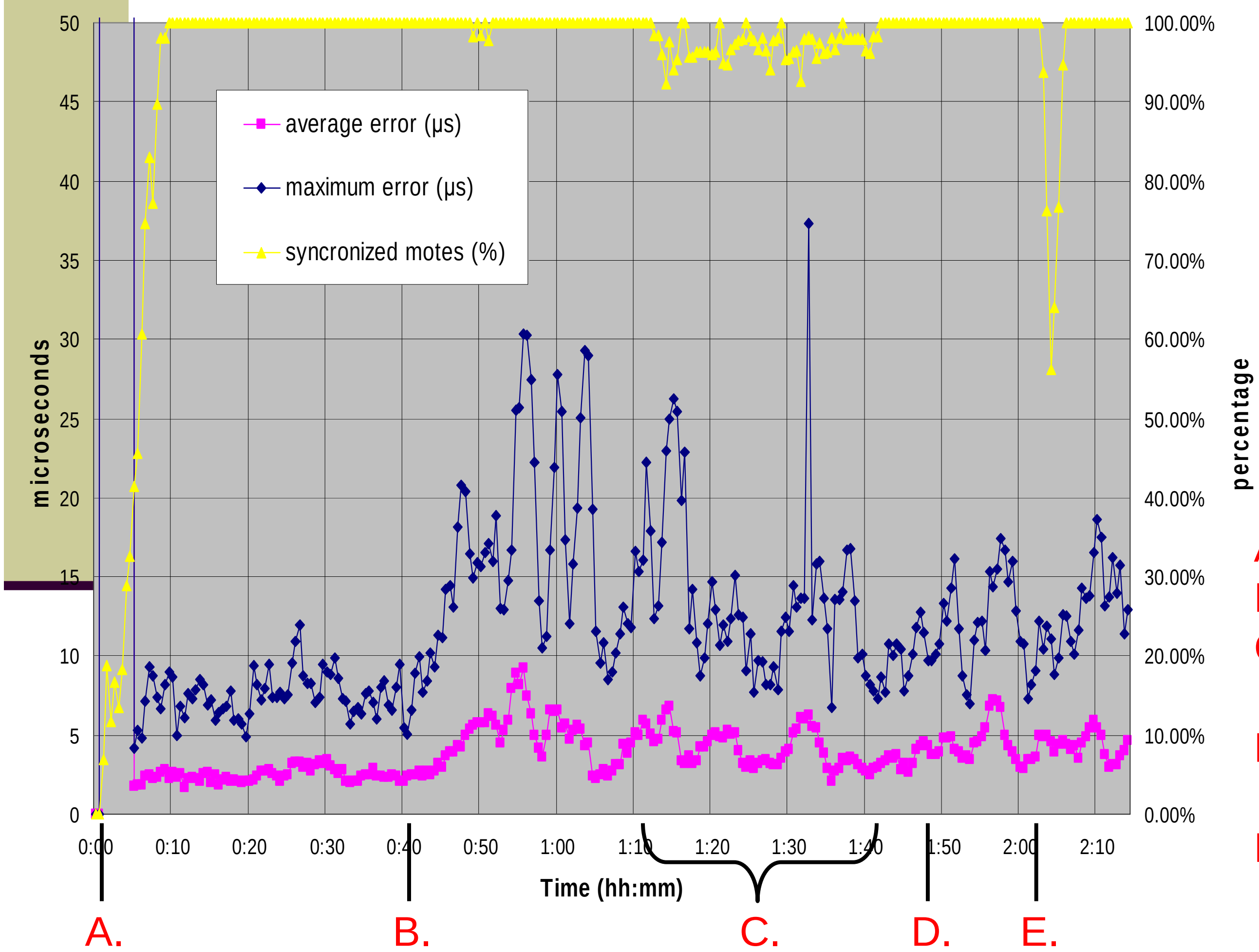


Mica2: 1.2 μs average error, 4.5 μs maximum error

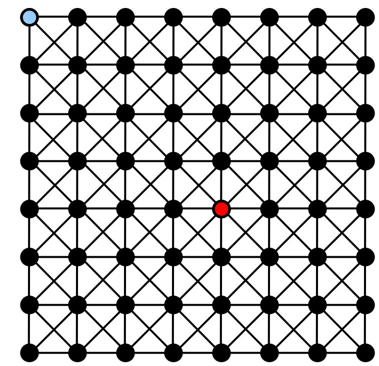
Mica2Dot: 4 μs average, 12 μs maximum error

Time Synchronization: Experimental Evaluation

1 message per 30 seconds per mote



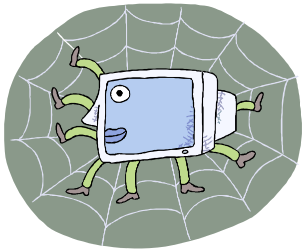
layout and links:



- first leader
- second leader

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

Middleware Services: Message Routing



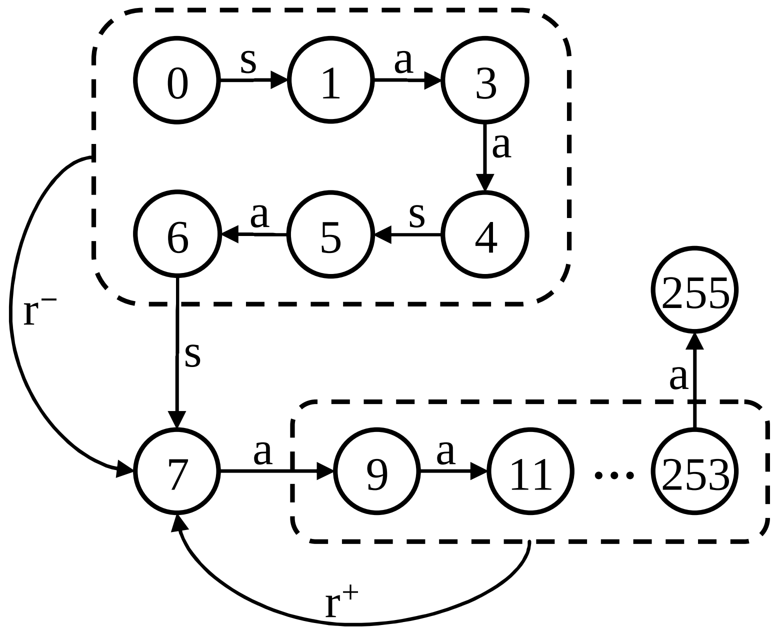
- Requirement: acoustic event triggers many motes at once; all need to get their data to base station with low latency
- Approach: convergecast to root using our directed flood routing framework:
  - Ad-hoc routing
  - Automatic aggregation
  - Implicit acknowledgments
- Performance: when max distance from root is 5 hops, base station receives ~15 measurements in the first second

Message Routing: Channel Behavior

- MICA2 under no load: single mote is transmitting
  - Effective region (95% delivery rate) is 0-10 feet
  - Transitional region (5-95% delivery rate) is 10-40 feet
- MICA2 under heavy load: most motes transmit
  - Effective region: 5 feet, transitional region: 5-30 feet
  - 70% of the motes in the transitional region receive messages with less than 30%
  - Polite (never transmits) and impolite (causes collision) motes
- Use probabilistic methods: rely on the unreliable
  - It is more probable that one of the motes with less that 30% delivery rate will receive a broadcasted message than one with a higher rate
  - Do not limit the next hop to a single node
  - Long unreliable links can route messages faster than short reliable ones

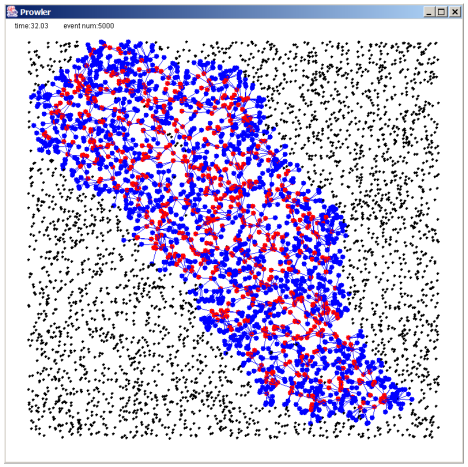
Message Routing: Flooding Policies

- Each flooding policy defines a state machine that describe the life cycle of data packets
- On each node each data packet is in one of the states
- Actions: received, sent, aged
- States are numbered from 0 (initial state) to 255 (final state)
- Packets with low numbered states are more important
- Packets with even numbered states are eligible for transmission

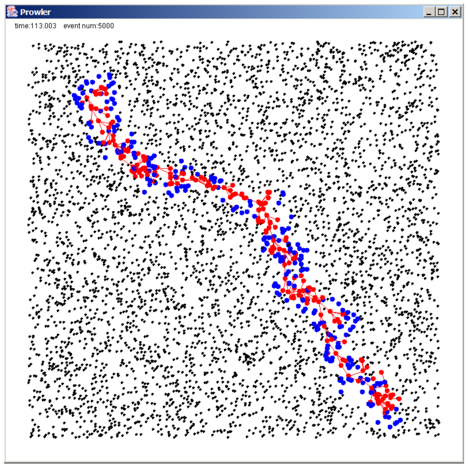


Fat Spanning-Tree Convergecast

- A spanning tree is formed
- Each node needs to know the node ID of its parent, grandparent, great-grandparent, and great-great-grandparent
- The “rank” of the node is the node ID of its grandparent
- If the rank of the sender is
  - the node ID of the grandparent of the receiver, then the sender is at the same distance
  - the node ID of the receiver or its parent, then the sender is further from the root than the receiver
  - the node ID of the great- or great-great-grand parent of the receiver, then the sender is closer to the root
  - non of the above: not in the same channel or further away.
- Increases the reliability and robustness of tree routing protocols
- Scales linearly with distance



gradient flooding



fat spanning-tree flooding

Middleware: Self Localization

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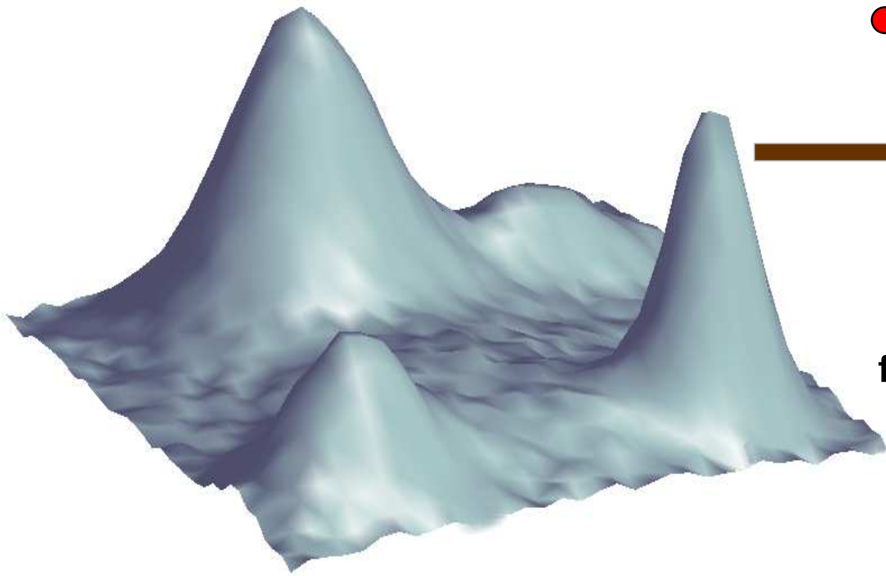
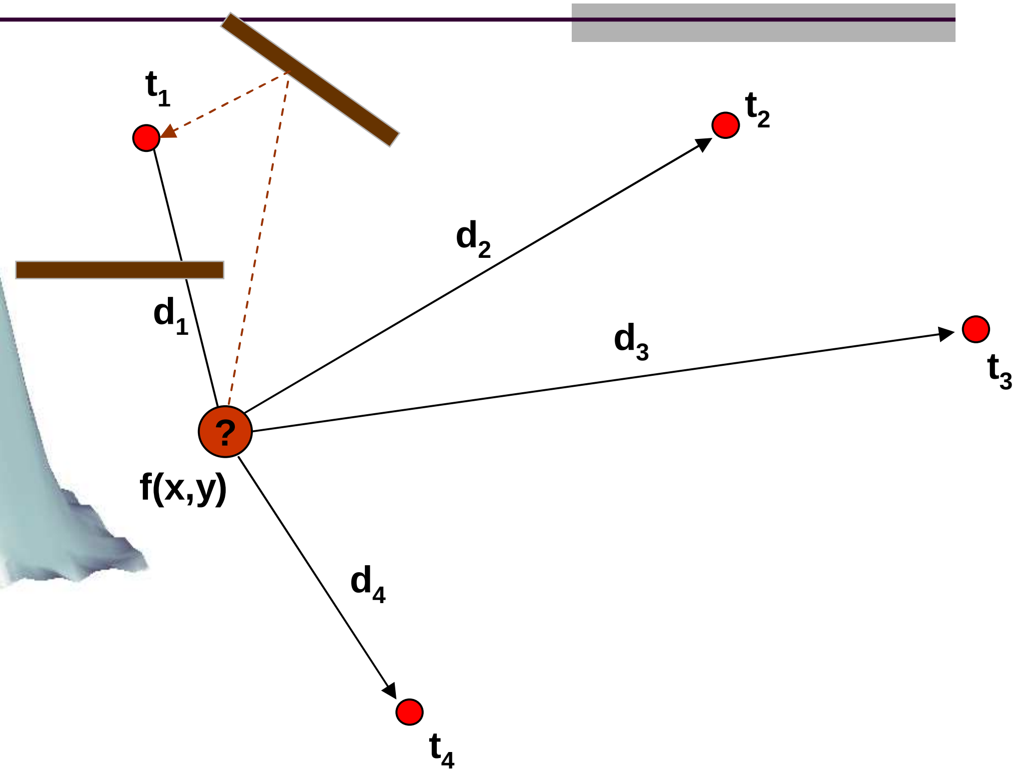
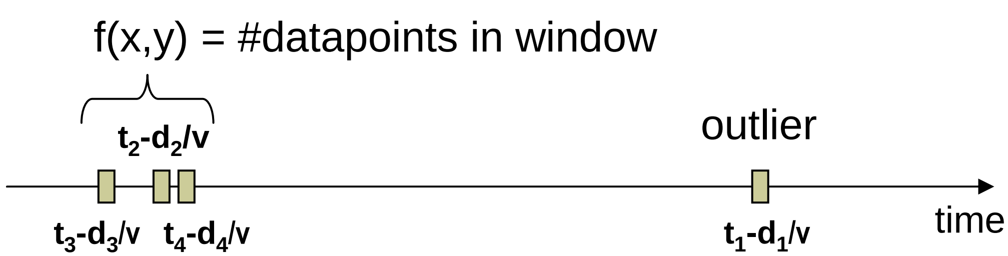
Sensor Fusion: Consistency Surface

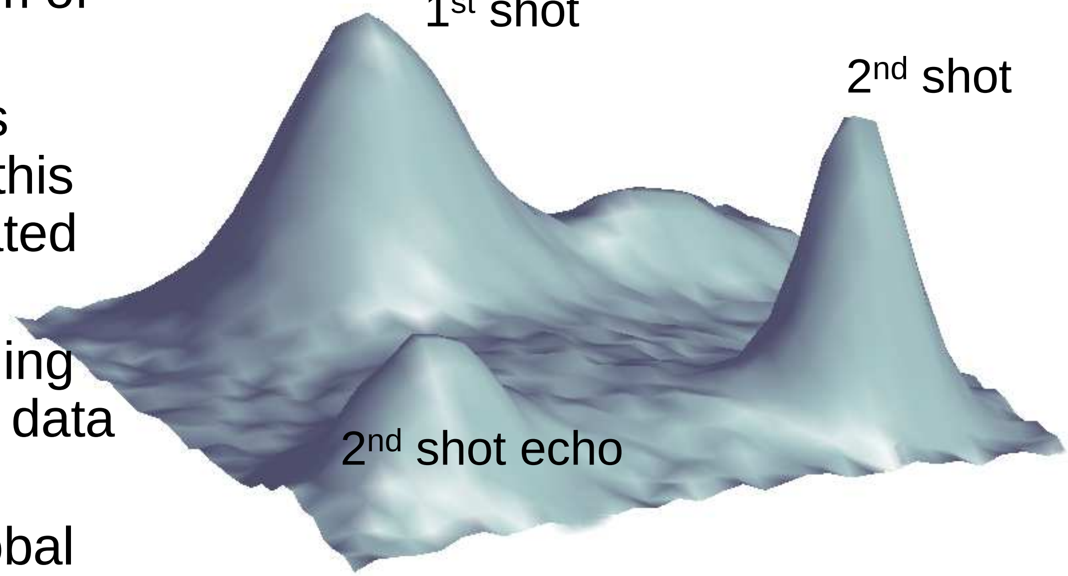






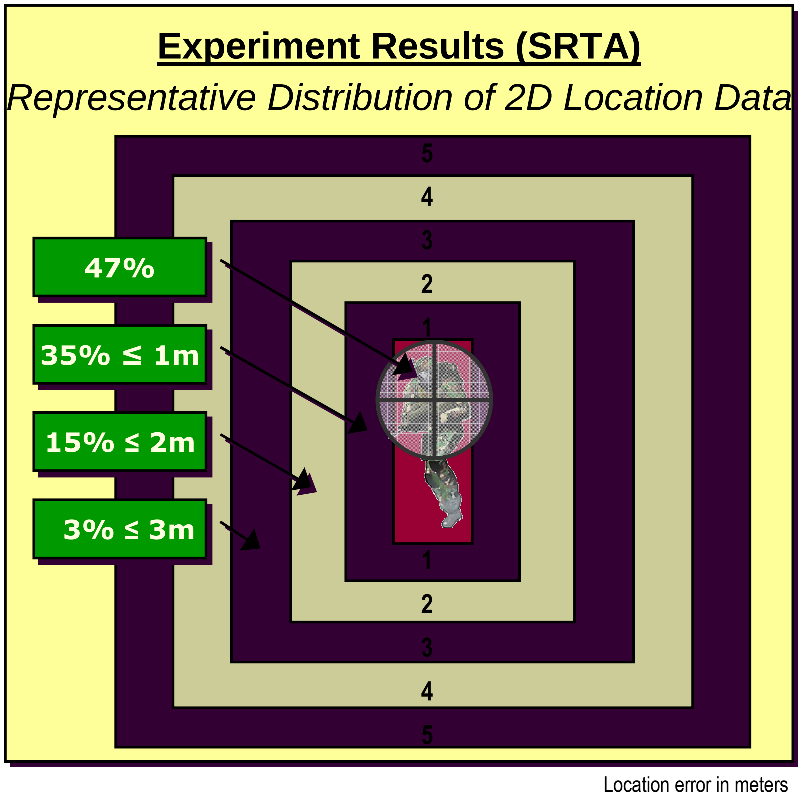
Sensor Fusion: Multiple Shots

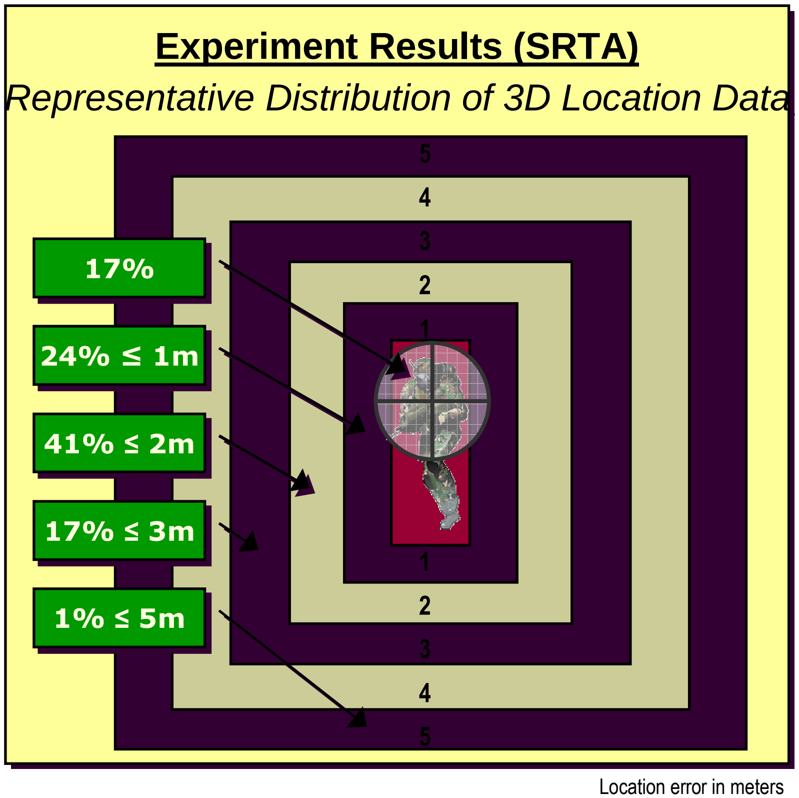
- Find the global maximum of the consistency surface
- If the global maximum is above a threshold then this position is the 1st estimated shooter position
- Remove the corresponding measurements from the data set
- Recalculate surface/ global maximum (next shots)
- Shot and its detected consistent echo have the same shot time → echo elimination



System Performance

- Latency: 2 seconds
- Average accuracy in 2D (x,y): 0.64 meter; in 3D (x,y,z): 1.5 meter
- Results below based on: 71 single SRTA shots; 20 different positions (McKenna MOUT Site, Ft. Benning); 60-mote network; 100x40 m area



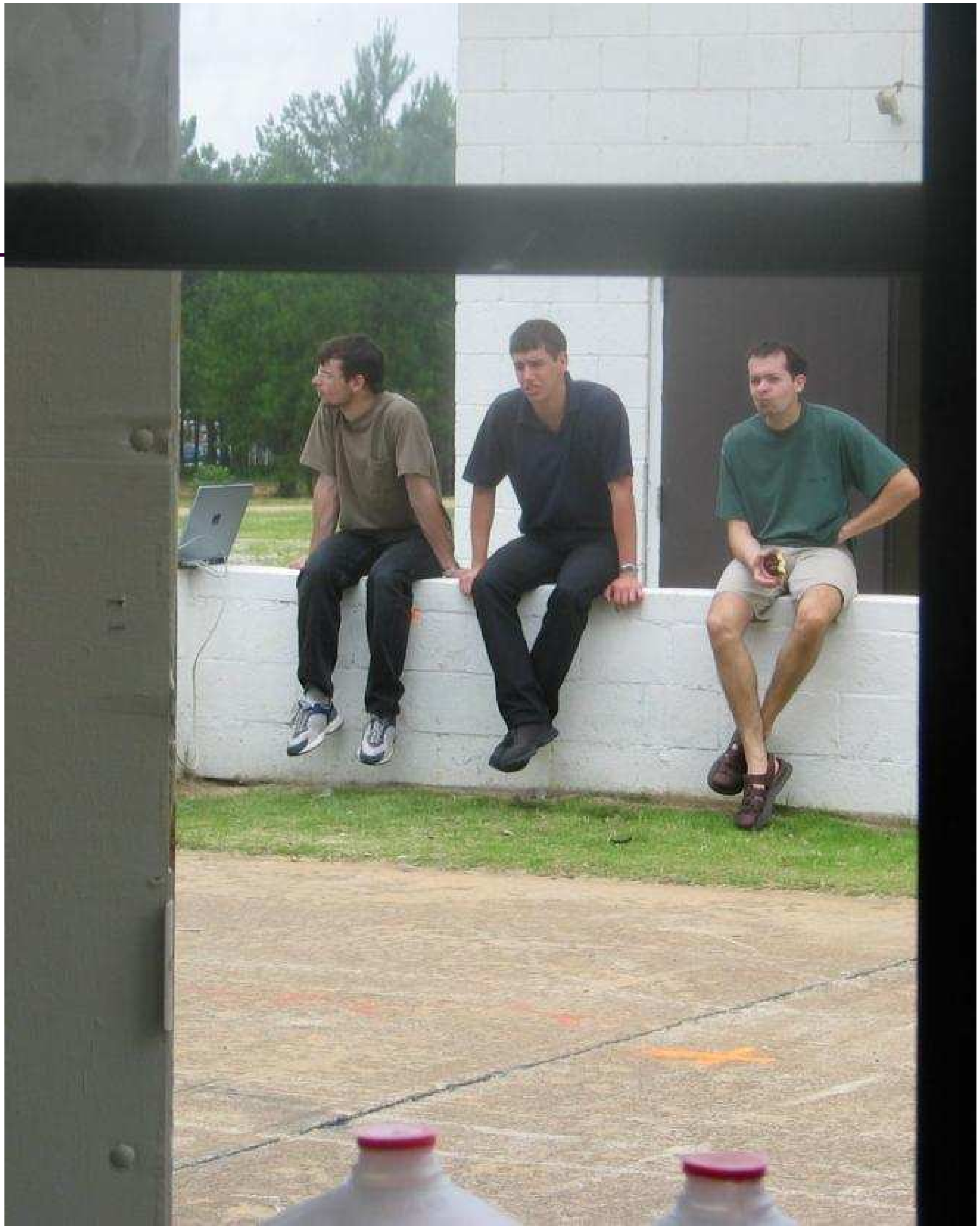


Observed Hardware Failures

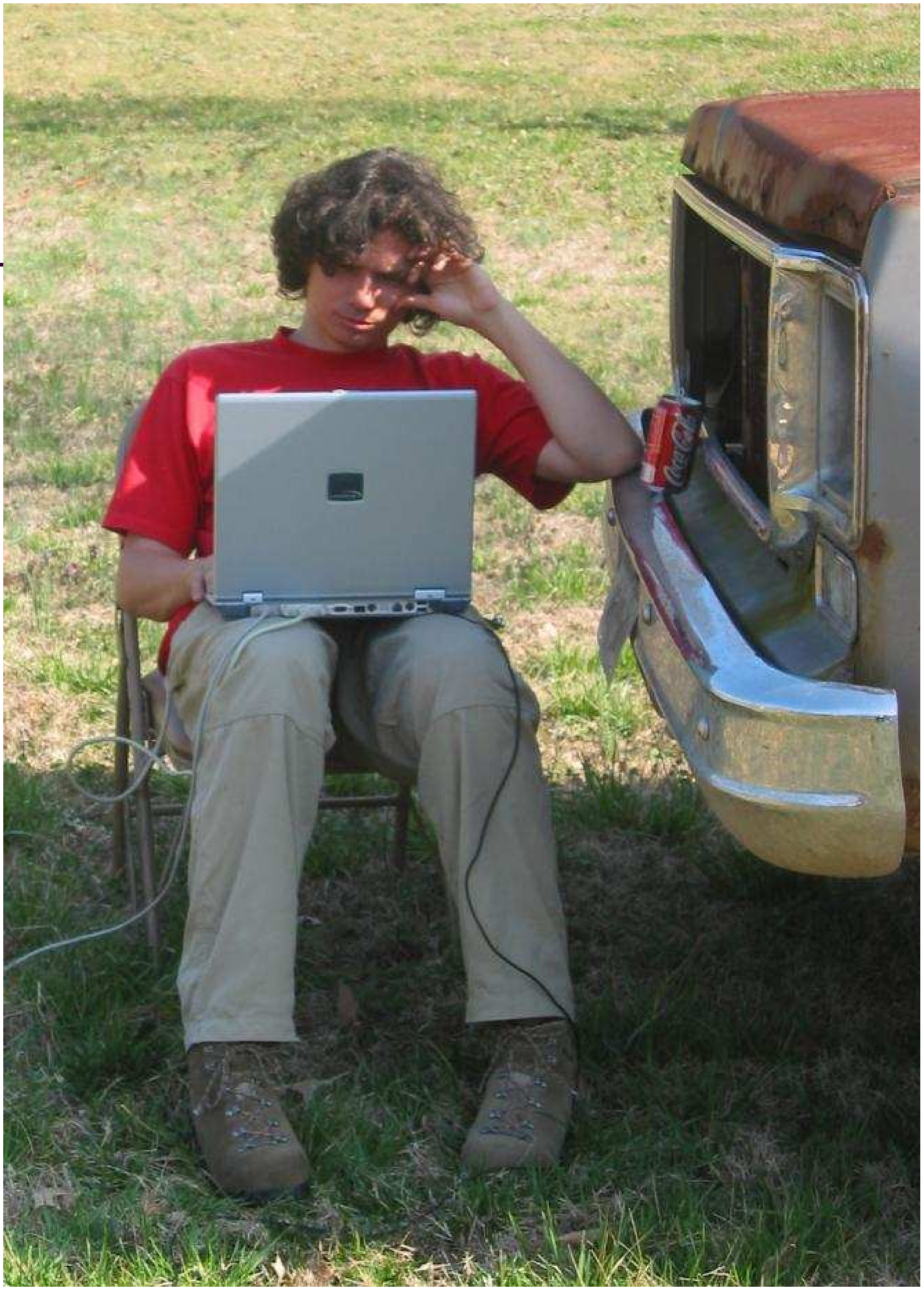
- Noisy or non-functional ADC (3%)
- Memory corruption (only one mote)
- One-way radio, only receive or transmit (3%)
- Battery exploded (only one, left in the programming board)
- Corrupted fuses (5%)
- Non-functional LEDs (1%)
- Motes overrun by cars and people (2%)
- Under direct sunlight the ADC and CPU clock of the motes changed their characteristics

Development Tools

Unionized NEST Workers



Middleware Development in Tennessee



Oops, we have to recruit a new graduate student again