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Sensor Network-Based Countersniper System

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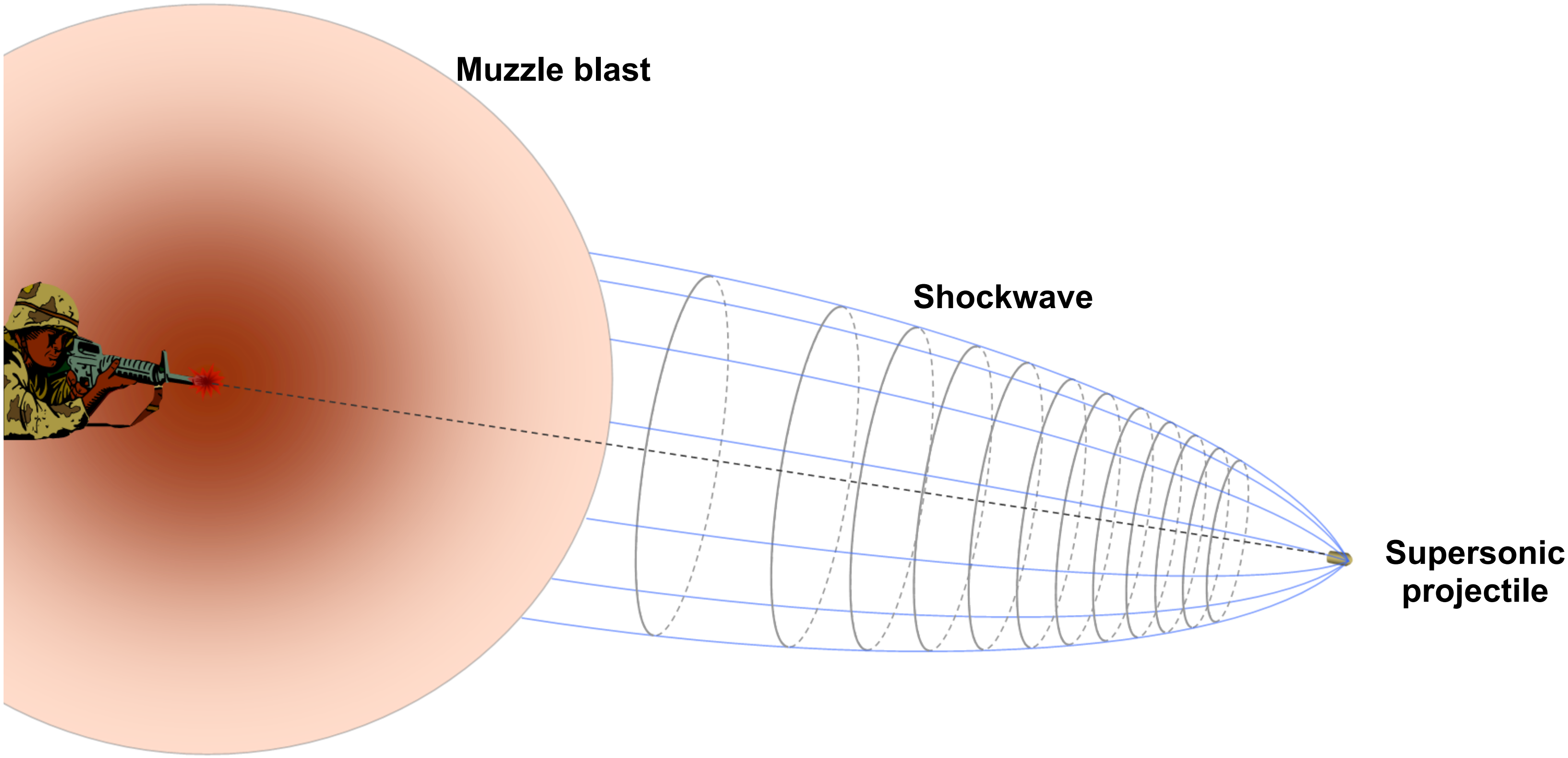
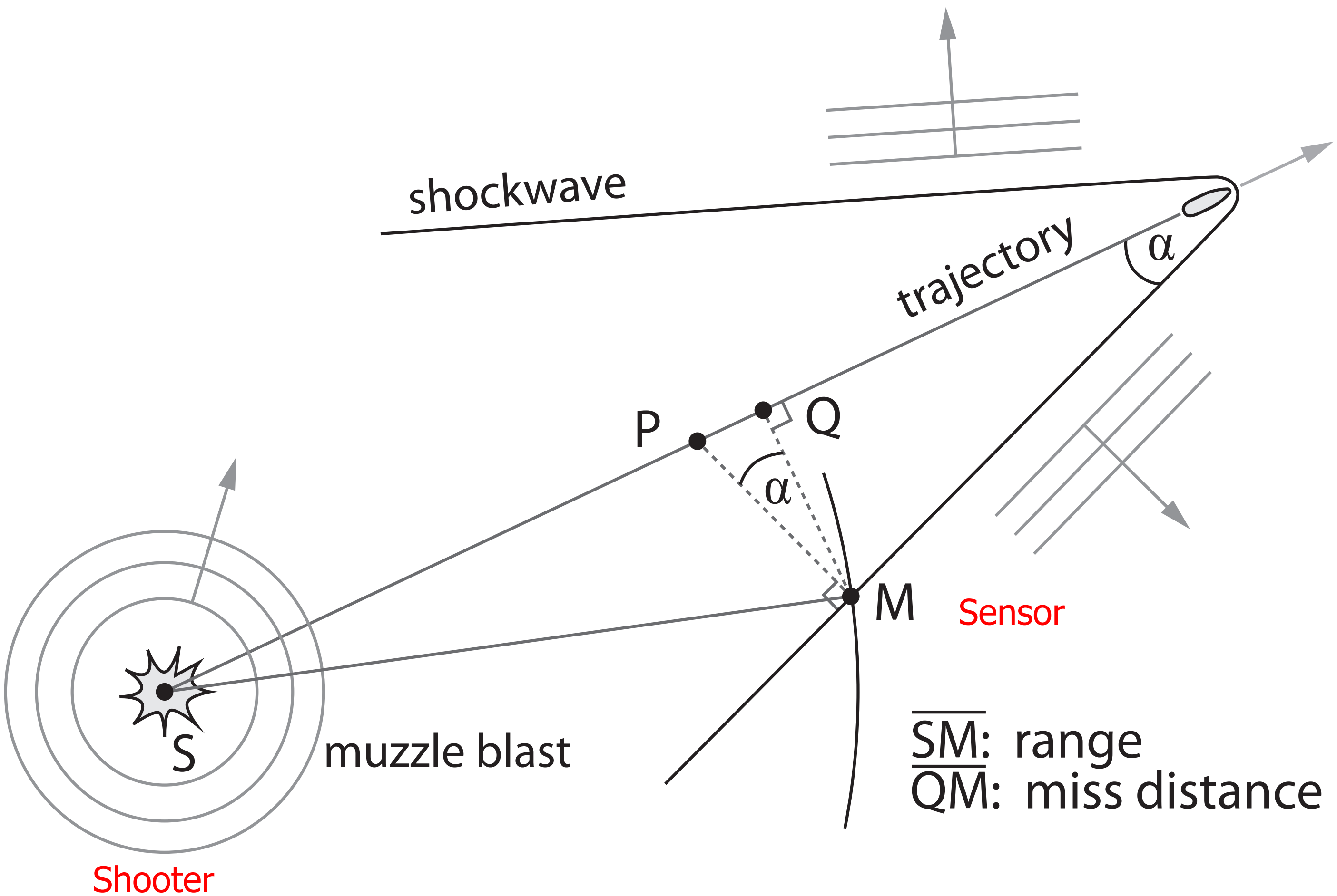
Acoustic Shooter Localization



- The muzzle blast originates at the gun and propagates spherically away at the speed of sound
- The shockwave is generated by the supersonic projectile as it slices through the air
- The wavefront has a conical shape
- Angle determined by the Mach number = speed of the bullet / speed of sound
- Miss distance = perpendicular distance from the sensor to the trajectory

Acoustic Events of a Typical Rifle Shot

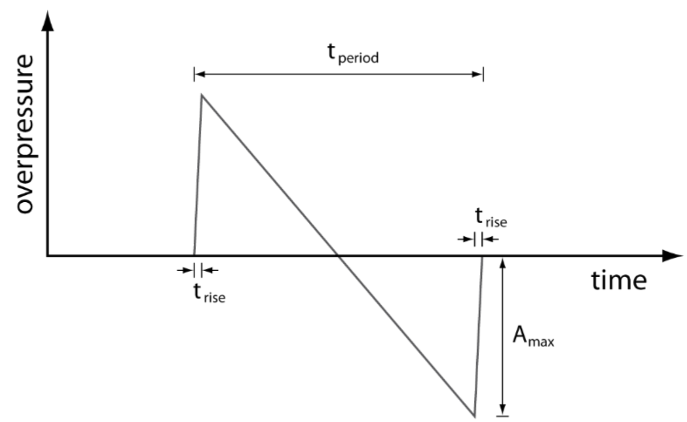


P: origin of shockwave heard at M
SP: at the speed of bullet
PM: at the speed of sound
α: shockwave cone angle

Acoustic Shooter Localization

Boomerang by Raytheon BBN Technologies

- Typical shockwave length: ~150-600 usec. It depends mainly on the caliber and miss distance.
- Using shockwave TOAs and muzzle blast TOAs gives TDOAs of both between pairs of microphones. On a microphone array, this gives AOA of muzzle blast (i.e. shooter) and AOA of shockwave.
- A simple analytical formula gives shooter position using the two AOAs and the TDOA of the shockwave and the muzzle blast (needs microphone array).
- Using distributed microphones, TDOA equations with muzzle blast TOAs at 3+ microphones can provide shooter location. However, location error of microphones and possible echoes due to non-LOS conditions make this very inaccurate.

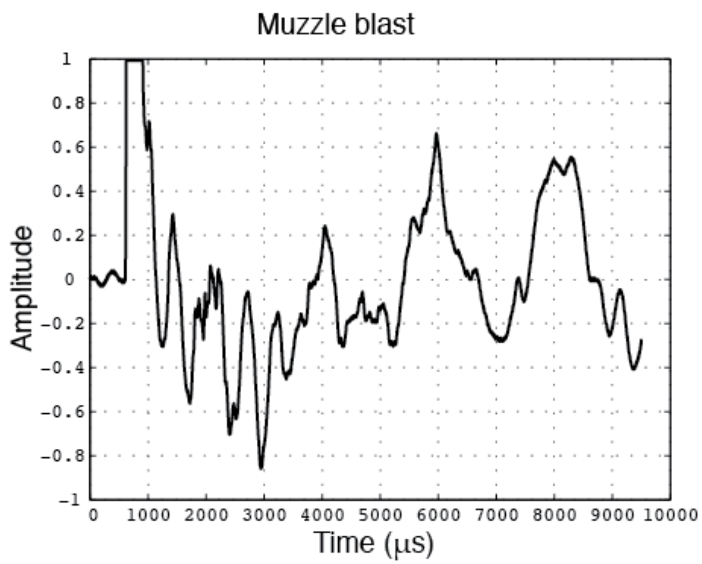


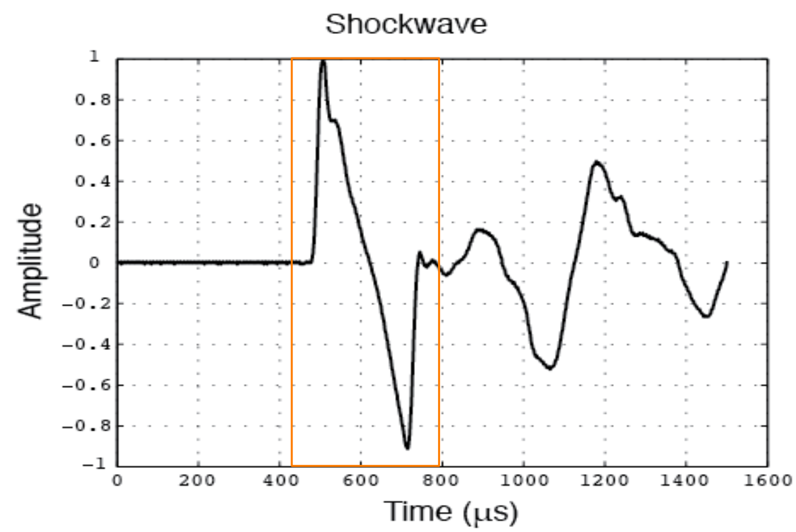
Shockwave signature

Some Sniper Detection Systems

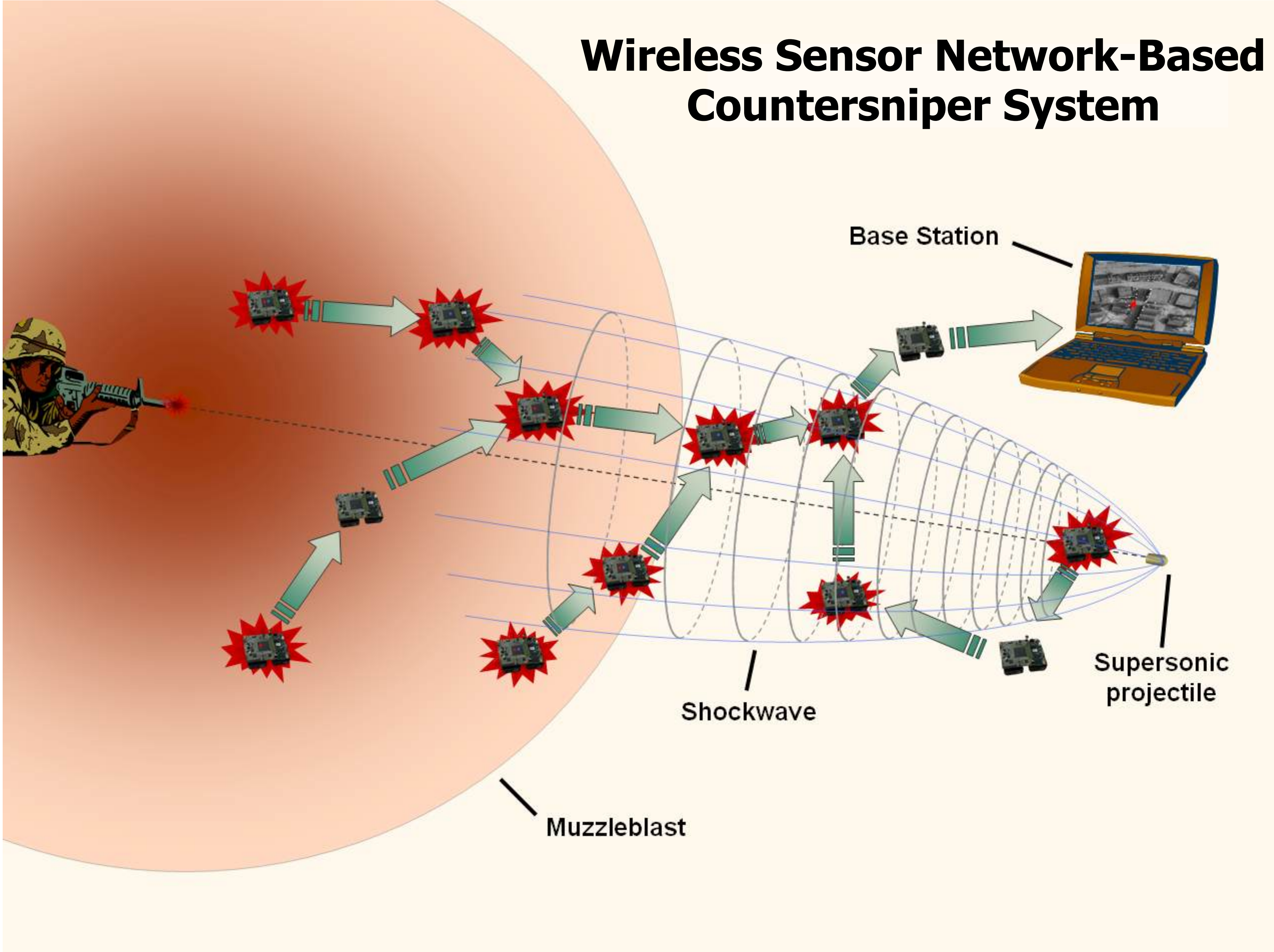
Name	Manufacturer	Muzzle Blast	Bullet Shock Wave	Muzzle Flash	Bullet in Flight (IR)	Optics Laser Reflection
Prototype	Sanders	X	X			
Bullet Detection Indicator	GD Associates		X			
Bullet Ears	BBN	X	X			
PD Cue	AAI Corporation		X			
Pilar	Metravib	X	X			
VIPER	Maryland Advanced Development Lab			X		
Prototype	Hughes Aircraft	X			X	
Integrated Sniper Location System	Sanders, LMIIS, and Sentech	X	X		X	
Sight Laser Detector (SLD)	Cilas					X
Target Observation and Locating System	Sanders					X
Sniper Acoustic Detection Sensor	Rafael	X				
SECURES	Alliant Techsystems	X				
Sentinel Sniper Location System	SAIC	X	X			
Fast IR Sniper Tracker	Thermo Trex			X		
Lifeguard	LLNL				X	

Signal Shapes





Wireless Sensor Network-Based Countersniper System



Problems to be solved

- Time sync to provide a common time base
- Localization
- Message routing to base station within bounded delay
- "Sensor fusion", i.e., localizing the shooter using information gathered at the distributed sensor nodes

Time Sync Challenges in Sensor Networks

- Transmitter delays
  - Send Time – Time to create message and issue request to MAC layer
  - Access Time – Time spent waiting for access to the channel
  - Transmission Time – Time to transmit the message
- Receiver delays
  - Reception Time – Time to receive message
  - Receive Time – Time to interpret the message
- Other delays
  - Interrupt Handling – Time between raising an interrupt and handling it
  - Encoding/Decoding Time – Time transforming to/from EM waves from/to binary data
  - Byte Alignment Time – Time needed to synch to different byte alignments between sender and receiver

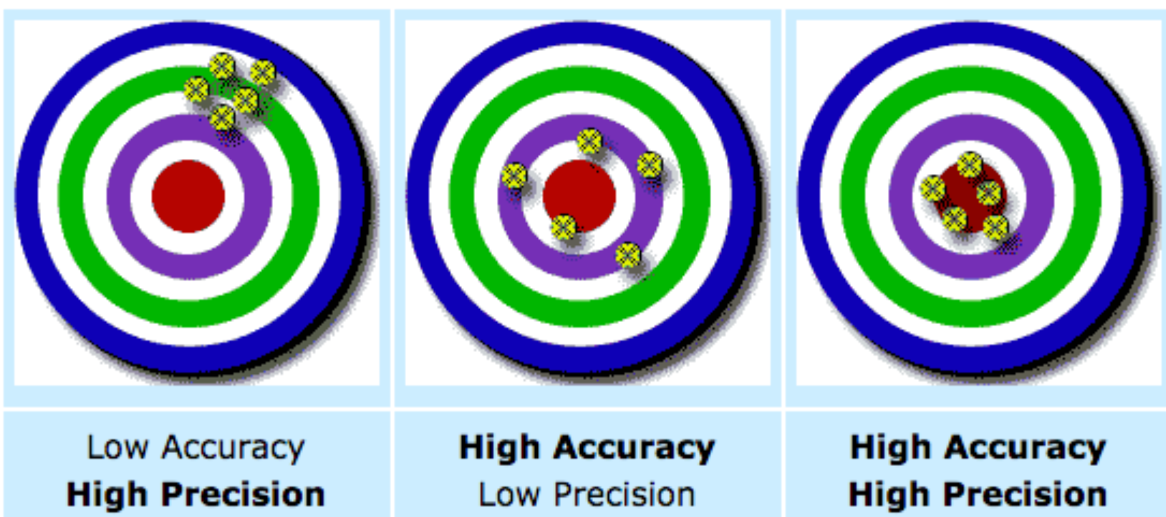
Table 1. The sources of delays in message transmissions

Time	Magnitude	Distribution
Send and Receive	0 – 100 ms	nondeterministic, depends on the processor load
Access	10 – 500 ms	nondeterministic, depends on the channel contention
Transmission / Reception	10 – 20 ms	deterministic, depends on message length
Propagation	< 1µs for distances up to 300 meters	deterministic, depends on the distance between sender and receiver
Interrupt Handling	< 5µs in most cases, but can be as high as 30µs	nondeterministic, depends on interrupts being disabled
Encoding plus Decoding	100 – 200µs, < 2µs variance	deterministic, depends on radio chipset and settings
Byte Alignment	0 – 400µs	deterministic, can be calculated

Delays on Mote devices

Time Sync Approaches

- Reference Broadcast Synchronization (RBS)
- Timing Sync Protocol for Sensor Networks (TPSN)
- Flooding Time Sync Protocol (FTSP)



RBS

- A reference sender broadcasts a wireless message
- (No timestamping at sender)
- Each receiver hearing message timestamps in the MAC layer upon reception (post decoding)
- Obtain multiple such references and run a linear regression to estimate time
- Multiple hops sync'd through intermediate nodes
- Empirically, precise to a few microseconds

TPSN

- Sender timestamps at lowest layer just prior to sending
- Receiver echoes in ACK
- Two back-to-back timestamp messages sent (and averaged)
- Empirically, a few microseconds of precision

FTSP

- Combines sender and receiver timestamping
- Creates rooted tree
- Each level syncs with level before
- Empirically, 1.2 microseconds precision

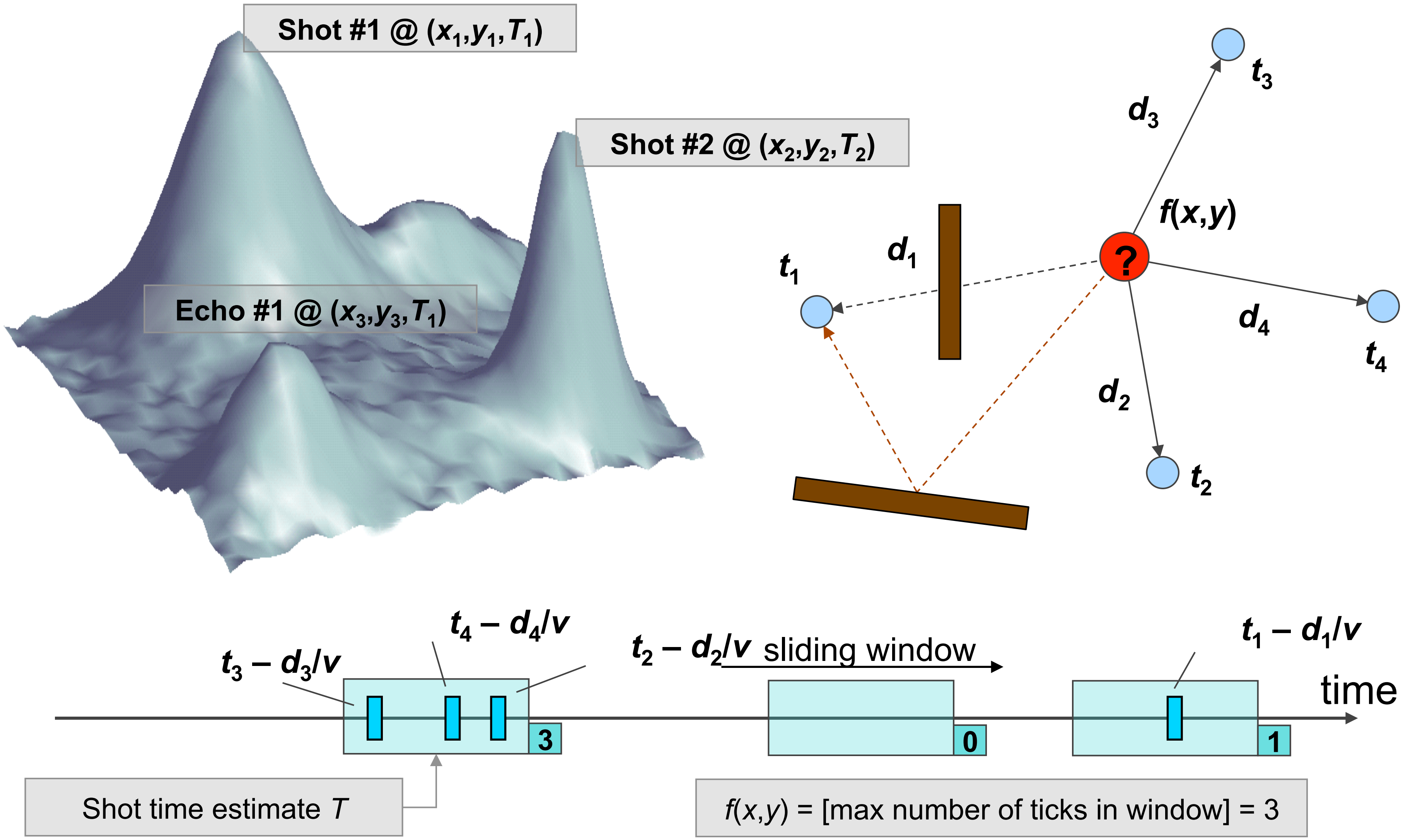
Sensor Localization

- Acoustic ranging (*a la* Cricket)
- Empirically, error was 11 cm (average) and 25 cm (worst case) in one experiment (30 x 15 meter area with 50 nodes)
- Acoustic chirps done periodically at pre-scheduled times
- Paper outlines different approach, called “passive acoustic sensor localization” (but wasn’t built)
  - Cricket developed a similar “mobile-assisted localization” scheme

Message Routing

- Each sensor obtains its “time of arrival” (TOA)
- Must deliver to base station promptly
  - Overall desired system delay is 2 seconds to localize shooter
- Each node transmits a message between 0 and 2 times depending on if it has heard a node closer to the root broadcast message

Sensor Fusion



Consistency Function

$$t_i(x,y,z,t) = t + \frac{\sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}}{v}$$

$$|\, t_i(x,y,z,t) - t_i \,| \le \tau \,,$$

$$C_\tau(x,y,z,t) = \underset{i=1,\ldots,N}{\text{count}} \left(\left| t_i(x,y,z,t) - t_i \right| \le \tau \right) .$$

Experiments at McKenna MOUT site at Ft. Benning

NORTH

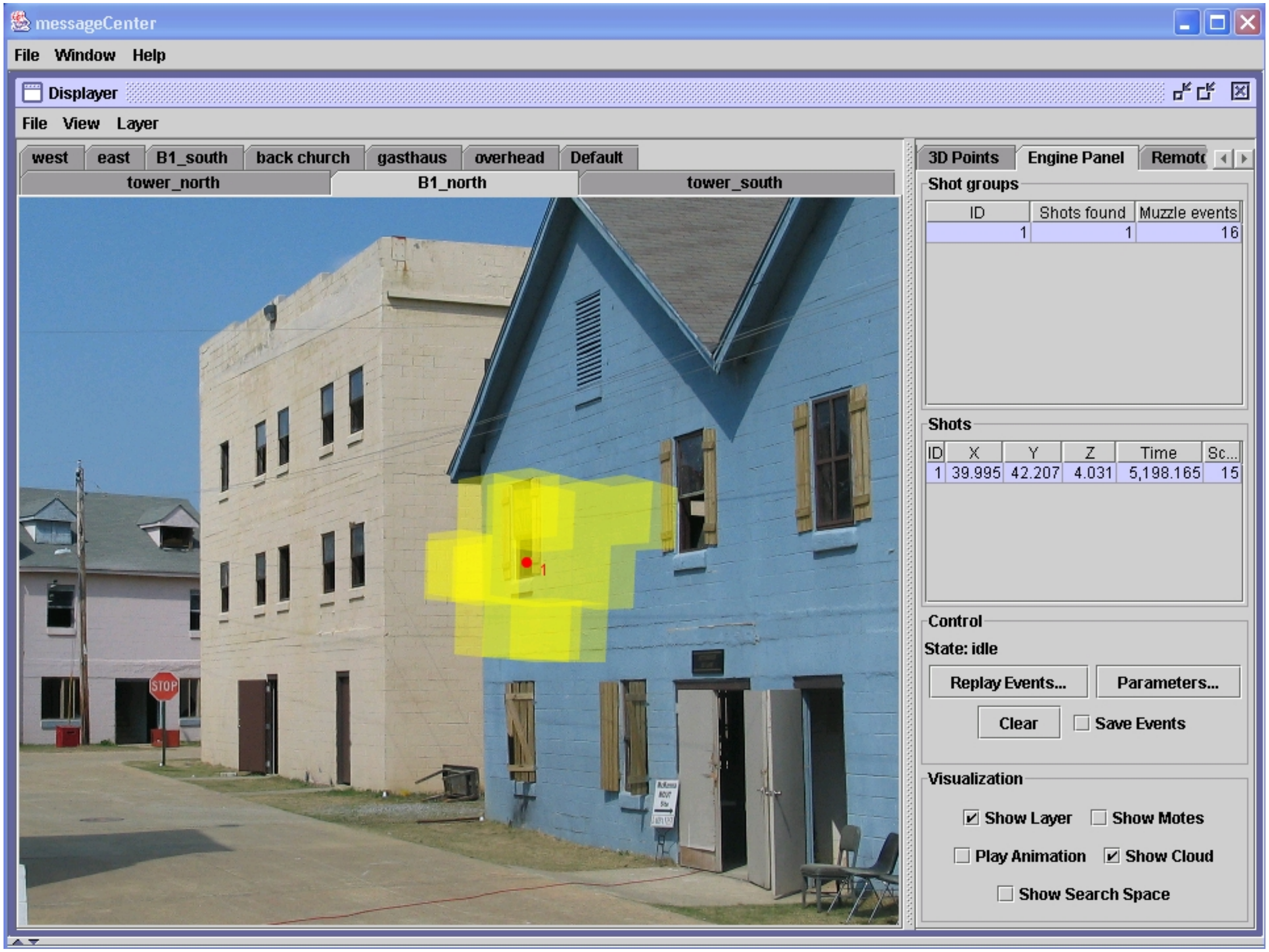
- Sep 2003: Baseline system
- Apr 2004: Multishot resolution

- 60 motes covered a 100x40m area
- Network diameter: ~7 hops
- Used blanks and Short Range Training Ammunition (SRTA)
- Hundreds of shots fired from ~40 different locations
- Single shooter, operating in semiautomatic and burst mode in 2003
- Up to four shooters and up to 10 shots per second in 2004
- M-16, M-4, no sniper rifle
- Variety of shooter locations (bell tower, inside buildings/windows, behind mailbox, behind car, …) chosen to absorb acoustic energy, have limited line of sight on sensor networks

- 1 meter average 3D accuracy (0.6m in 2D)

- Hand placed motes on surveyed points (sensor localization accuracy: ~ 0.3m)

2.5D Display, Single shot



Red circle:
→ **Shooter position**

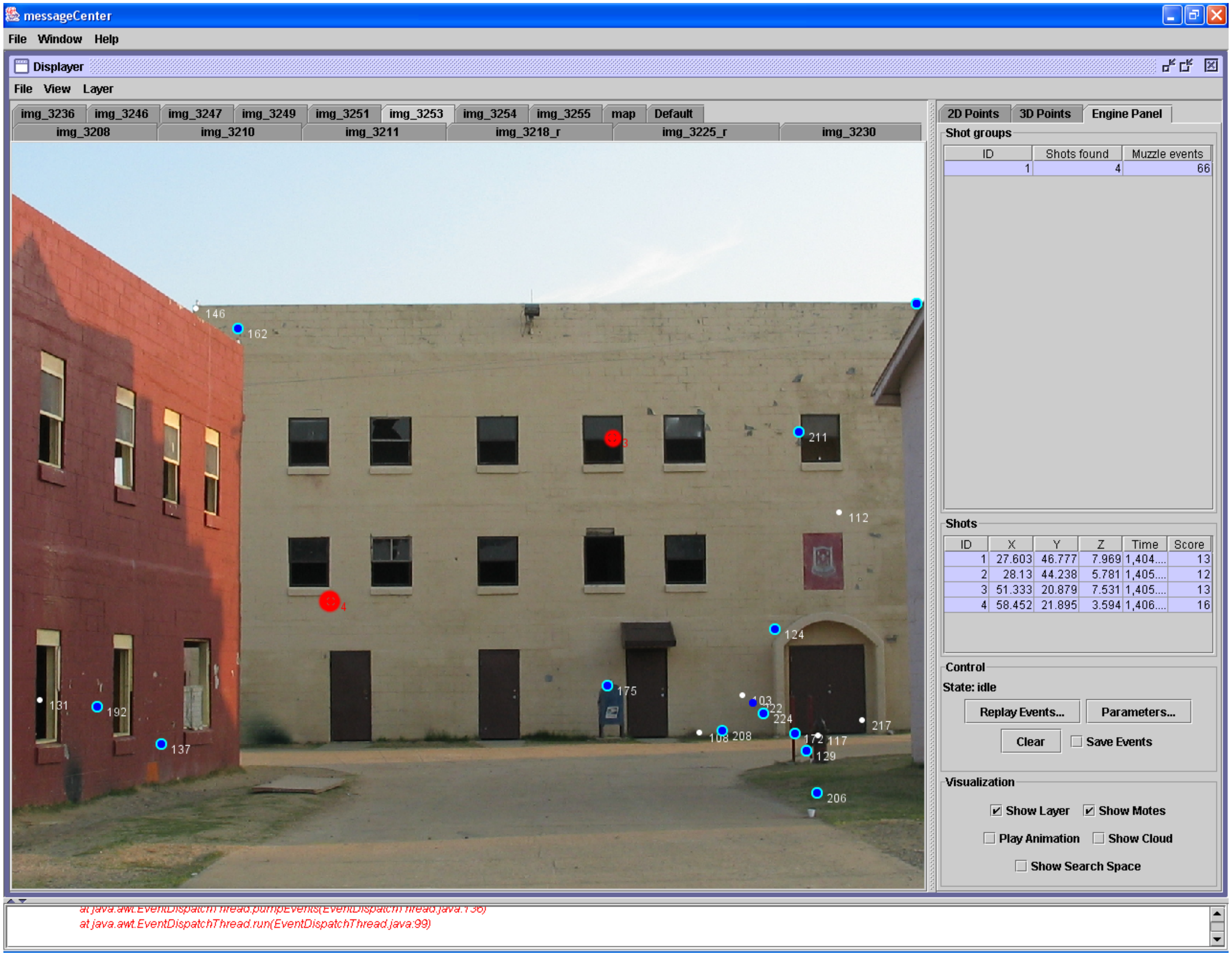
White dot:
→ **Sensor node**

Small blue dot:
→ **Sensor Node that detected current shot**

Cyan circle:
→ **Sensor Node whose data was used in localization**

Yellow Area:
→ **Uncertainty**

2.5D Display, Multiple Shots



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Yellow Area:
→ Uncertainty