Mission-Critical Networking and Situation-Awareness

Nader Moayeri

Presented at George Mason University
September 26, 2008

Contributors

- J. Braga
- A. El-Kik
- C. Gentile
- J. Geissbuehler
- D. Kaspar
- L. KleinBerndt
- L. Miller
- J. Perez
- M. Refaei
- K. Sayrafian
- M. Souryal
- A. Wapf
- H. You

Introduction / Terminology

- Mission-Critical Operations
  - Military
  - Emergency Response
  - Search and Rescue
    - Urban
    - Mine Incidents
- Situation-Awareness
  - Wireless Sensor Networks
    - Sensing the Environment
    - Physiological Monitoring of Workers
  - Indoor Localization and Tracking

Presentation Outline

- Real-Time Deployment of Multihop Relays (“Breadcrumbs”) for Communication Range Extension
- An Overview of Indoor Localization Research at NIST

Real-Time Deployment of Multihop Relays (“Breadcrumbs”) for Communication Range Extension

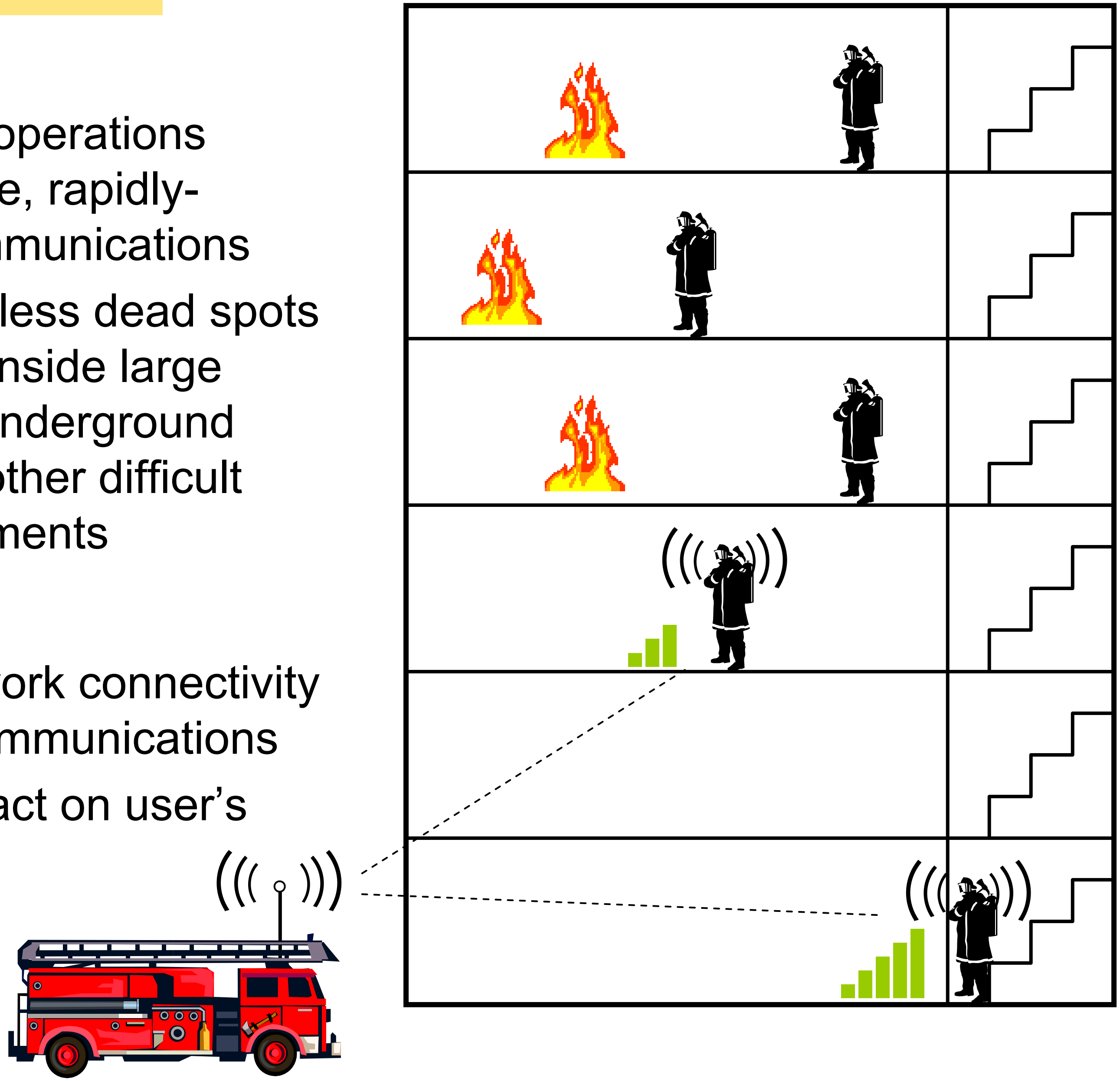
Motivation & Objectives

Motivation

- Public safety operations require reliable, rapidly-deployed communications
- Frequent wireless dead spots encountered inside large buildings, in underground tunnels, and other difficult radio environments

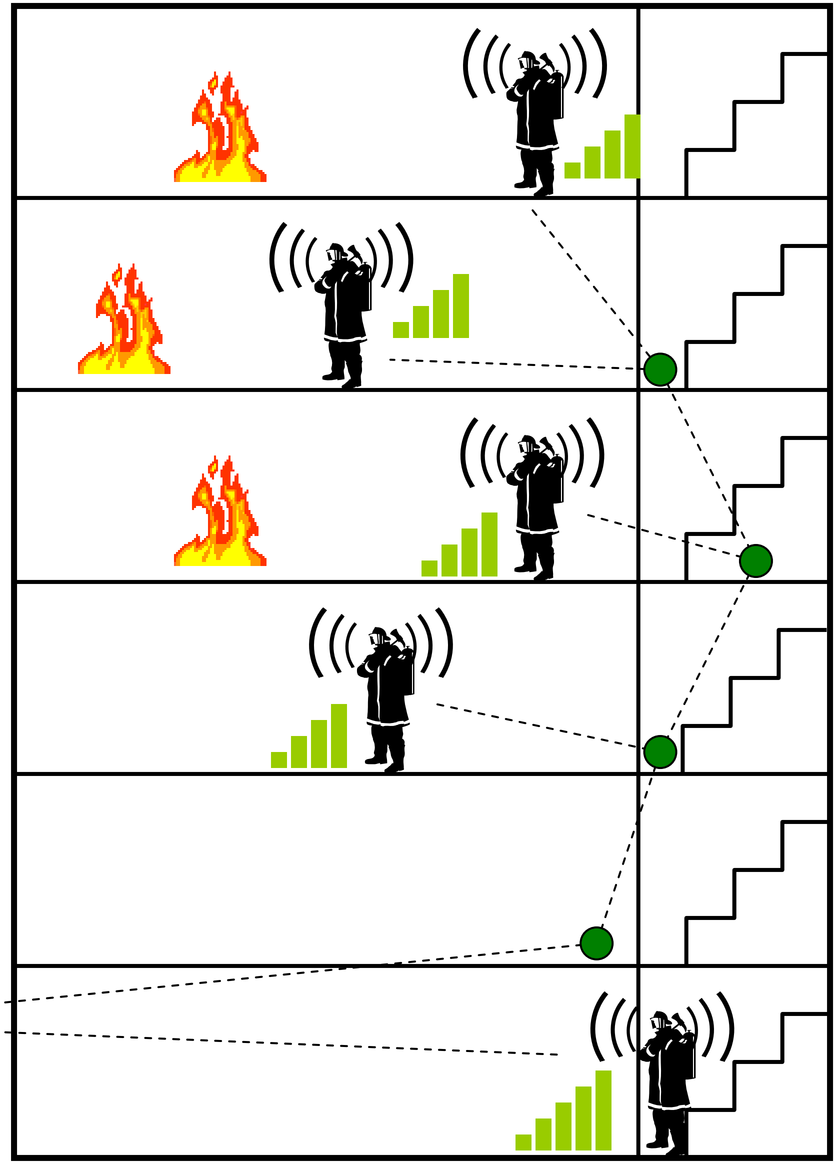
Objectives

- Maintain network connectivity for reliable communications
- Minimize impact on user's mission



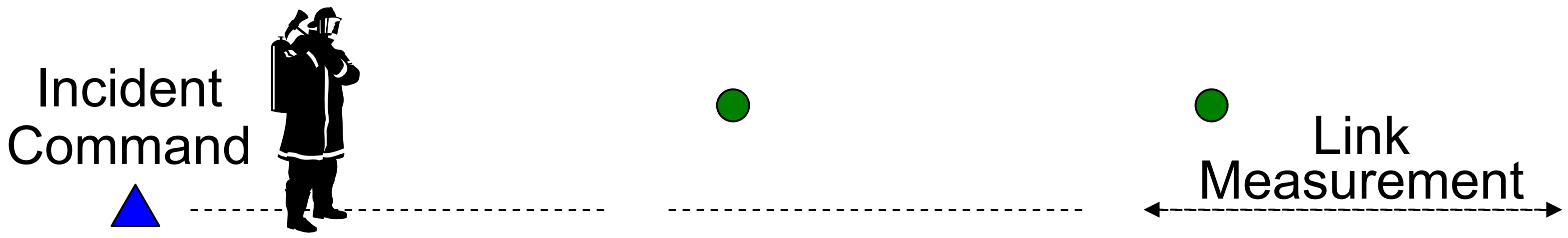
Approach

- Extend signal coverage through a multihop network that relays data/voice between first responders and Incident Command (IC)
- "Breadcrumb" relays (●) are automatically deployed at appropriate points along path, creating a multihop network
- Link layer and routing protocols provide reliable two-way communications, transfer of user vital signs, etc.



Technical Challenges

- Automating the deployment process…When/where to deploy relays?



- Reliable end-to-end transmission
  - » Link-quality-sensitive route metric
  - » Link and network layer retransmission
- Adapting to changes in link quality and topology
  - » Timely route updates
  - » Power control

Questions & Overview

Questions to Address

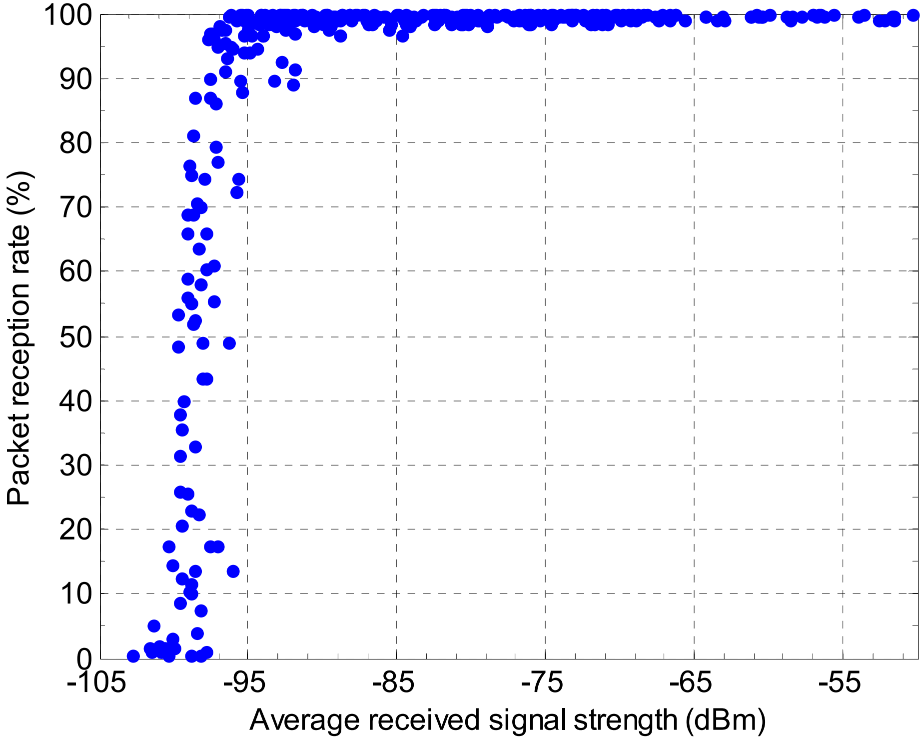
- How to measure the quality of a wireless link reliably and efficiently? (in order to determine when to deploy a new relay)
- What criteria should be used to trigger deployment?
- Is real-time on-the-fly deployment feasible? (Will it result in well-connected networks capable of reliable communications?)

What Follows

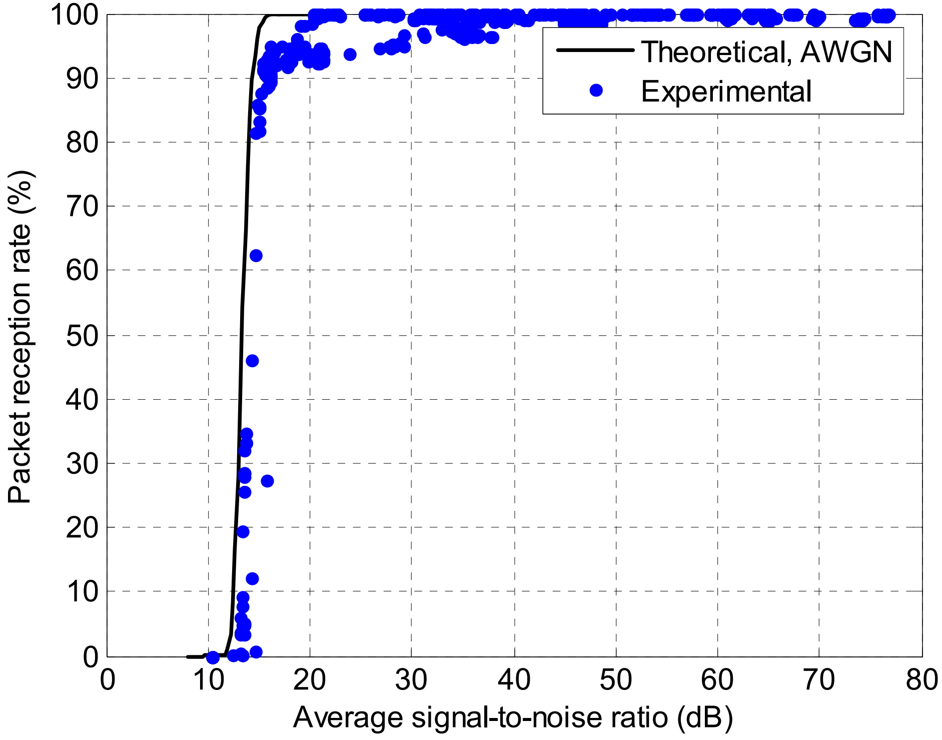
- Approach to real-time deployment
- Overview of 900 MHz and 2.4 GHz prototypes
- Test results of 2.4 GHz prototype
- Next steps

Link Reliability Measurements

Packet Reception Rate vs. Average Received Signal Strength at 900 MHz



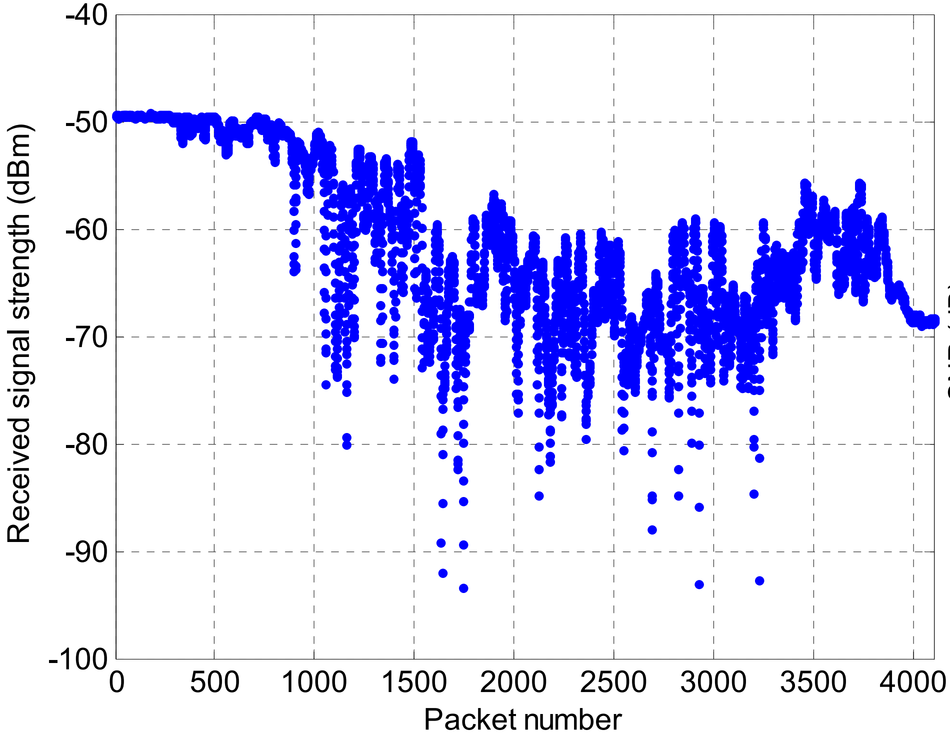
Packet Reception Rate vs. Average Signal-to-Noise Ratio at 2.4 GHz



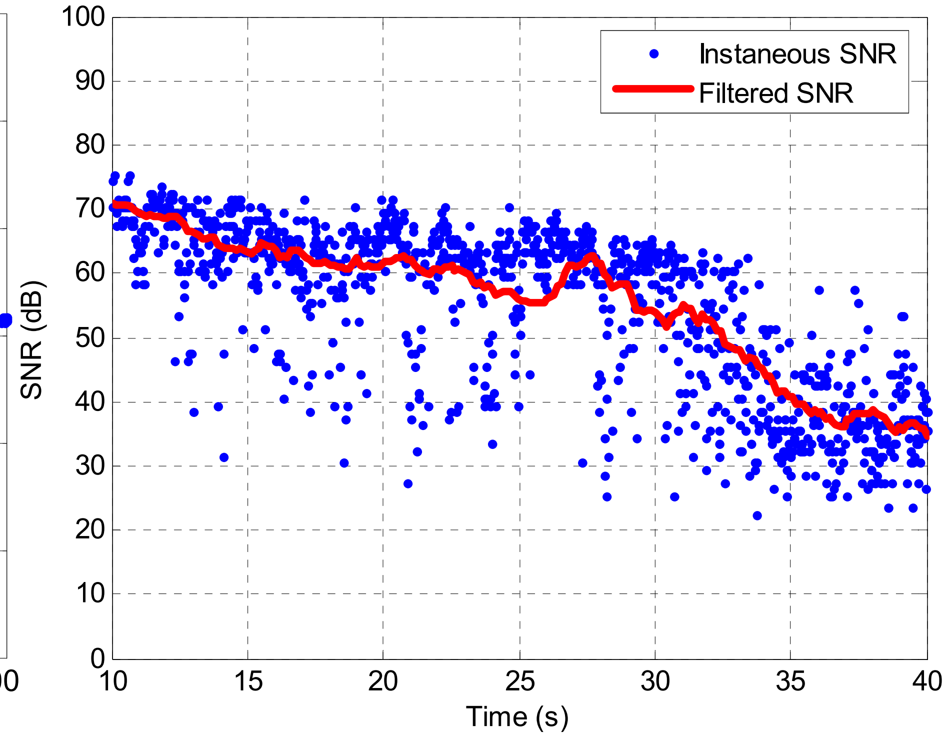
- Collected over a fixed topology on single floor of an office building
- Clear threshold ⇒ RSS/SNR as indicator of link reliability

Mobile Link Measurements

RSS vs. Time on a 900 MHz Mobile Link

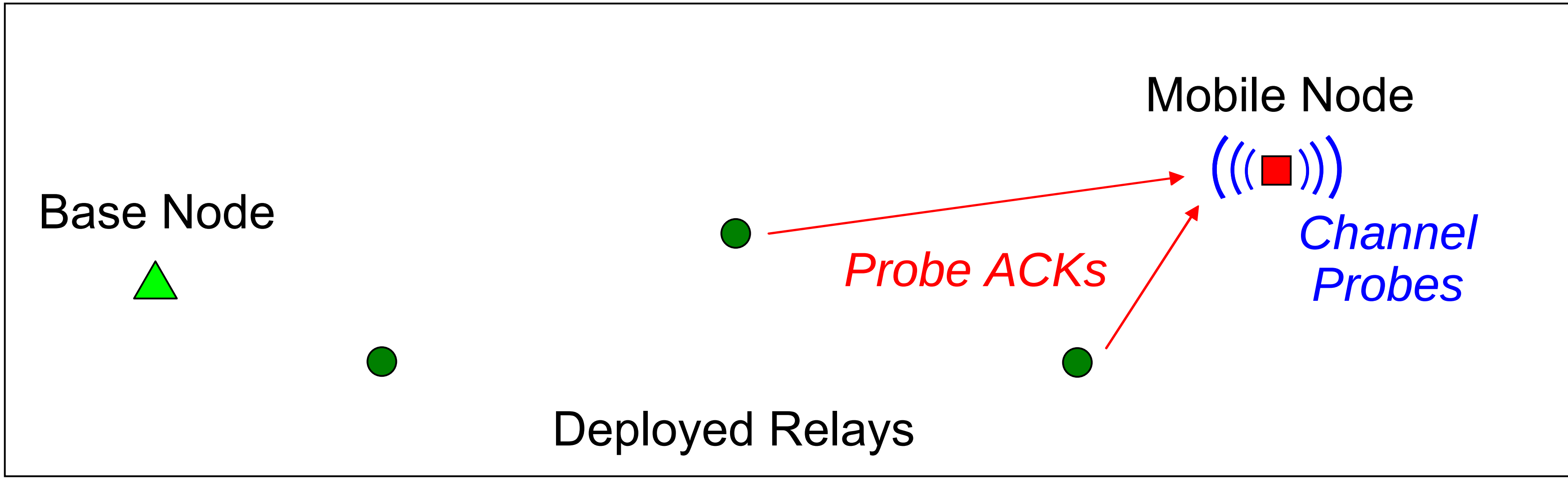


SNR vs. Time on a 2.4 GHz Mobile Link

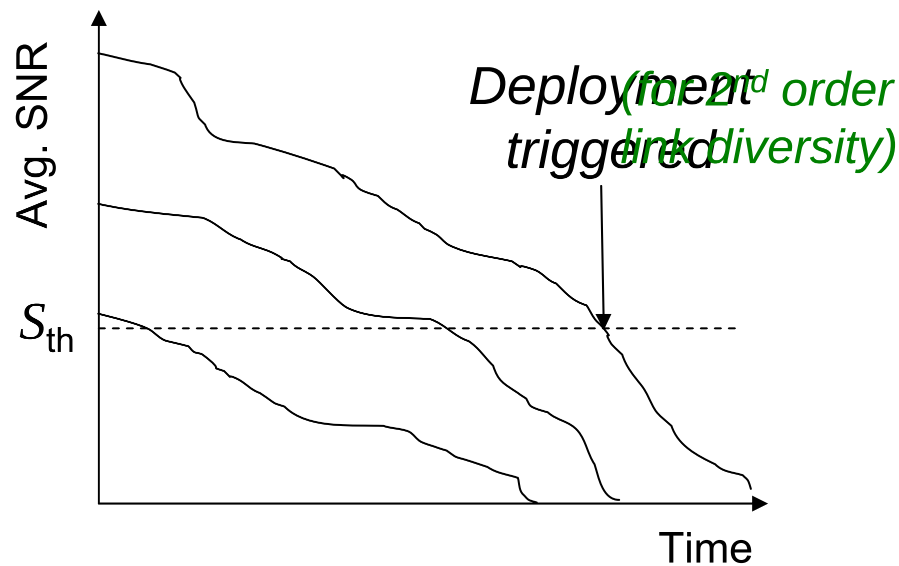


- Measured by a mobile rx moving at fixed velocity down an office corridor
- $\Rightarrow$ Approaches needed to cope with multipath fading

Overview of Deployment Algorithm



1. Mobile node probes channel every Δ sec.
2. Measures SNR of each Probe ACK (bidirectional)
3. If average SNR of each responding relay is less than a threshold, trigger deployment of new relay.



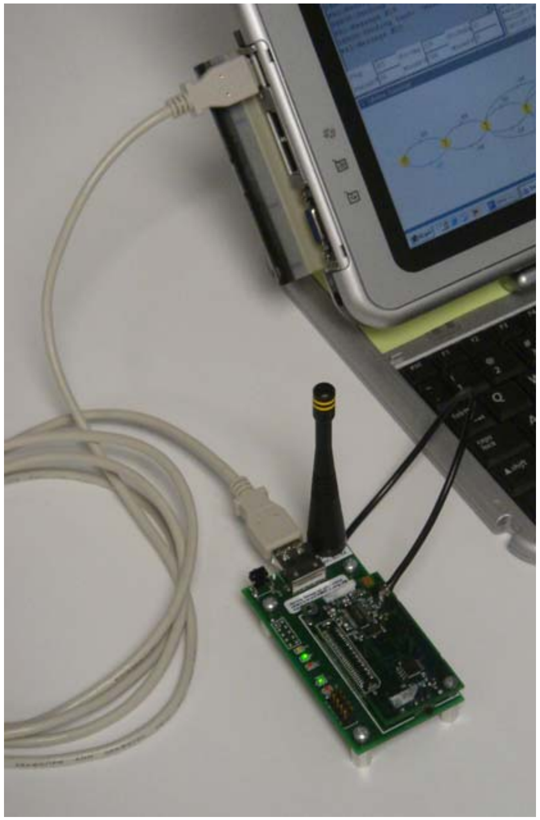
900 MHz Experimental Platform

- Crossbow MICA2 Mote (MPR400CB)
  - ChipCon CC1000 transceiver at 916 MHz
  - 8-bit ATMega128L 7.37 MHz processor
  - 128 kB program memory, 4 kB SRAM
  - Powered by 2 AA batteries
  - 5 dBm max. RF power

- Multi-Sensor Module (MTS310)
  - Light, Temperature
  - Acoustic, Sounder
  - 2-Axis Accelerometer
  - 2-Axis Magnetometer

900 MHz Prototype System

Base Node



Mobile Node

Relays

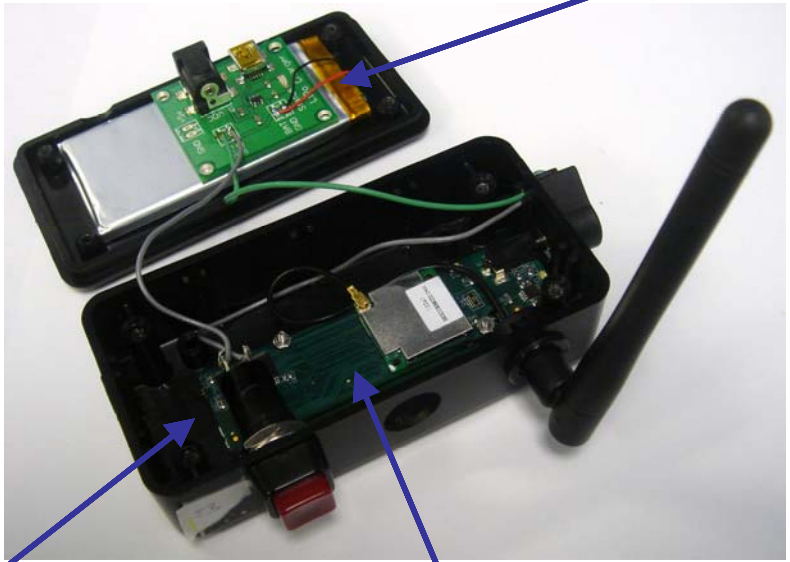
Applications

- Continuous monitoring of Mobile Node's sensors
- Two-way text messaging between Base and Mobile
- Display approximate location of Mobile Node
  - using RFID location tags

Technical Features

- Rapid link measurement w/ adaptive probing
- Real-time deployment w/ local placement assistance
- Modified DSDV routing with link quality metric
- Power control

2.4 GHz Prototype Breadcrumb



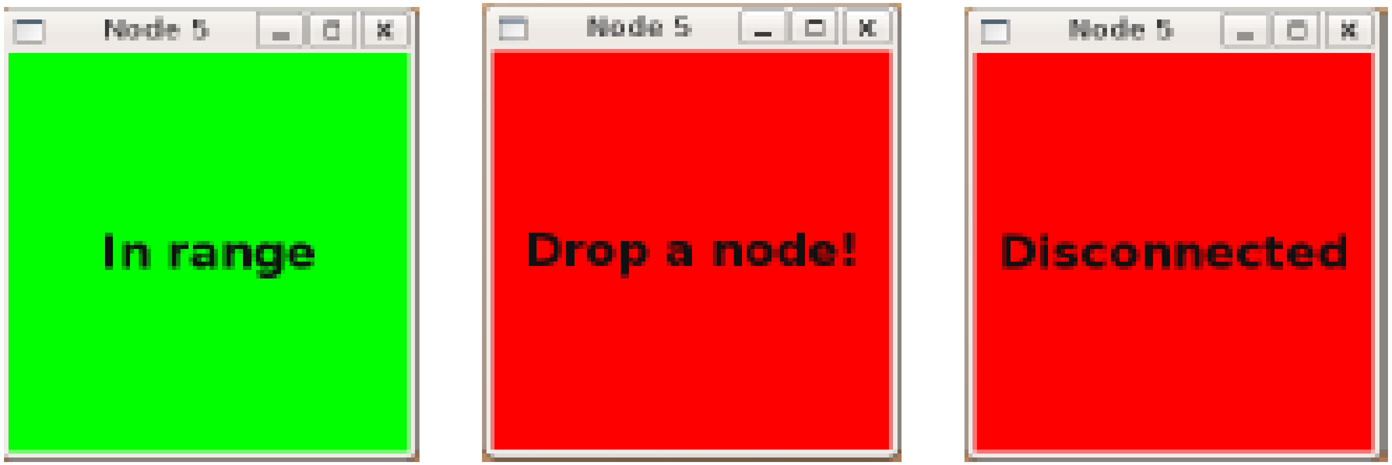
Lithium polymer battery & charger

Gumstix motherboard
- 400 MHz Linux computer
- 16 MB Flash
- 64 MB SDRAM
- 8 cm × 2 cm

Wifistix expansion board
- IEEE 802.11b/g
- Open source driver
- 8 cm × 2 cm

Deployment Monitor

- Next breadcrumb to be deployed continuously probes and measures link quality to its neighbors.
- Deployment monitor on mobile display:



- When that breadcrumb is deployed, next breadcrumb is set to probe.

2.4 GHz Prototype System Features

Applications

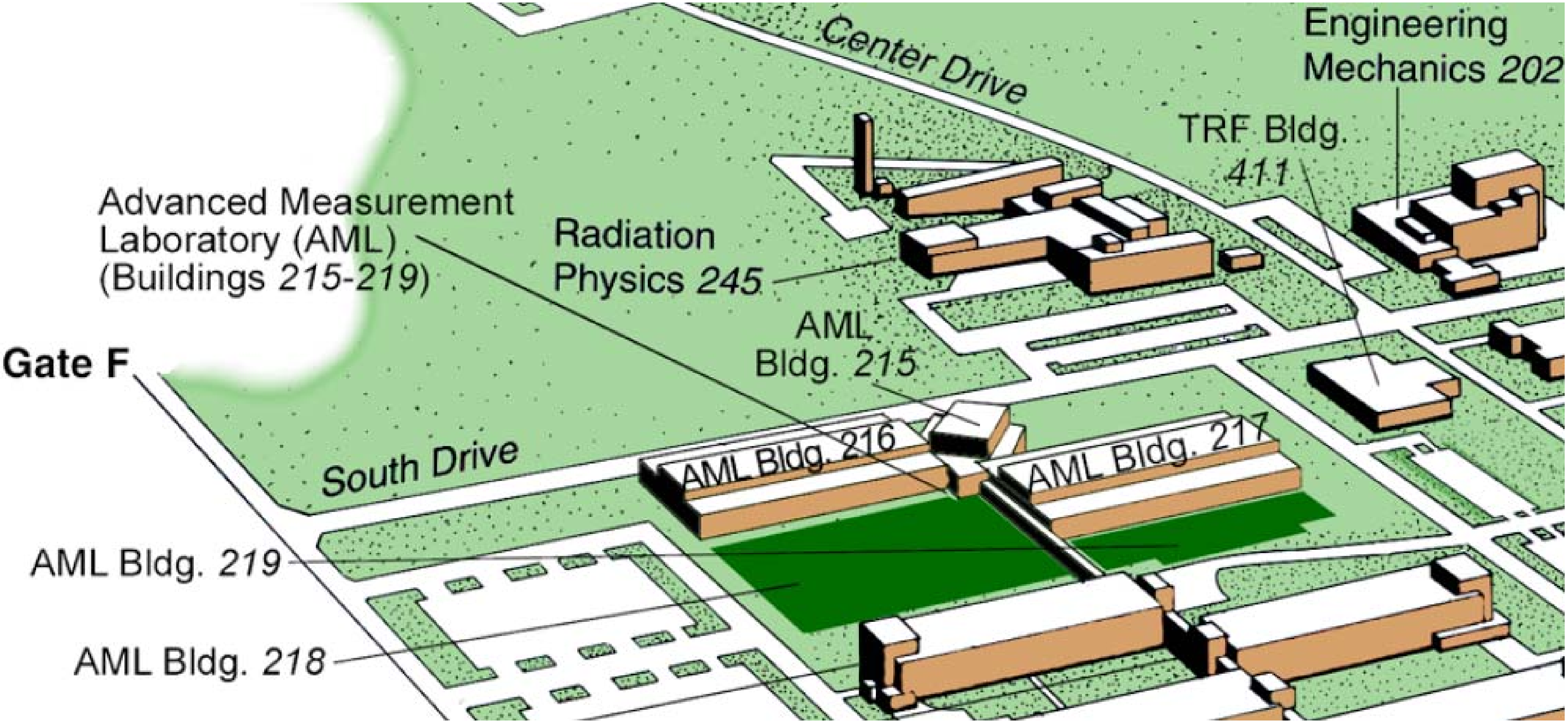
- Two-way voice between Base and Mobile Node
- Continuous monitoring of Mobile Node's sensors
- Display approximate location of Mobile Node
  - using RFID location tags
- Video

Technical Features

- Rapid link measurement
- Real-time deployment w/ local placement assistance
- IEEE 802.11 PHY/MAC
- OLSR routing w/ ETX metric
- IP support

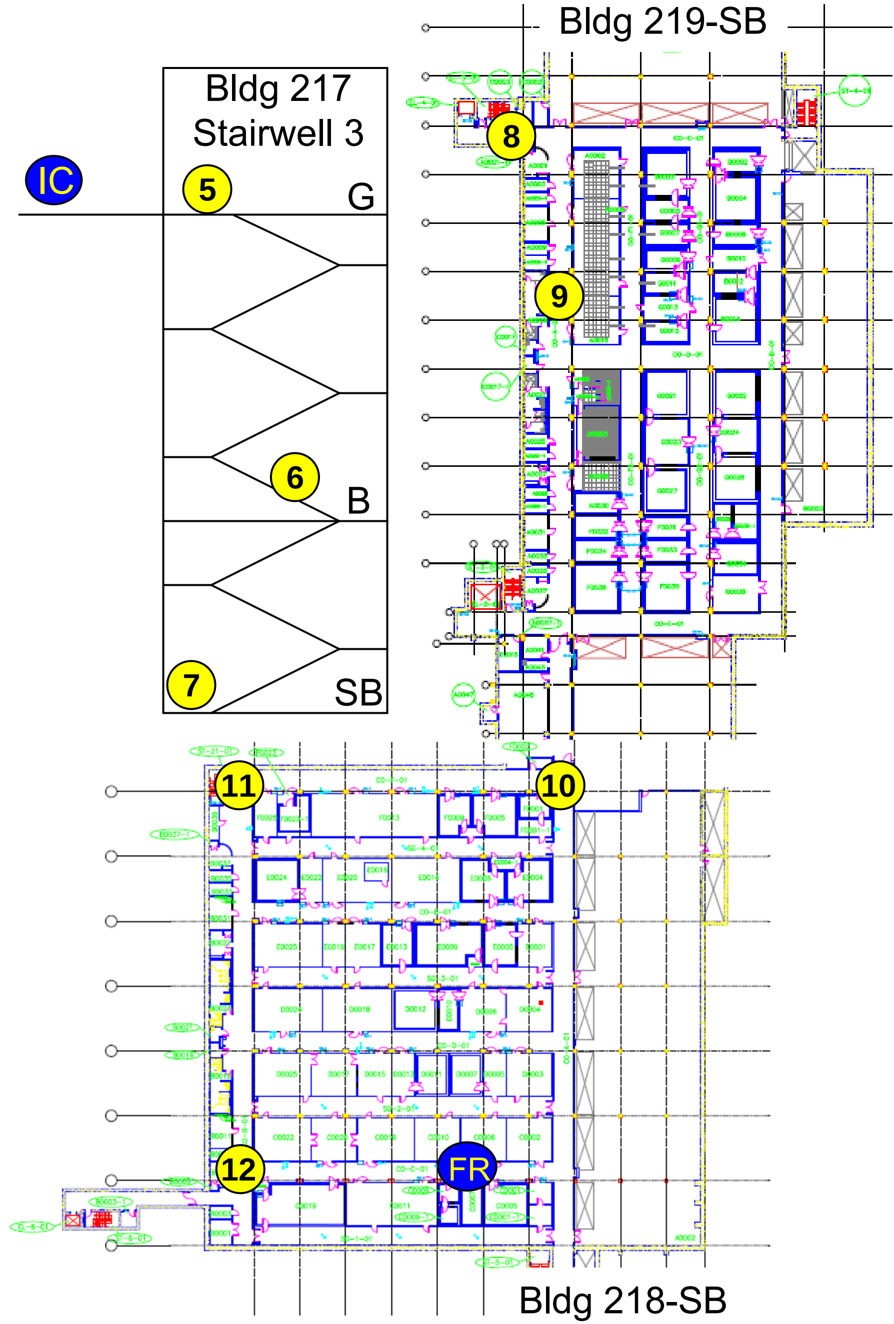
Test in NIST AML

- March 24 & 26, 2008
- Buildings 217, 218, and 219

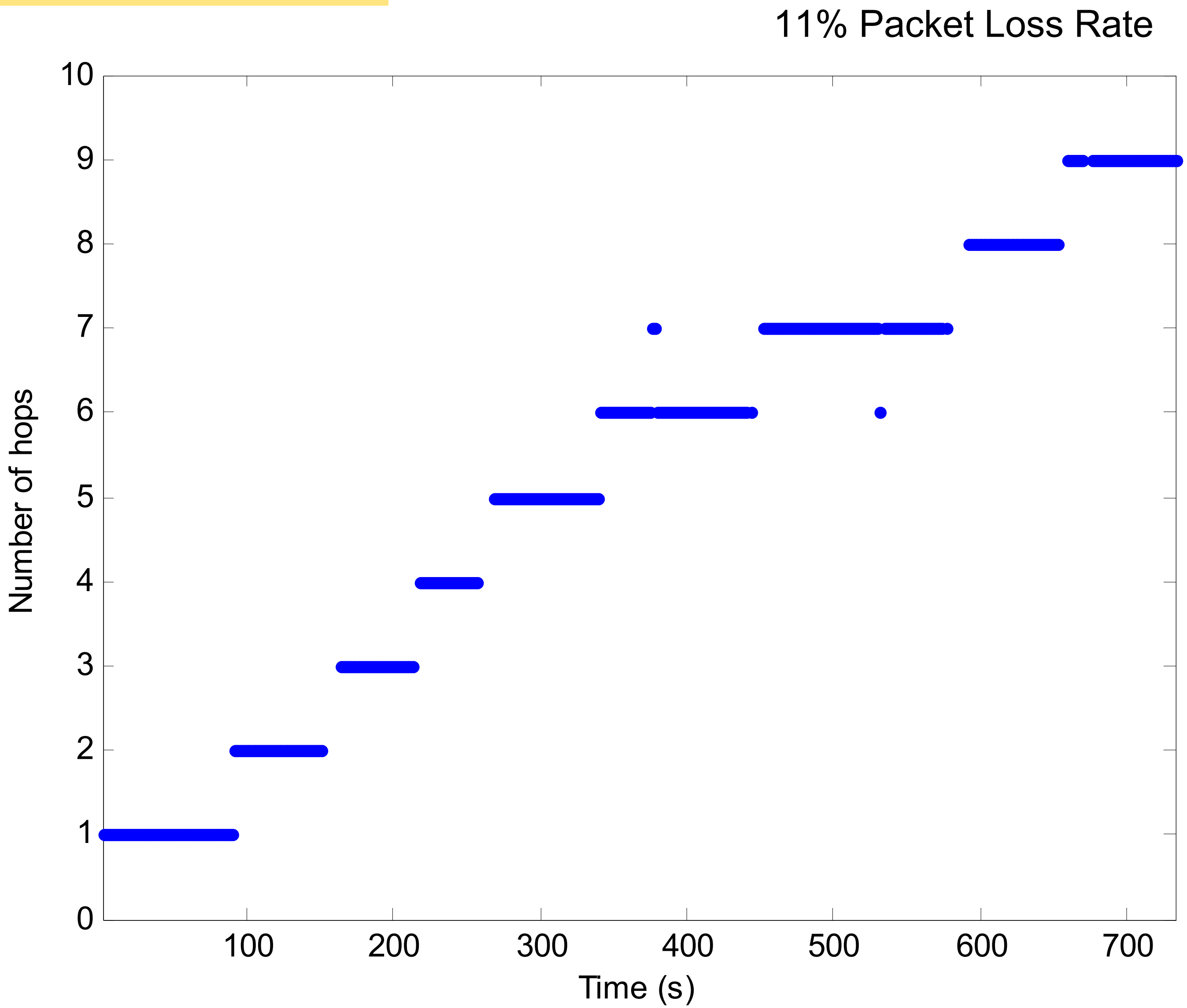


Deployment Example

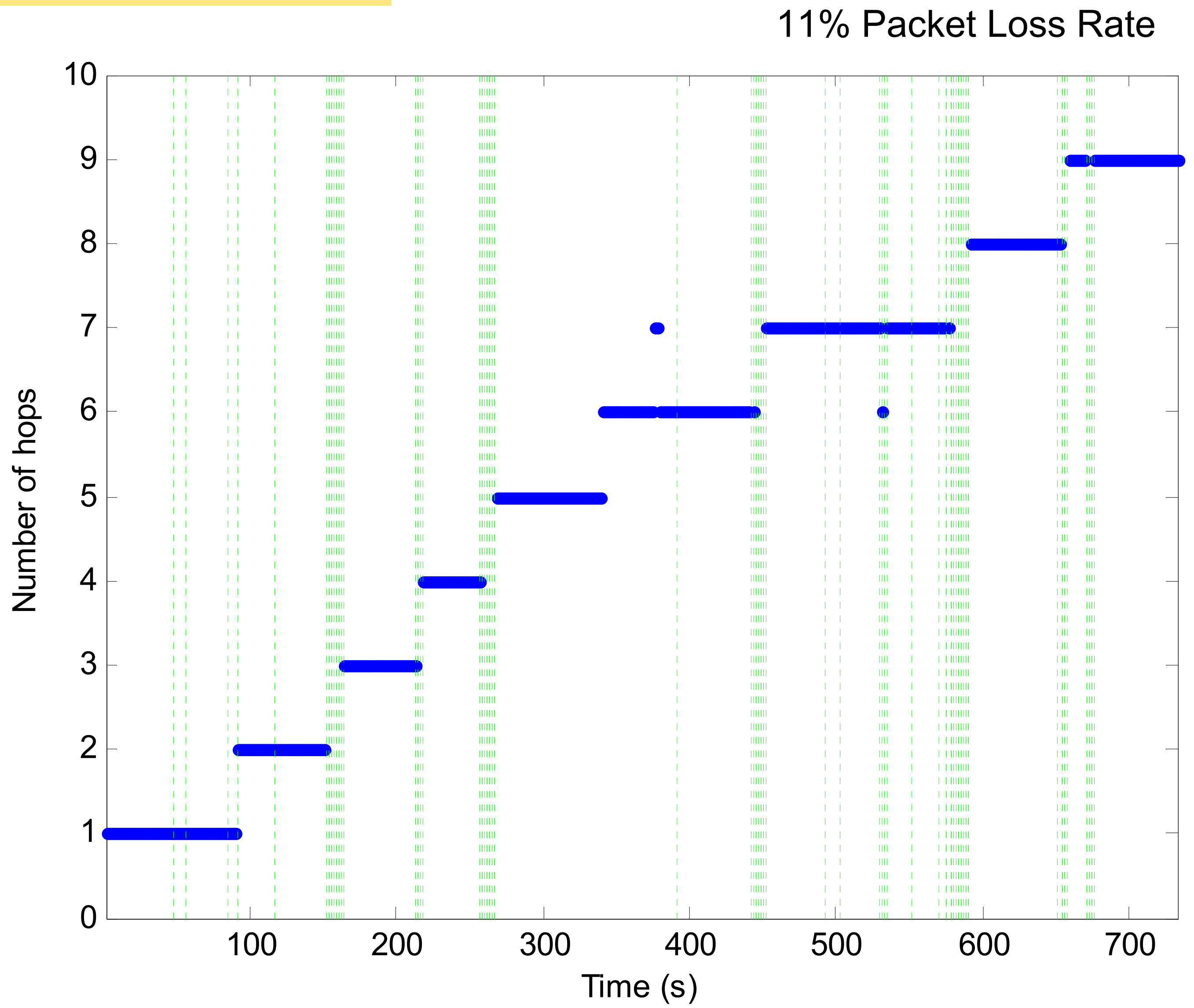
- 8 breadcrumbs deployed
- IEEE 802.11 2-Mbps data rate
- OLSR
  – HELLO period 0.5 s
- During deployment:
  – 28 kbps full-duplex VoIP call between IC and FR
  – Ping every second
- After deployment:
  – 10 MB file transfer
  – Audio recording



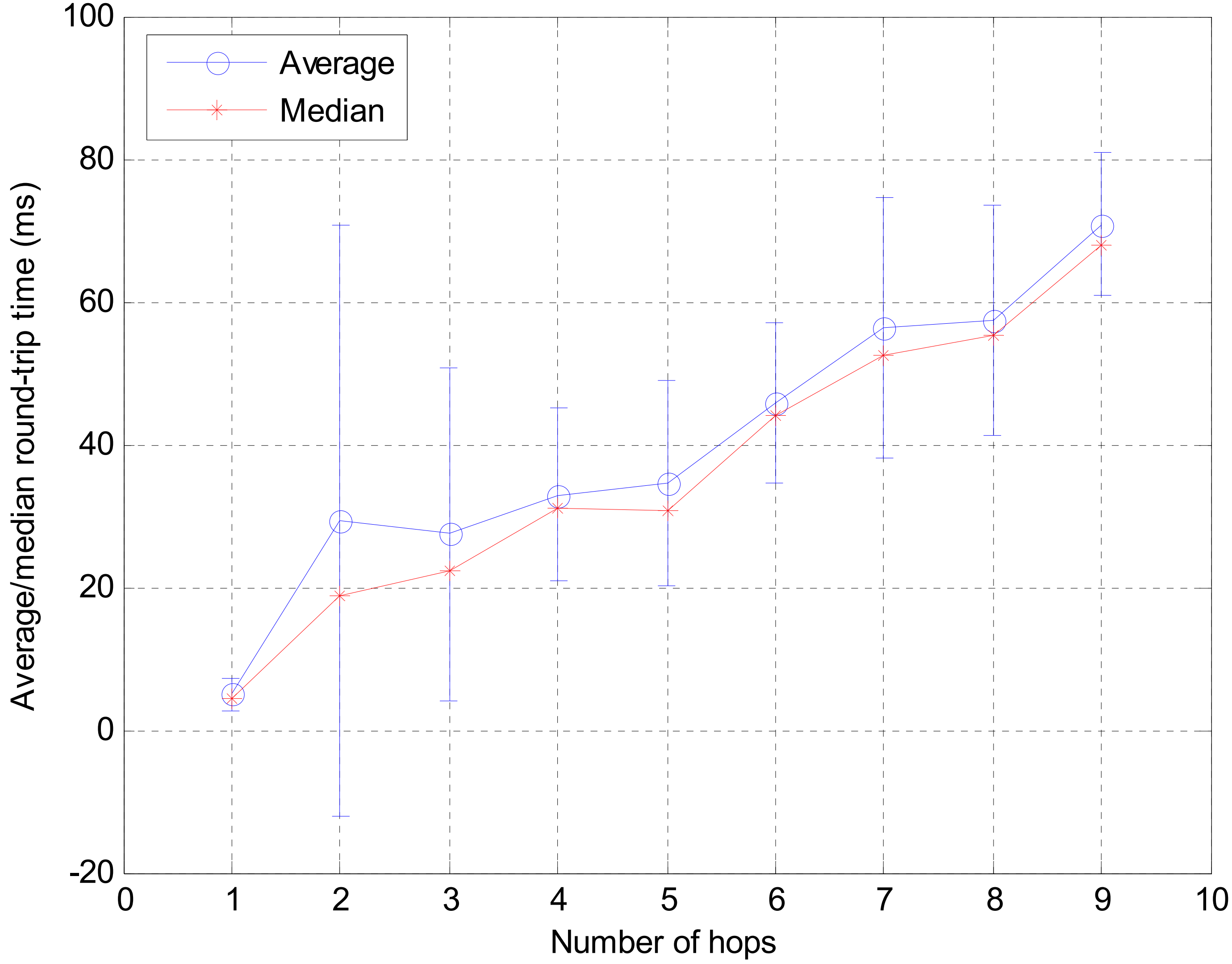
During Deployment



During Deployment: Packet Losses

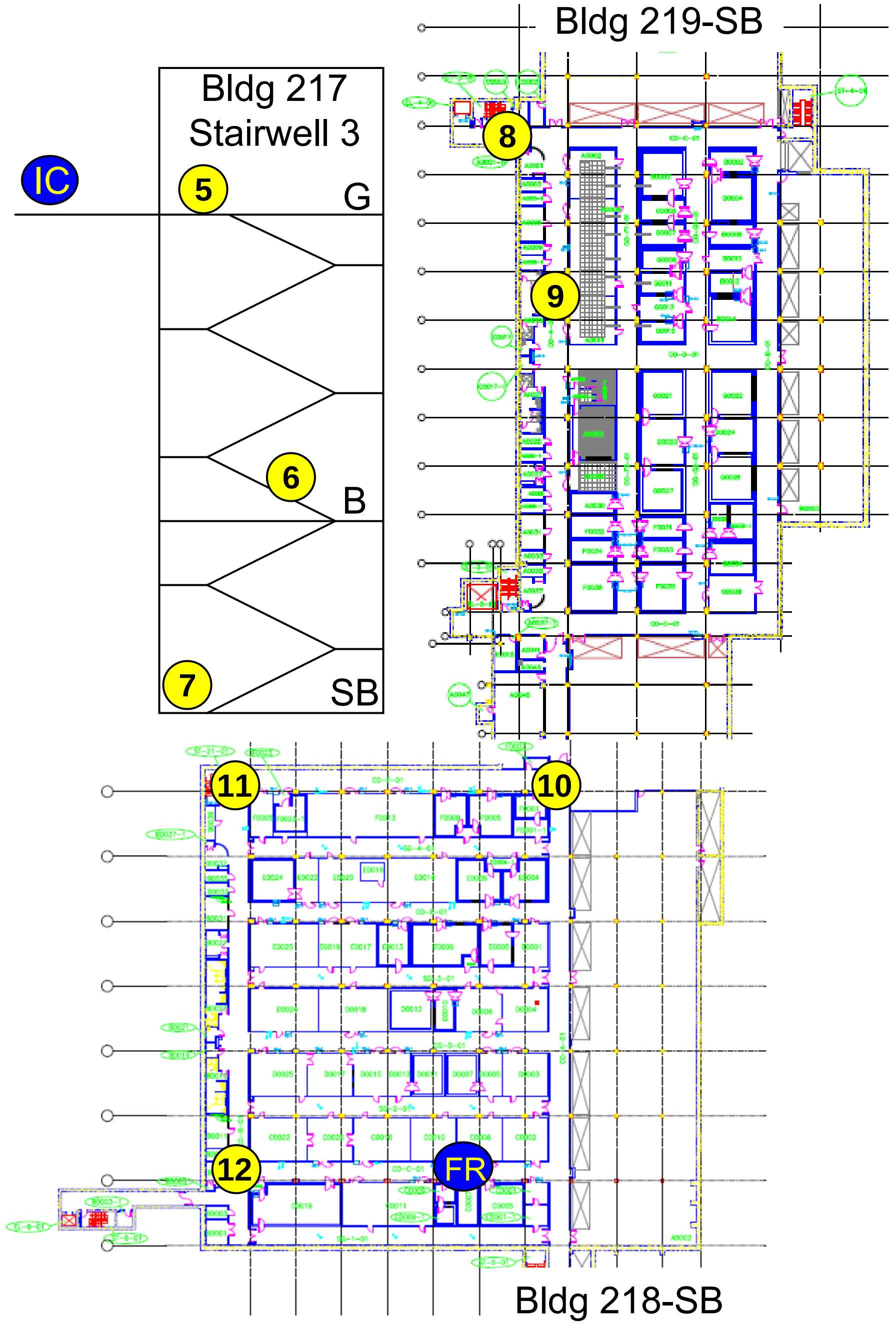


During Deployment: Round-Trip Time



File Transfer

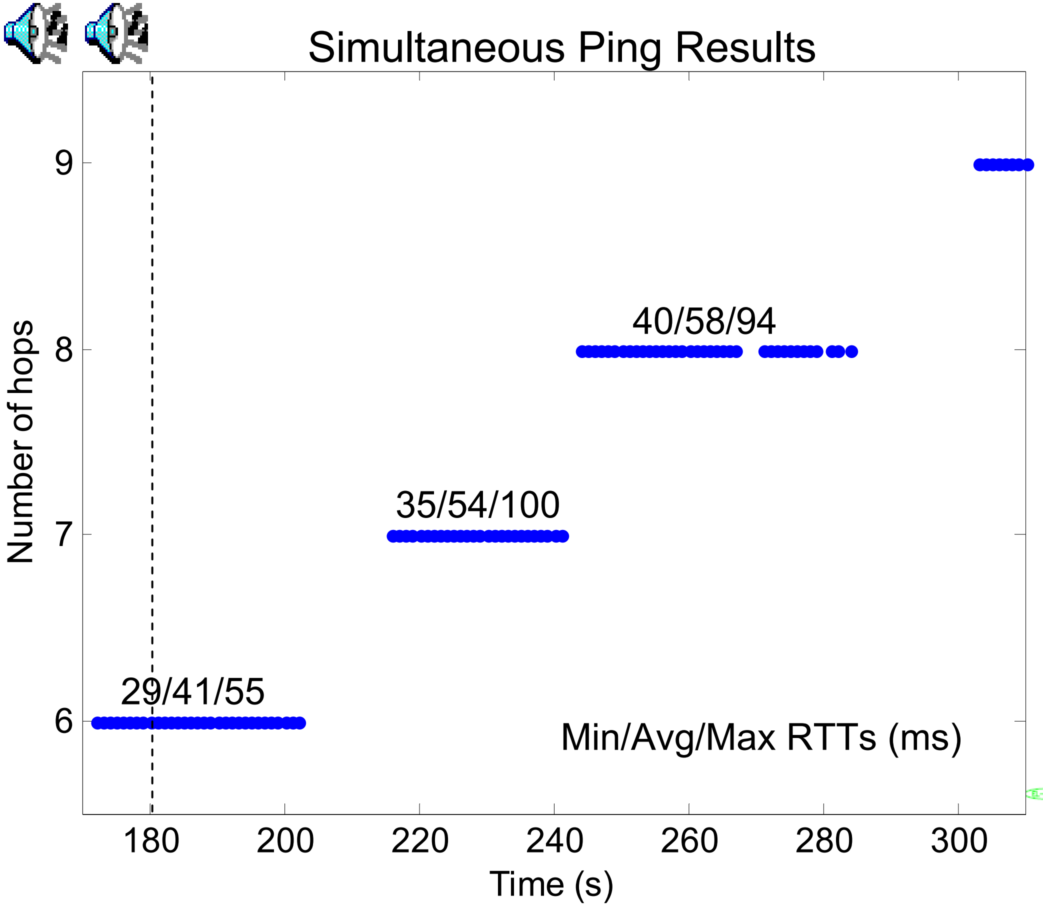
- 9-hop route
- 10 MB file
- Transmission time: 8 min 3 s
  - Average throughput: 166 kbps
  - Peak throughput: 232 kbps
- Simultaneous ping:
  - Average RTT: 173 ms
  - Packet loss rate: 36%

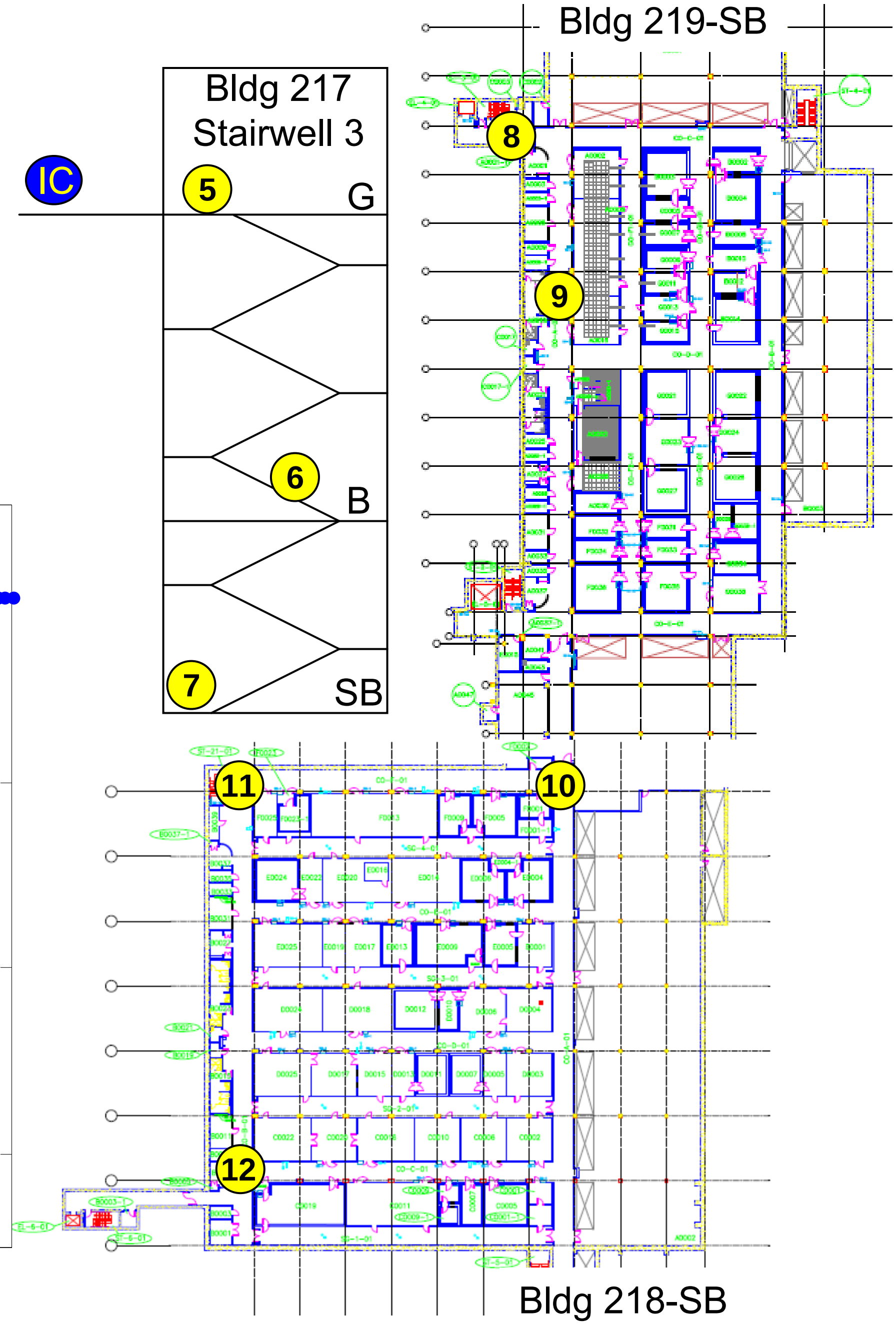


Audio

- Reading of Gettysburg Address
- Linphone VoIP connection with 16 kHz Speex codec at 28 kbps

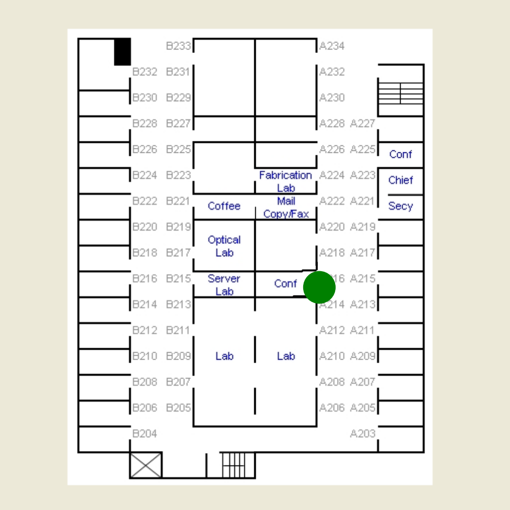
orig recv





Ongoing and Future Work

- Systematic study of link quality measurement techniques
- Routing protocol improvements
  - Smoother route transitions
  - Incorporate new link quality metrics
- Feasibility of image/video over deployed multihop network
- Integration of Inertial Navigation Unit
  - To provide estimate of user's location between RFID tags
- Network simulation of cognitive radio breadcrumbs



Publications

- "Interference avoidance in rapidly deployed wireless ad hoc incident area networks," M. T. Refaei, M. R. Souryal, and N. Moayeri, in *Proc. 2nd IEEE Workshop on Mission Critical Networking (MCN)*, April 2008.
- "Real-time deployment of multihop relays for range extension," M. R. Souryal, J. Geissbuehler, L. E. Miller, and N. Moayeri, in *Proc. ACM MobiSys*, June 2007.
- "Link assessment in an indoor 802.11 network," M. R. Souryal, L. Klein-Berndt, L. E. Miller, and N. Moayeri, in *Proc. IEEE WCNC*, April 2006.
- "Measuring indoor mobile wireless link quality," A. Wapf and M. R. Souryal, submitted to *IEEE Globecom 2008.*

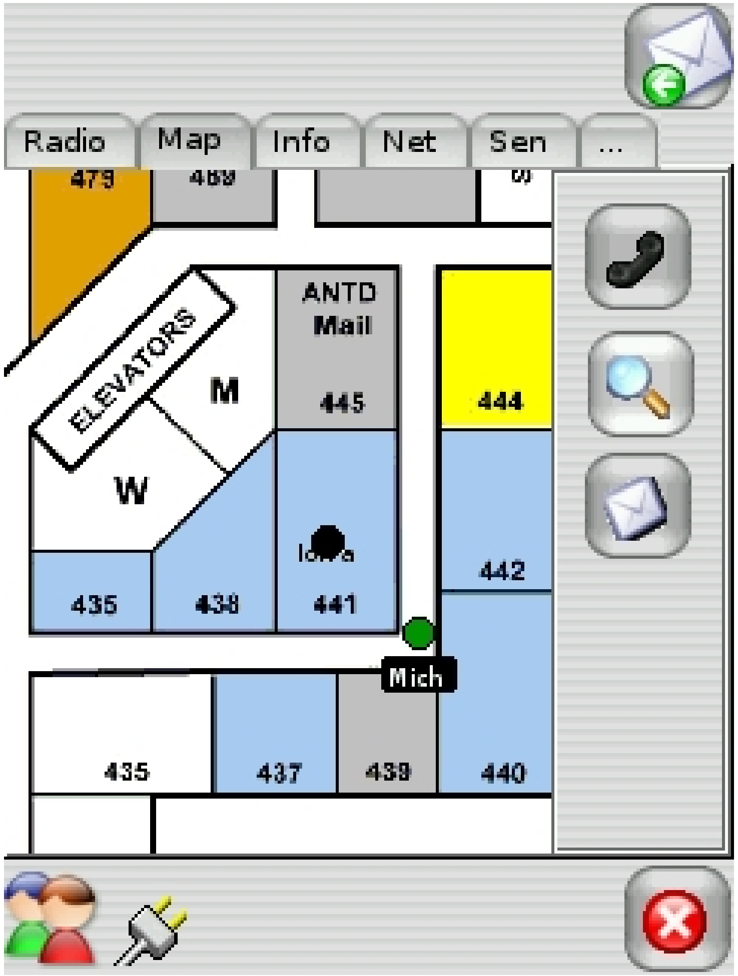
An Overview of Indoor Localization Research at NIST

Program Scope

- Performance evaluation of various ranging, direction estimation, and localization techniques through simulations and prototyping
- Evaluation of COTS localization products
- Participation in IEEE & NFPA standardization activities
- Basic research and development of new localization techniques

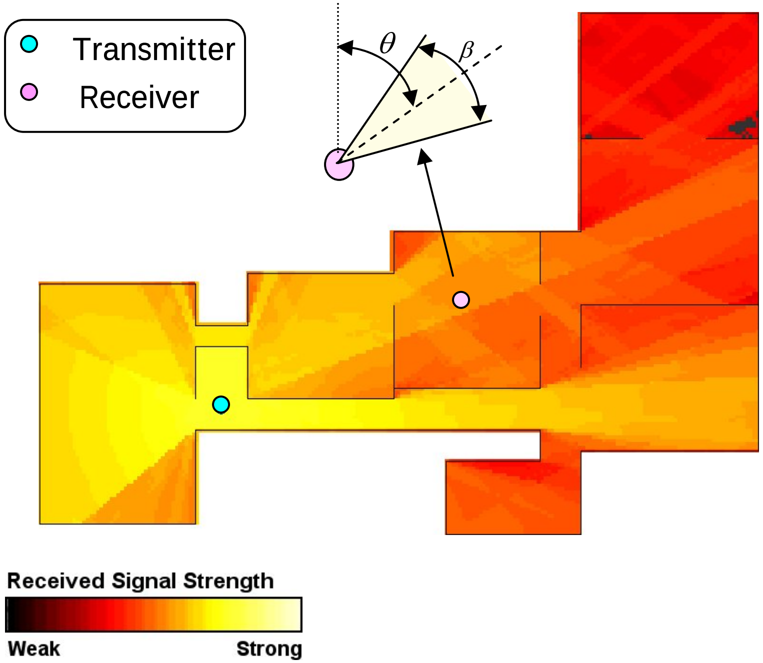
NIST Location System

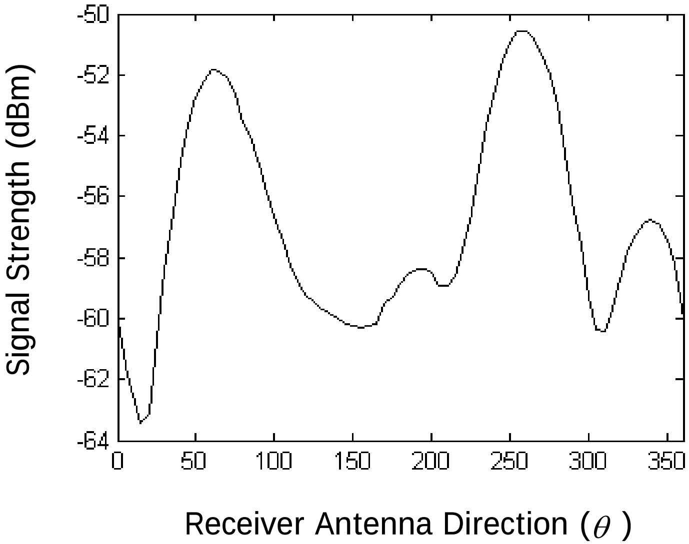
- Developed in 2003.
- Works based on Received Signal Strength (RSS) measurements and IEEE 802.11b technology.
- Locates mobile nodes within 2 meters in 80% of queries.
- Software available for download at: www.antd.nist.gov/wctg/NISTlocation/locationdemo.htm



Extension to Use of Spatial Spectrum

Given a directional antenna, spatial spectrum is basically a two-dimensional graph of the received power versus azimuth of main lobe. Each point on this graph indicates the received signal strength when the main lobe of the antenna is directed toward the corresponding azimuth.





Conjecture: Spatial Spectrum, as measured by a receiver, is unique per layout and transmitter location.

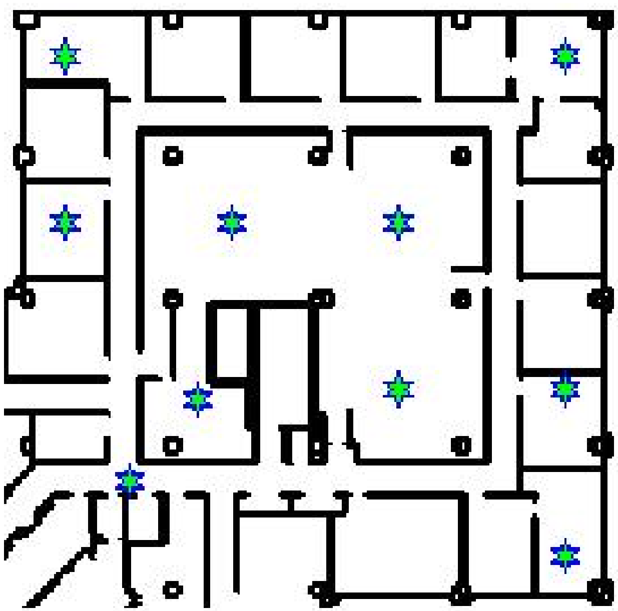
Performance Results

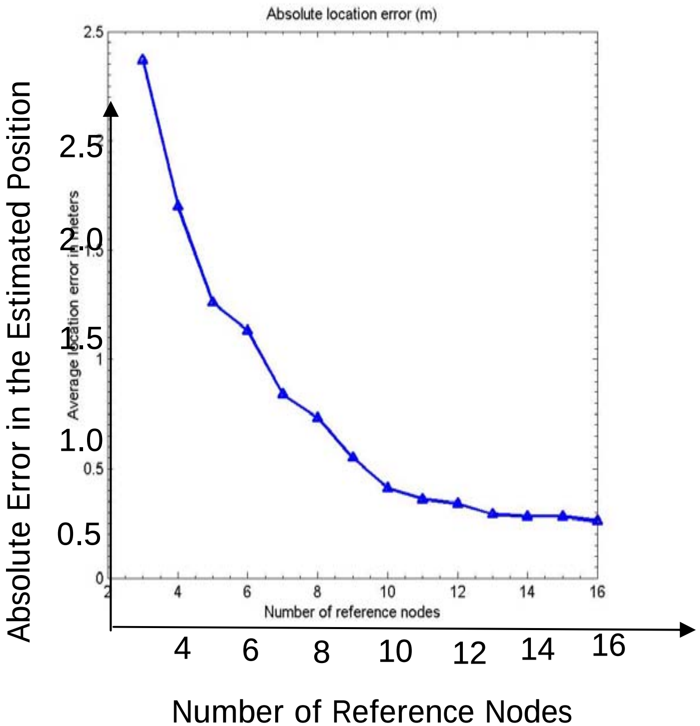
	Radio Map Res: 1x1			Radio Map Res: 2x2			Radio Map Res: 3x3		
	AP=1	AP=2	AP=3	AP=1	AP=2	AP=3	AP=1	AP=2	AP=3
SS – L1	0.83	0.82	0.82	3.1	2.12	2.12	5.07	4.58	2.9
SS – L2	1.03	0.86	1.06	3.2	2.46	2.34	5.05	4.11	2.77
SS – EMD	1.05	1.04	1.02	3.22	2.28	2.25	5.95	4.49	3.07
SS – PPD	1.90	1.50	1.45	4.97	4.10	3.31	6.88	6.03	4.41
SS – HD	2.30	1.59	1.55	5.12	3.11	3.08	7.94	4.52	3.68
SS – KL	2.64	1.35	1.34	5.88	4.28	3.13	7.56	5.52	4.25
RSS – L2	15.78	4.37	2.5	16.04	5.54	4.32	16.37	6.66	5.53

Average position error in meters (array size:8, step-size:5 deg)

Localization Using Relative Signal Strength

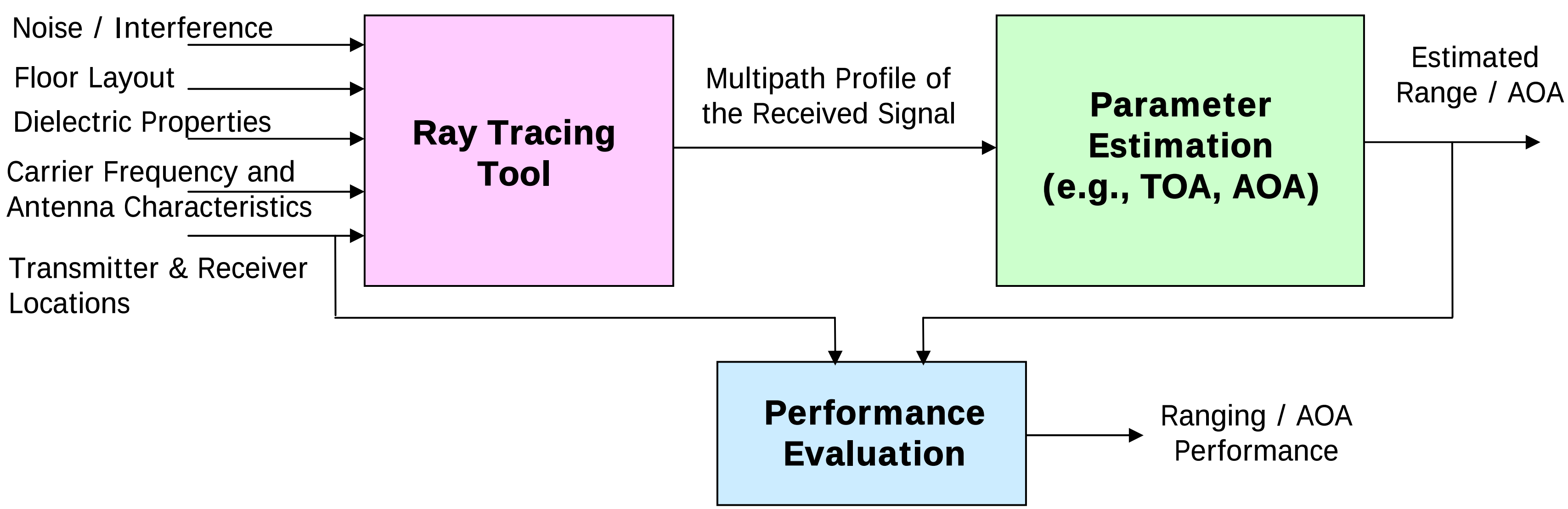
Relative ordering of the received signal strengths from several sensors located inside a building can be used to identify the location of a mobile. This approach potentially provides better performance with imperfect layout information or noisy signal strength measurements.





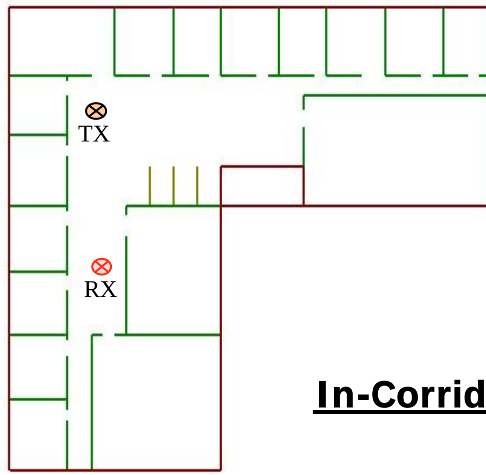
Simulation Testbed of an RF-Based Indoor Localization Systems Using a Ray-Tracing Tool

Given a specific building layout and a transmitter location, a ray-tracing tool predicts the multipath profile of the channel at any given point. A simulation testbed as shown below is used to evaluate the performance of different ranging/AOA algorithms that are used in a localization process.

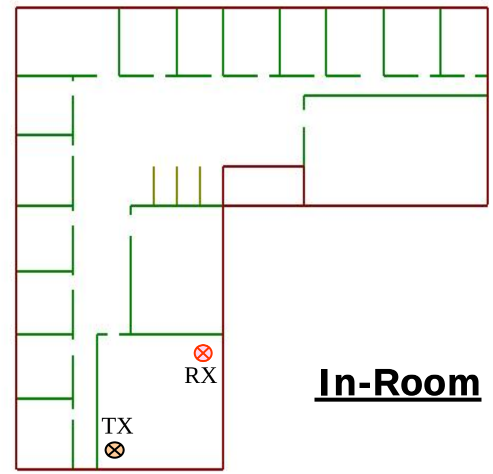


Test Scenarios

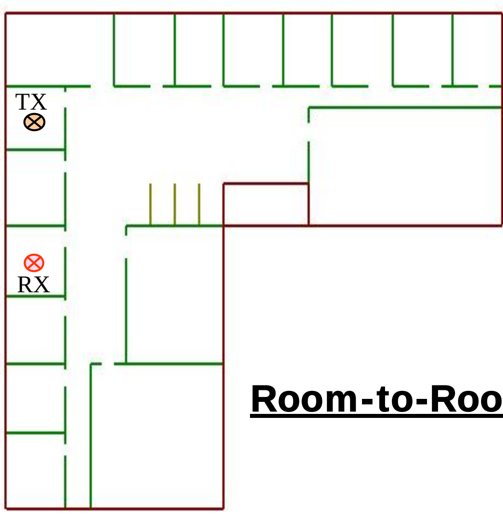
Multiple Test scenarios have been chosen to represent various canonical propagation conditions that normally occur in indoor environments.



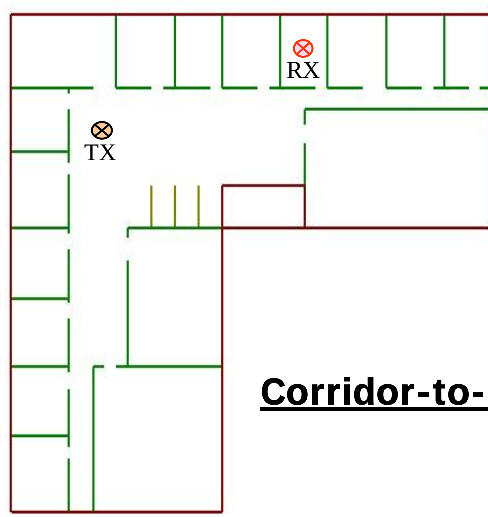
In-Corridor



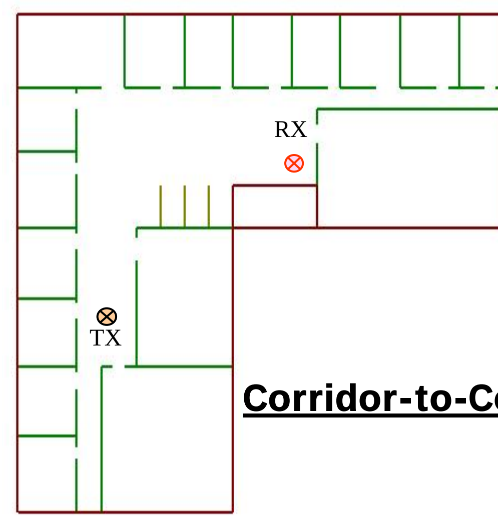
In-Room



Room-to-Room

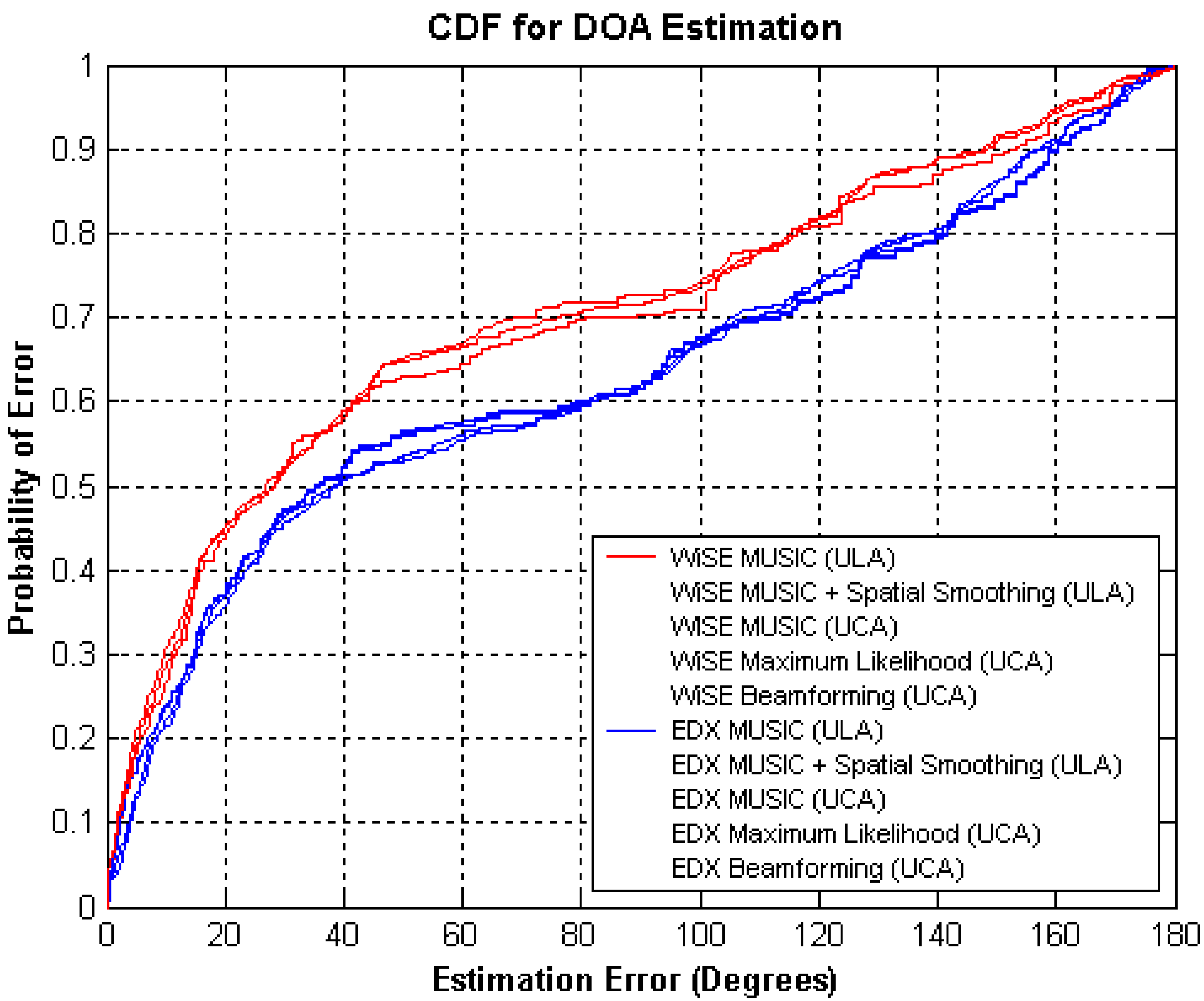


Corridor-to-Room

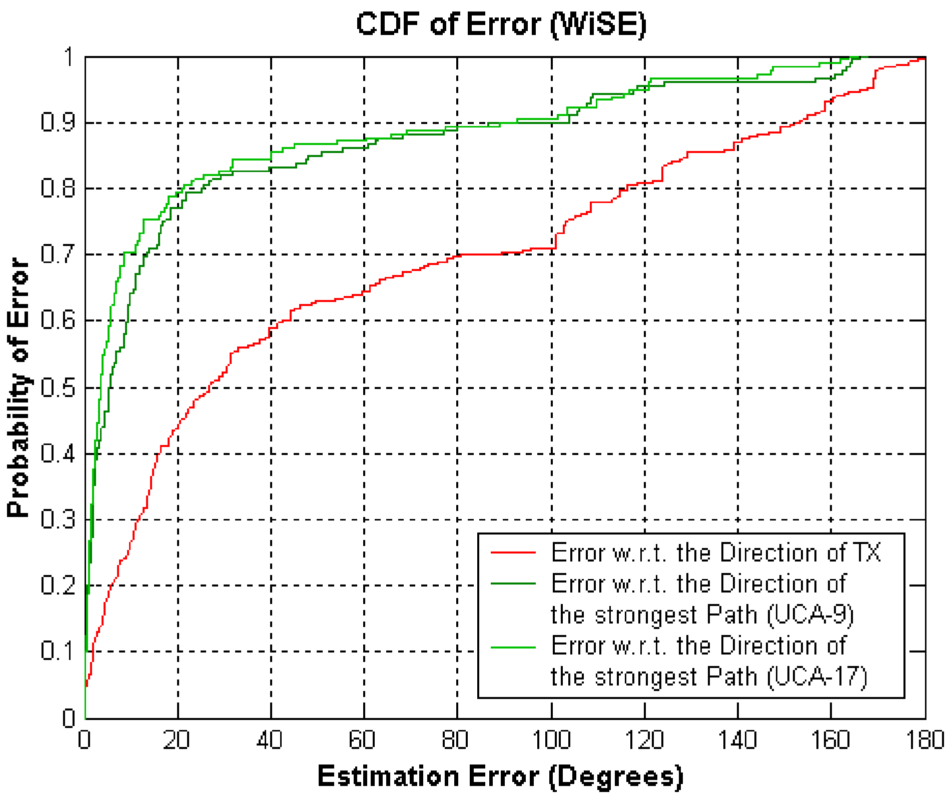


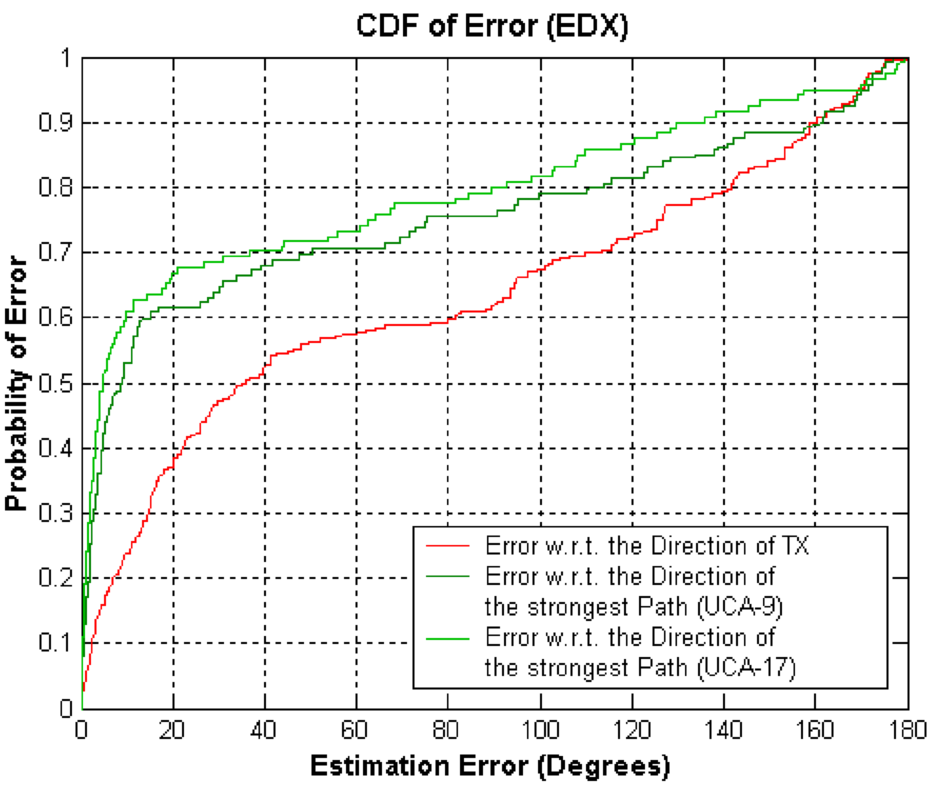
Corridor-to-Corridor

Overall Performance

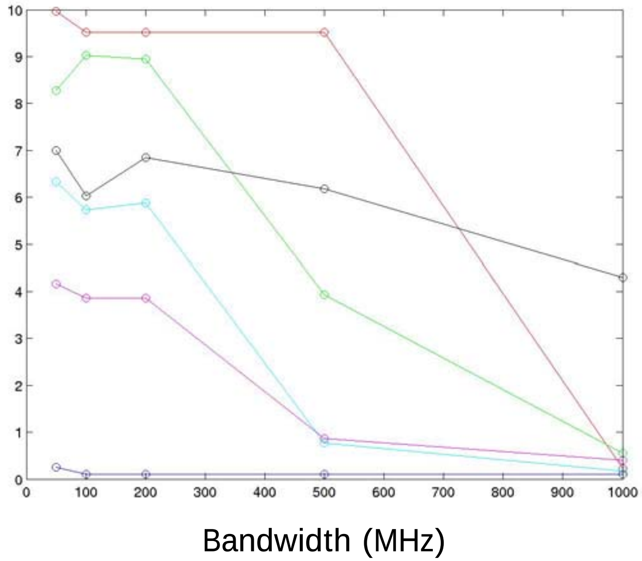


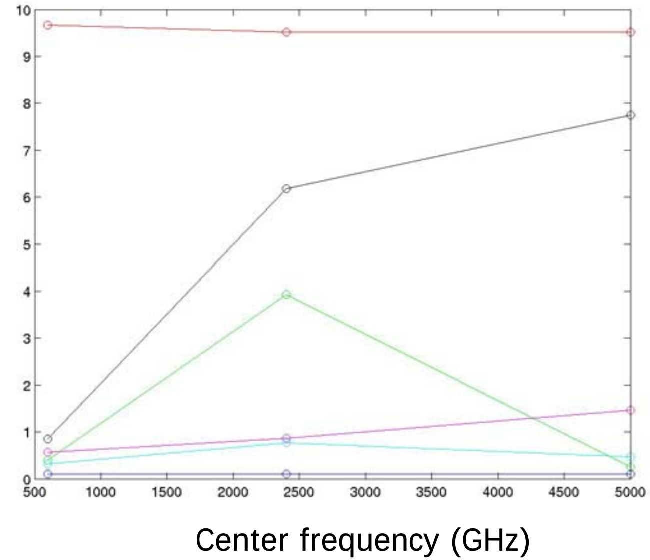
Error w.r.t. the Strongest Ray



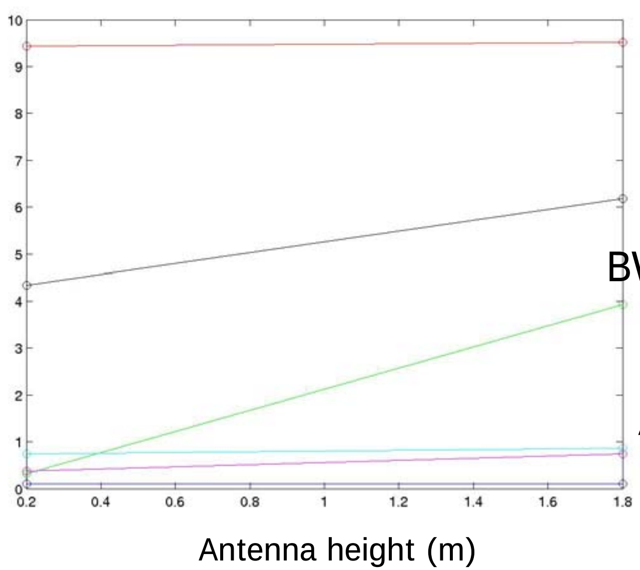


Range Error (m)





- Scenario 1
- Scenario 2
- Scenario 3
- Scenario 4
- Scenario 5
- Scenario 6



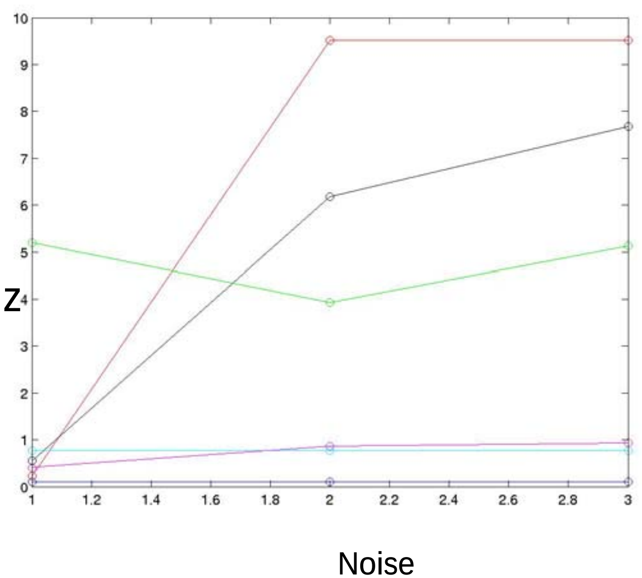
Nominal Parameters:

BW = {0.05, 0.1, 0.2, 0.5, 1} GHz

Fc= {0.6, 2.4, 5} GHz

Noise = {No, Moderate, High}

Antenna height = {0.2, 1.8} m



Can TOA-Based Localization Meet First Responders' Expectations?

Range Error (m)

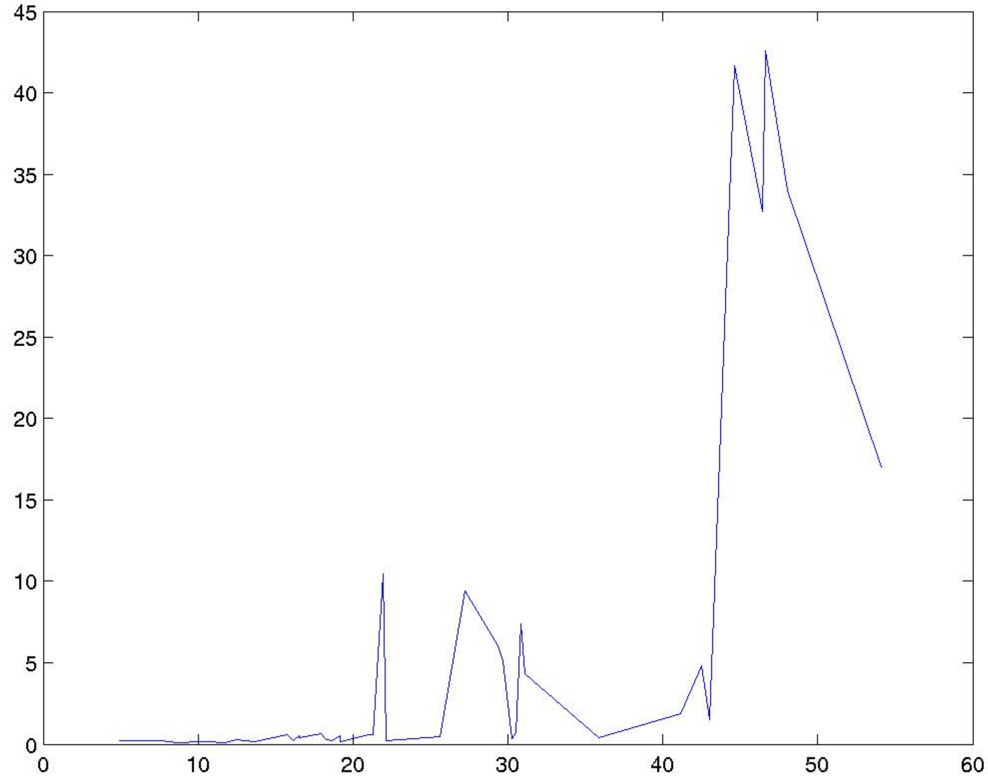
Test Parameters:

BW = {0.05, 0.1, 0.2, 0.5, 1} GHz

Fc= {0.6, 2.4, 5} GHz

Noise = {No, Moderate, High}

Antenna height = {0.2, 1.8} m



TX-RX Distance (m)

Evaluation of COTS Products

- Evaluated three UWB ranging/localization systems:
  - Multispectral Solutions, Inc. (MSSI) Pal650 System
  - MSSI ranger designed and developed for CERDEC
  - Time Domain, Inc. PulseON P210 Radio System
- Evaluations were done in four NIST buildings using many deployment scenarios.

Overview of UWB Ranging

- UWB cited as most promising technology for precision location systems (cms error)
- A standardization effort is completed through the IEEE 802.15.4a Task Group incorporating ranging into their UWB radio
- Several companies (MSSI, Time Domain, Aether Wire & Location) have delivered products with precision location and ranging capabilities for indoors
- The scope of our work is to push UWB ranging to the limit and conduct an extensive measurement campaign to characterize its performance
  - 1 W power emission
  - 6 GHz bandwidth
  - 150 dB dynamic range
- Open questions: How does UWB ranging perform . . .

  . . . as a function of wall material?

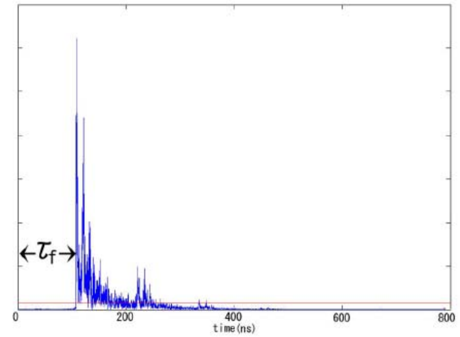
  . . . at long ranges up to 45 meters?

  . . . as a function of bandwidth?

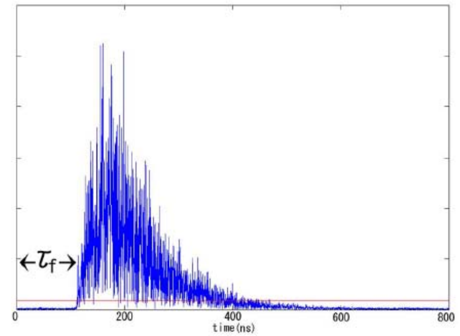
  . . . as a function of center frequency?

UWB Ranging Measurement System

- Time-domain measurements:
  - Tx emits a UWB pulse
  - Rx measures received pulses which together form the channel impulse response
  - Thresholding determines first arrival of the direct path



(a) Line-of-sight conditions



(b) Non line-of-sight conditions

- Frequency-domain measurements:
  - Tx emits a series of synchronized tones
  - Rx measures the amplitude and phase shift of each which together form the channel frequency response impulse response recovered through the IDFT

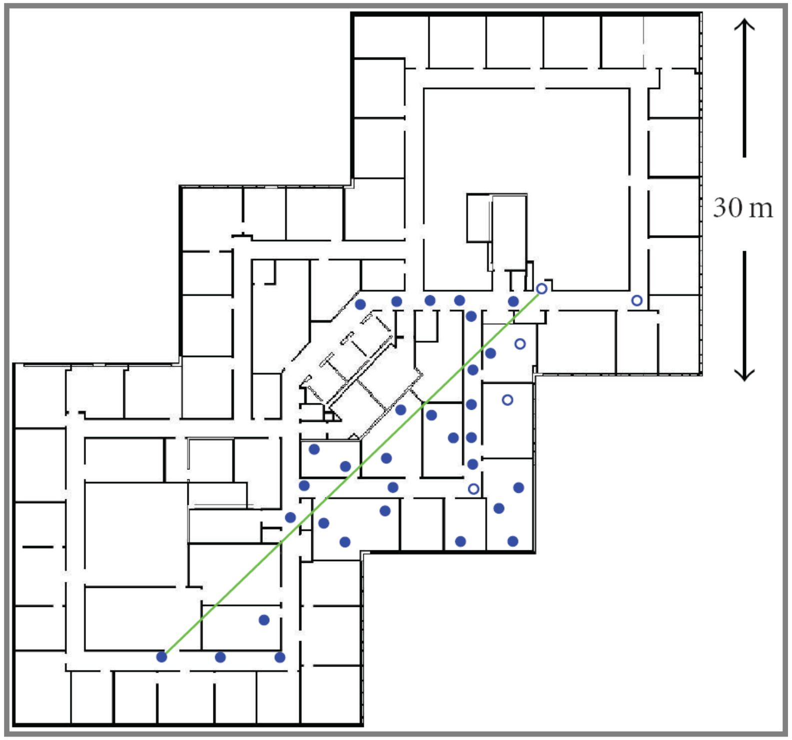
Gives flexibility to vary bandwidth and center frequency of UWB pulse

Measurement Campaign

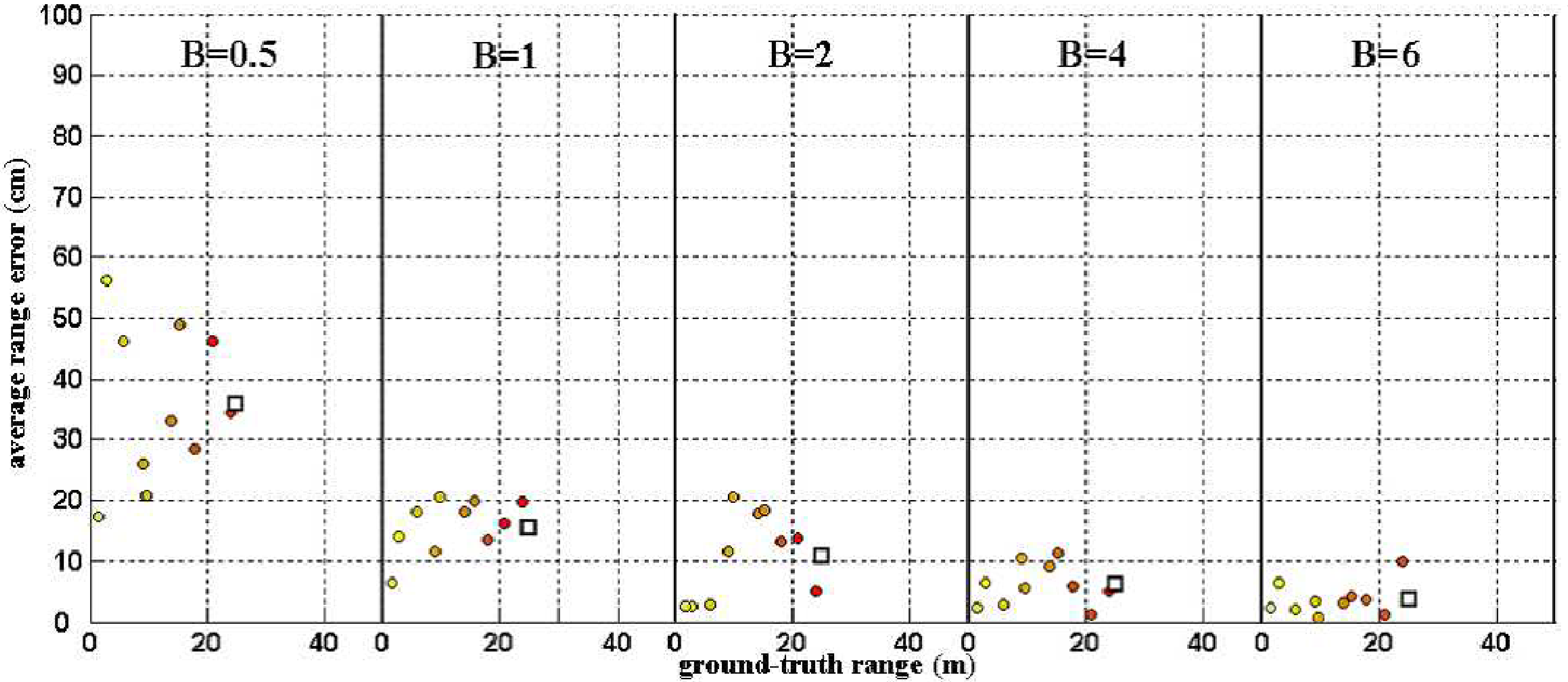
Building	Wall material	LOS range (10)	NLOS range (40)
NIST North	Sheet rock/ aluminum studs	1.2–24.3 m	1.7–40.7 m max wall no.: 12
Child Care	Plaster/ wooden studs	2.0–15.7 m	4.7–33.0 m max wall no.: 7
Sound	Cinder block	3.4–45.0 m	5.9–40.8 m max wall no.: 9
Plant	Steel	2.9–43.7 m	4.9–44.0 m max wall no.: 8

- Testing in four buildings with uniform interior walls allows gauging performance according to construction material.
- 50 experiments conducted in each building on our NIST campus.

- Building layout of *NIST North* Building*:*
  - Solid points indicate the varying positions of the TX
  - Hollow points indicate the varying positions of the RX
  - In the test with the longest range, the signal must traverse 12 walls in the direct path

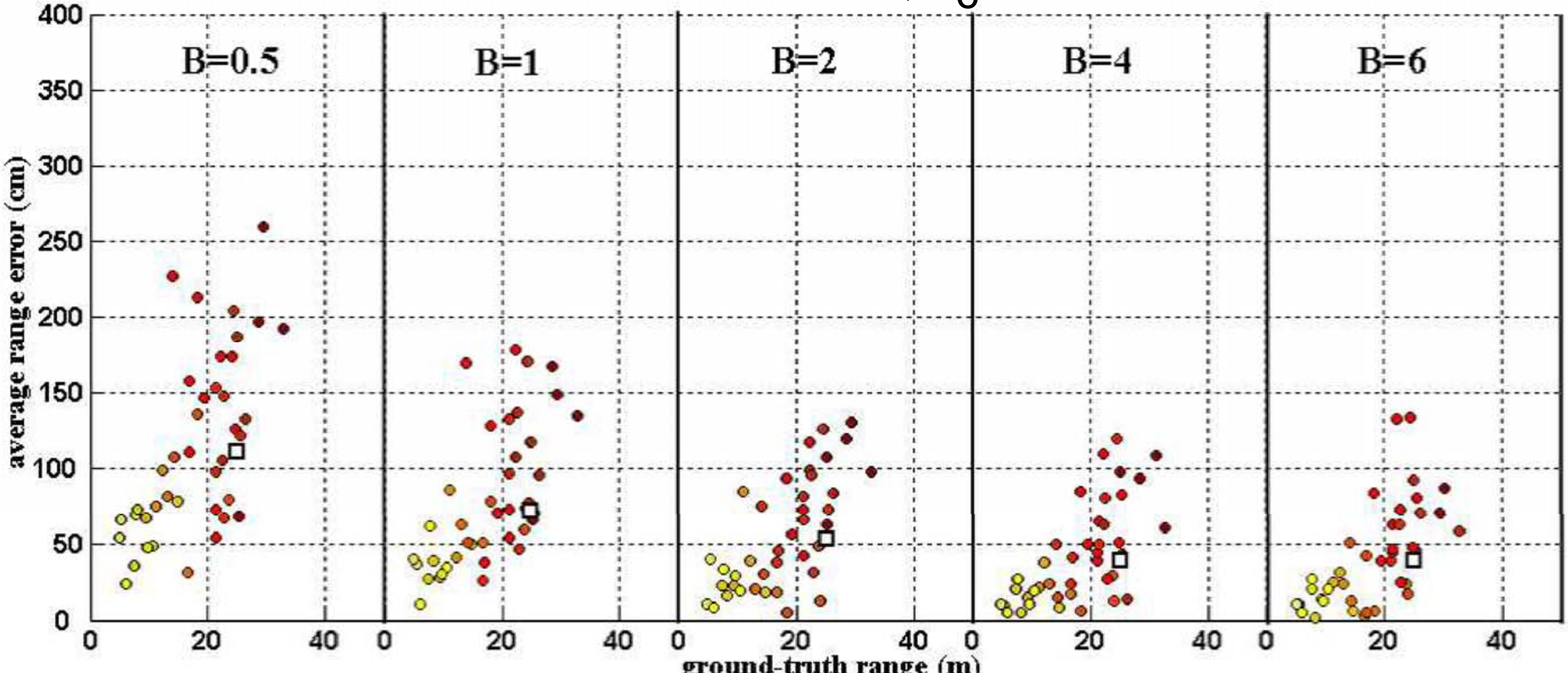


Results: Line-of-Sight
NIST North, f_c= 5 GHz



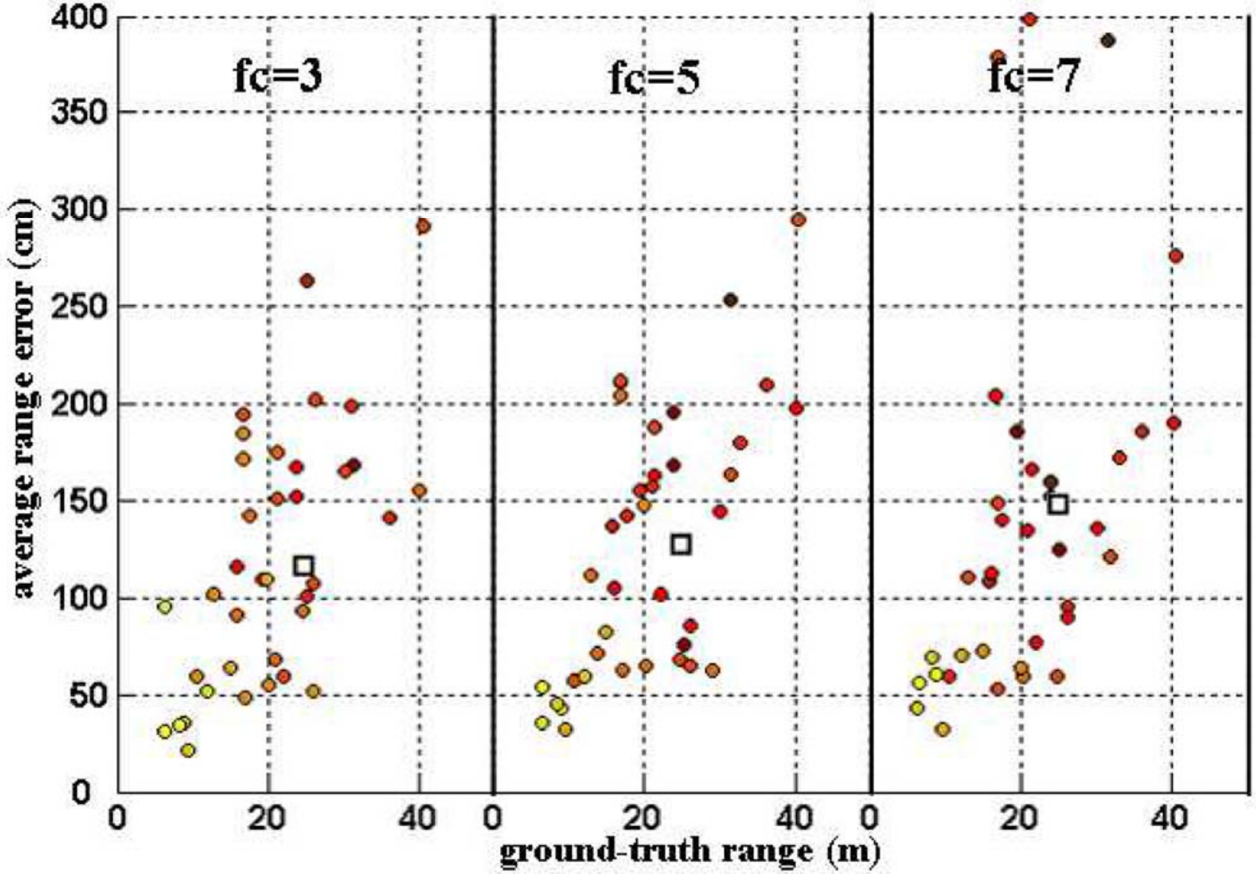
- There is no apparent correlation between range error and ground-truth range
- The average range error decreases with increasing bandwidth
- The average range error decreases at a diminishing rate
- The average range error at B = 6 GHz is 6 cm throughout all four buildings

Results: Non line-of-sight
Child Care, f_c = 5 GHz



- The range error increases with increasing ground-truth range
- The signal propagates through walls at a speed slower than light, and so introduces error in the range estimate
- The average range error decreases with increasing bandwidth, but at a diminishing rate
- The average range error at 6 GHz is:
  - 24 cm in *NIST North*
  - 38 cm in *Child Care*
  - 84 cm in *Sound*
  - 350 cm in *Plant*

Results: Non line-of sight
Sound, B = 1 GHz



- The effects of center frequency are more pronounced in cinder block than other materials tested
- The average range error increases 30 cm from f_c=3 GHz to f_c=7GHz (25%)
- Similar increase in average range error at B = 2 GHz and B = 4 GHz in cinderblock
- Increases of about 5 cm in sheet rock and 10 cm in plaster

Conclusions

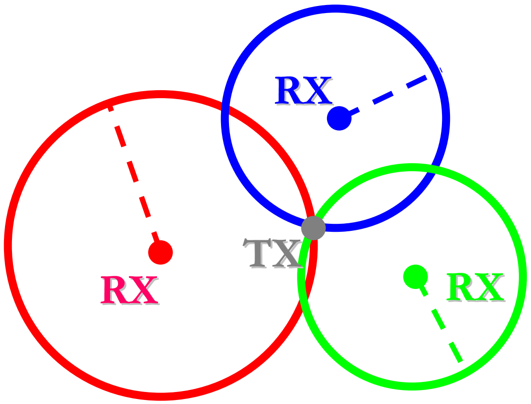
	building	B = 0.5	B = 1			B = 2			B = 4			B = 6
		$f_c = 5$	$f_c = 3$	$f_c = 5$	$f_c = 7$	$f_c = 3$	$f_c = 5$	$f_c = 7$	$f_c = 4$	$f_c = 5$	$f_c = 6$	$f_c = 5$
LOS	*NIST North*	36, 13 17, 56 42, 1.6	15, 5 6, 25 42, 1.3	15, 5 6, 21 42, 1.5	25, 13 8, 47 42, 1.6	6, 6 1, 20 40, 1.4	11, 7 2, 21 43, 1.5	14, 9 1, 27 43, 1.6	6, 4 1, 12 41, 1.4	6, 3 1, 11 44, 1.3	6, 3 2, 12 43, 1.5	4, 3 1, 10 42, 1.4
	Child Care	23, 14 9, 47 43, 2.2	14, 8 6, 24 40, 2.2	12, 6 6, 23 44, 2.1	15, 10 6, 35 44, 2.1	10, 5 5, 20 38, 2.3	10, 5 4, 23 45, 1.8	11, 7 5, 25 46, 2.0	8, 6 2, 18 41, 2.1	8, 6 2, 18 45, 1.8	9, 7 1, 18 45, 1.9	7, 6 0, 16 42, 2.1
	Sound	43, 16 23, 64 34, 2.4	23, 10 9, 38 37, 1.8	31, 12 9, 46 33, 2.5	34, 12 22, 57 28, 2.8	12, 7 0, 23 34, 2.0	19, 9 8, 36 34, 2.4	22, 11 8, 44 29, 2.7	7, 5 1, 14 34, 2.1	10, 6 4, 22 35, 2.2	7, 4 1, 15 31, 2.6	4, 2 0, 8 32, 2.3
	Plant	62, 20 38, 98 35, 2.0	35, 11 21, 52 36, 1.7	43, 22 19, 83 36, 2.0	40, 15 11, 53 34, 2.2	17, 8 4, 24 34, 1.7	25, 15 5, 53 37, 1.9	22, 12 4, 38 34, 2.1	15, 11 2, 30 35, 1.8	15, 8 2, 24 37, 1.8	12, 8 2, 22 35, 2.0	9, 9 1, 27 35, 1.9
NLOS	*NIST North*	103, 67 16, 355 27, 4.6	59, 29 10, 145 25, 4.5	58, 28 18, 150 27, 4.6	60, 26 17, 160 23, 4.9	38, 21 5, 85 21, 4.7	39, 17 7, 85 27, 4.6	45, 21 11, 130 25, 4.8	27, 11 4, 51 24, 4.6	28, 10 4, 52 27, 4.5	27, 10 4, 50 26, 4.7	24, 9 1, 41 24, 4.6
	Child Care	111, 58 23, 259 17, 6.4	65, 46 10, 173 18, 5.8	71, 39 10, 167 17, 6.4	79, 39 11, 157 13, 6.9	46, 39 4, 157 18, 5.6	52, 34 5, 130 17, 6.4	59, 39 4, 150 14, 7.0	44, 32 3, 132 19, 5.7	39, 31 4, 119 18, 6.3	47, 40 3, 158 16, 6.6	38, 33 2, 133 19, 5.8
	Sound	171, 88 34, 363 29, 5.2	116, 62 21, 292 28, 4.8	127, 70 32, 295 30, 5.1	147, 97 32, 398 30, 5.3	89, 59 17, 306 26, 4.8	94, 70 20, 325 30, 5.1	117, 78 19, 427 33, 5.2	78, 65 7, 309 28, 4.9	86, 84 8, 244 31, 5.0	103, 68 7, 236 31, 5.1	84, 82 6, 157 29, 4.9
	Plant	537, 331 28, 1170 38, 3.2	490, 350 32, 1149 39, 2.8	483, 345 23, 1110 38, 3.2	522, 347 24, 1161 38, 3.3	444, 326 39, 1096 37, 2.8	466, 342 37, 1125 39, 3.2	531, 371 38, 1187 39, 3.3	432, 359 43, 1160 38, 2.9	408, 330 41, 1199 40, 3.0	450, 378 43, 1184 39, 3.2	350, 260 44, 948 39, 2.9

LEGEND
μ_e (cm), σ_e (cm) $\min_e$ (cm), $\max_e$ (cm) PL_0, γ

- In LOS conditions, the UWB ranging system has 6 cm average error in all four buildings
- In NLOS conditions, the UWB ranging system has:
  - 1% average error in sheet rock
  - 2% average error in plaster
  - 4% average error in cinder block
  - 10% average error in metal up to 15 m
- The range error is significantly reduced in translating to position error through triangulation

How to Compute Location?

Location from Range:

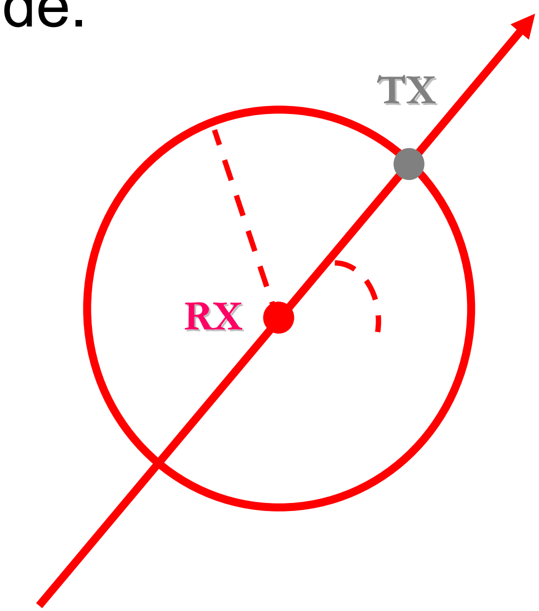


Location from Range and Angle:

- A backbone network with at least three RXs is required to compute two-dimensional location.
- The RXs triangulate the three ranges to the TX to a single point as the intersection of the three circles.

☹ Requires pre-installation of the RXs outside the building and long range to reach the TX inside.

- If a RX could also determine the angle of the TX, then no backbone network would be required!
- The RX could pinpoint the location of the TX <u>relative</u> to the RX as the intersection between a circle and a directed line.
- A firefighter could then find the locations of trapped victims equipped with TX beacons.

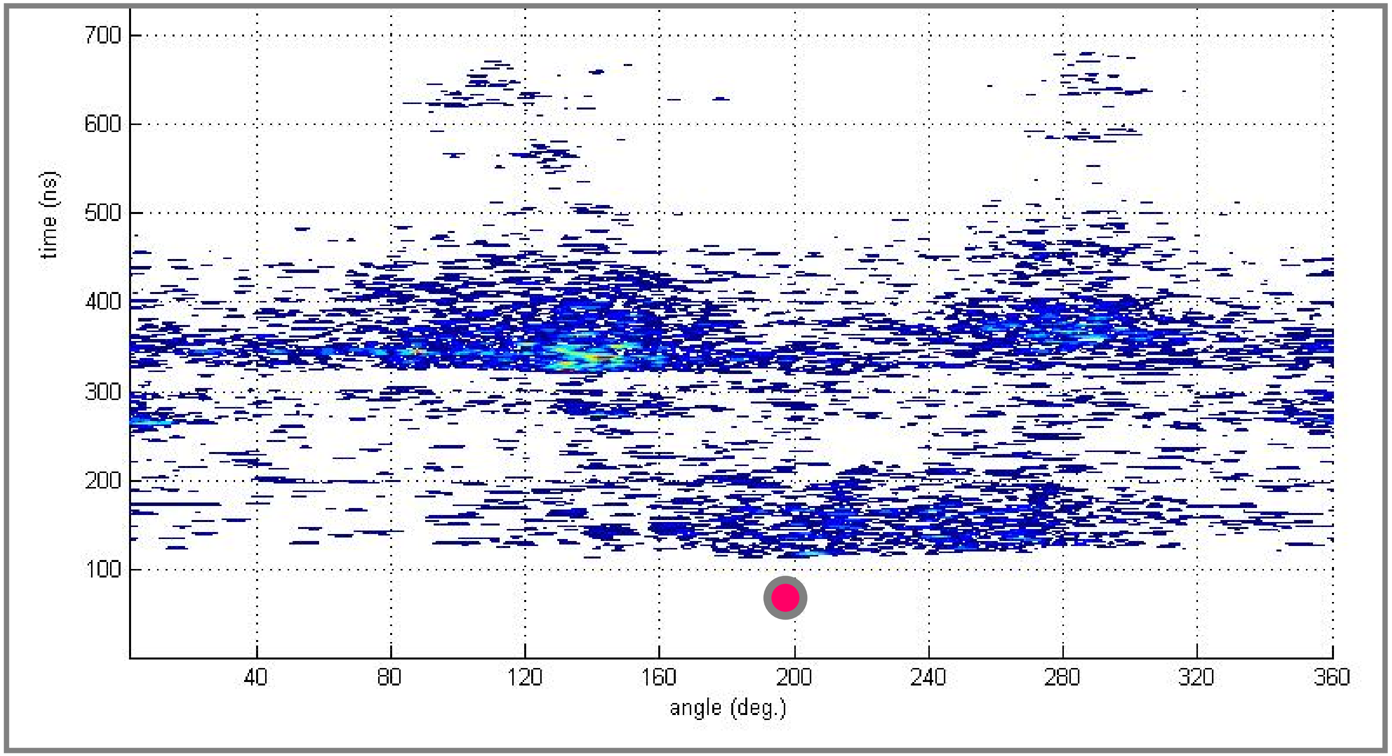


Spatial-Temporal Channel Sounder

- Extended temporal channel sounder to a spatial-temporal channel sounder by mounting the receiver antenna on a two-dimensional positioning table.
- The circular array pattern was realized <u>virtually</u> by tracing the element positions sequentially.

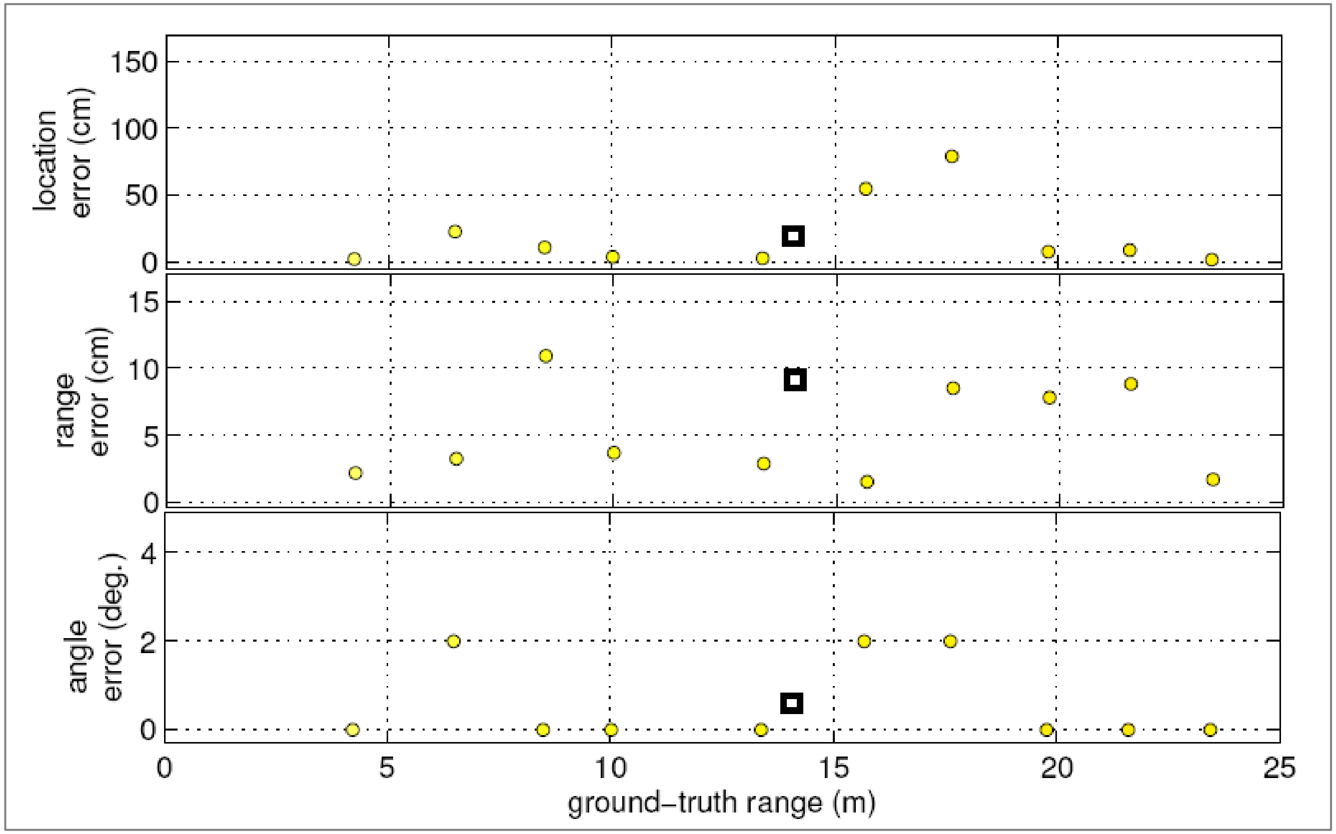
Spatial-Temporal Channel Impulse Response

h(t,θ)



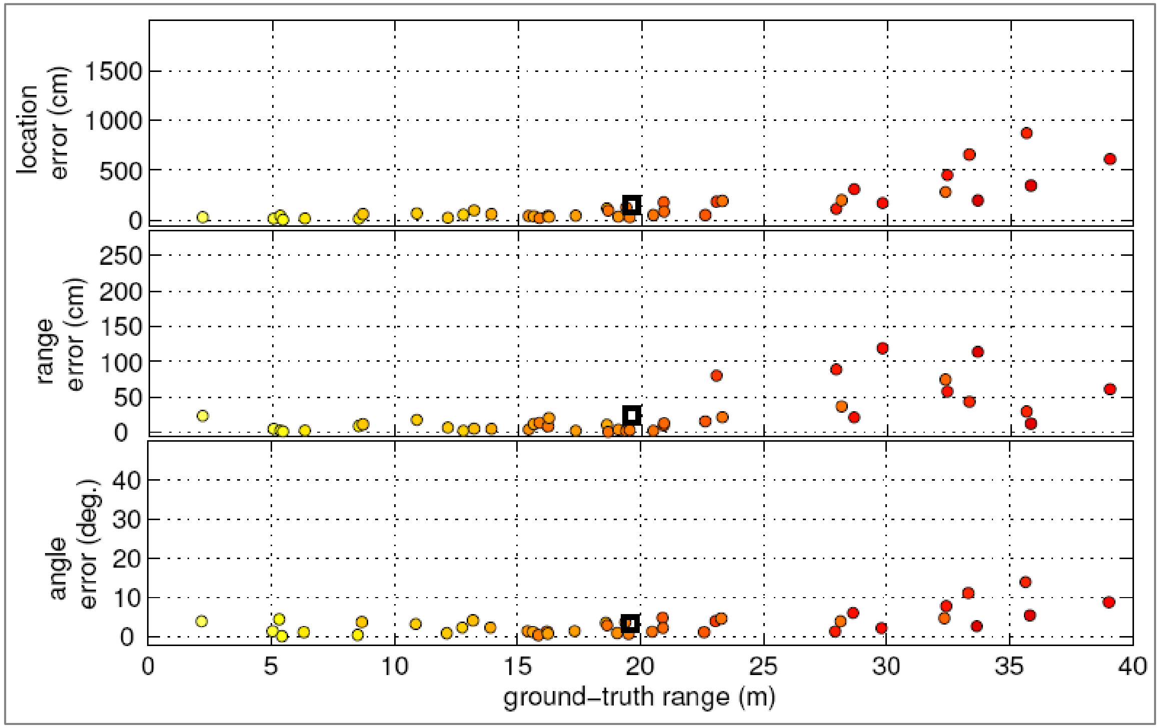
- The frequency sweeps taken at each element of the virtual array can be processed together to generate the spatial-temporal channel impulse response h(t,θ).
- Now the first arrival indexed in time and angle can be extracted from the response, giving both the range and direction of the TX with respect to the RX.

Results: LOS, NIST North, $B = 6$ GHz, $f_c = 5$ GHz



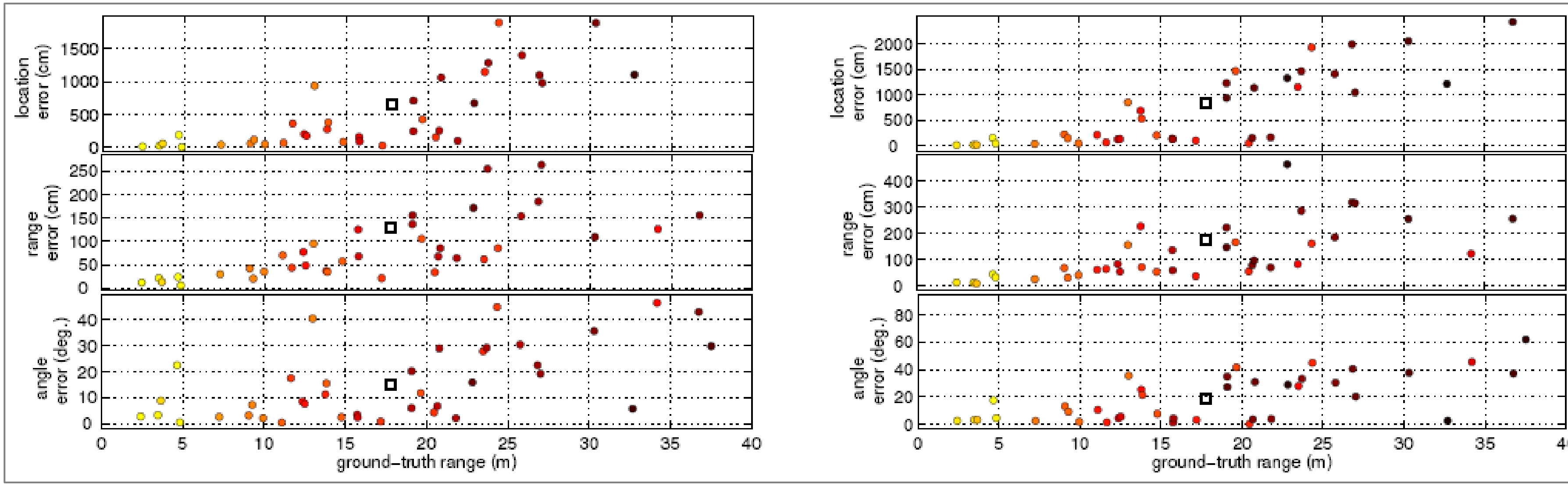
- No apparent correlation between errors and ground-truth range
- Errors decrease with increasing bandwidth, but at diminishing rate
- Throughout all four buildings, average angle error of 1.1°
  range error of 20 cm
  location error of 31 cm

Results: NLOS, NIST North, B = 6 GHz, f_c= 5 GHz



- Errors increase with increasing ground-truth range
- More and more walls between the TX and RX with increasing ground-truth range:
  - Range error: the signal propagates through walls at a speed slower than light, so the estimated range is always greater than the actual range
  - Angle error: the walls deflect the signal off its original angle from the transmitter
- Average location error in *NIST North* is 150 cm, *Child Care* is 159 cm
  Sound is 656 cm, *Plant* is 995 cm

Results: NLOS, Sound, B = 2 GHz



$f_c = 3$ GHz

$f_c = 7$ GHz

- The signal penetrates the walls better at lower frequencies, so the average range error is smaller.
- The angular resolution is higher at larger frequencies, so the average angle error is smaller.
- The two phenomena compensate for each other, so the average location error is the same at lower and higher frequencies.

Results: Compiled Results

	building	B = 6 GHz, f_c = 5 GHz				B = 2 GHz, f_c = 3 GHz				B = 2 GHz, f_c = 7 GHz			
		ϕ_e	d_e	$\mathbf{x_e}$	PL	ϕ_e	d_e	$\mathbf{x_e}$	PL	ϕ_e	d_e	$\mathbf{x_e}$	PL
LOS	*NIST*	0.6, 1	9, 14	19, 26	44.2	1.3, 2.8	12, 16	44, 76	46.7	1.3, 1.3	18, 22	48, 42	42.2
	North	0, 2	2, 11	2, 54	1.6	0, 9	2, 54	2, 247	1.0	0, 4	0, 69	4, 143	2.0
	Child	1.5, 1	20, 35	38, 36	40.6	2.5, 1.2	25, 33	57, 37	39.1	1.5, 1	24, 33	39, 35	39.6
	Care	0.7, 3.1	2, 118	10, 119	2.1	0.8, 4	1, 113	14, 115	2.0	0.7, 3.1	1, 113	10, 114	2.4
	Sound	1.2, 1.3	18, 43	61, 88	43.3	1.7, 1.5	26, 37	67, 61	43.9	1.3, 0.8	23, 43	77, 69	41.9
		0.1, 4.5	1, 139	5, 277	2.9	0.1, 4.3	3, 129	6, 185	1.6	0.3, 2.6	2, 144	5, 166	2.4
	Plant	0.8, 0.8	33, 34	64, 53	41.2	1.8, 3.2	32, 32	71, 76	40.4	0.9, 0.9	30, 27	62, 66	41.0
		0.2, 2.2	3, 90	14, 161	1.7	0.2, 10.6	1, 84	13, 248	1.3	0.2, 3.2	2, 84	16, 234	1.9
NLOS	*NIST*	3.4, 2.9	24, 31	150, 194	29.2	6.7, 7.6	41, 66	284, 381	27.6	5.5, 6.1	39, 53	261, 364	29.4
	North	0.2, 14	1, 119	2, 872	4.0	0.5, 35.4	2, 320	7, 1771	3.8	0.4, 24.7	0, 245	8, 1473	4.2
	Child	5.5, 4.5	45, 36	159, 153	12.6	9.9, 7.6	47, 41	289, 291	12.3	8.4, 7.3	56, 46	247, 224	8.3
	Care	0.2, 18	4, 150	7, 779	6.7	0.1, 28.9	1, 148	24, 1263	6.2	0.3, 29.1	3, 150	7, 743	7.5
	Sound	15.2, 14.1	128, 205	656, 778	33.4	17, 16.1	169, 259	756, 965	30.4	18.8, 16.7	177, 258	830, 979	34.7
		0.4, 46.5	6, 1042	7, 2758	5.1	0.1, 61.9	10, 1322	14, 4496	4.8	0.3, 61.9	9, 1202	17, 4560	5.4
	Plant	23.2, 18.4	419, 357	995, 782	52.7	29.8, 21.2	454, 369	1111, 828	49.5	24.5, 20.2	489, 371	1143, 822	53.8
		1.2, 89.4	11, 1622	32, 2978	1.6	0.8, 85.5	5, 1617	54, 3116	1.5	0.2, 89.6	21, 1602	37, 3211	1.8

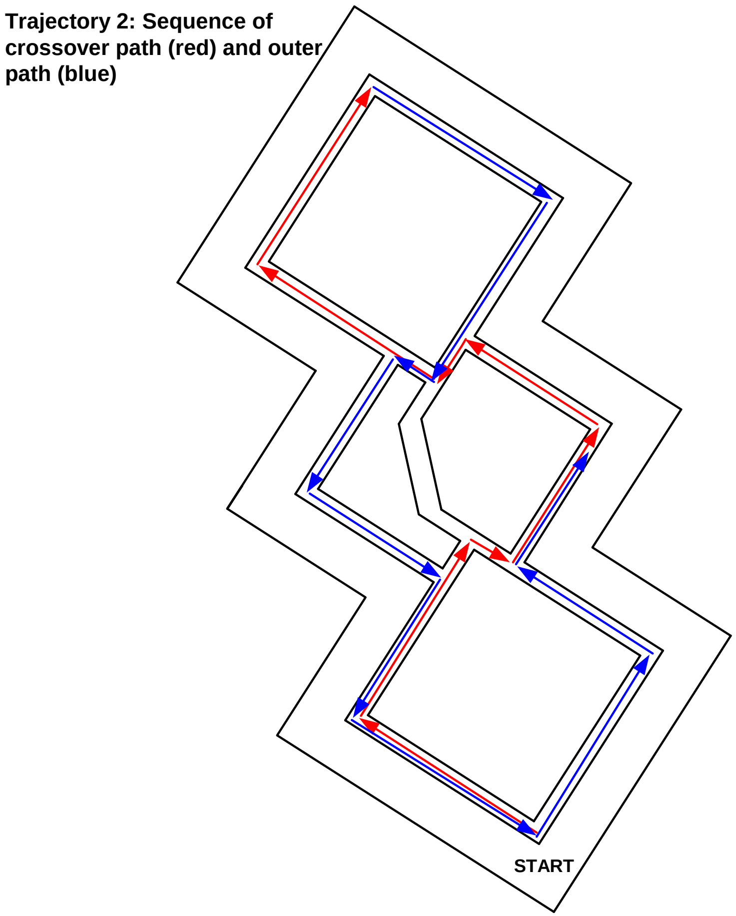
LEGEND			
ϕ_e	d_e	$\mathbf{x_e}$	PL
μ_{ϕ_e} (deg.), σ_{ϕ_e} (deg.) $\min_{\phi_e}$ (deg.), $\max_{\phi_e}$ (deg.)	μ_{d_e} (cm), σ_{d_e} (cm) $\min_{d_e}$ (cm), $\max_{d_e}$ (cm)	$\mu_{\mathbf{x_e}}$ (cm), $\sigma_{\mathbf{x_e}}$ (cm) $\min_{\mathbf{x_e}}$ (cm), $\max_{\mathbf{x_e}}$ (cm)	PL_0 (dB) γ

Localization Using Inertial Navigation Systems & RFID

Indoor first responder localization using inertial and magnetic sensors, RFID

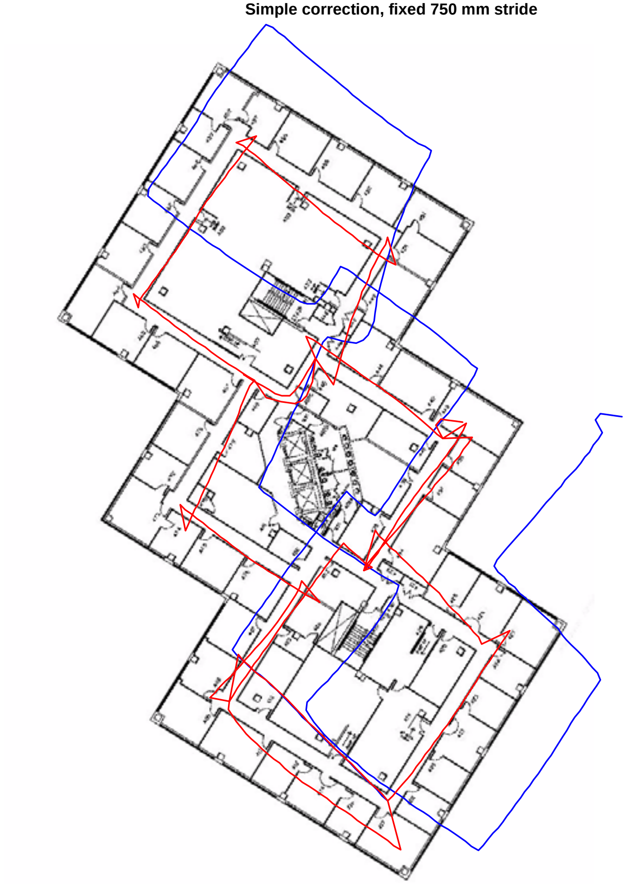
Red: start of trajectory, involving two crossovers.

Blue: continuation of trajectory with long loop.



Cont’d

Indoor first responder localization using inertial and magnetic sensors, RFID



Blue: unassisted DRM with magnetic heading sensor and step counting.

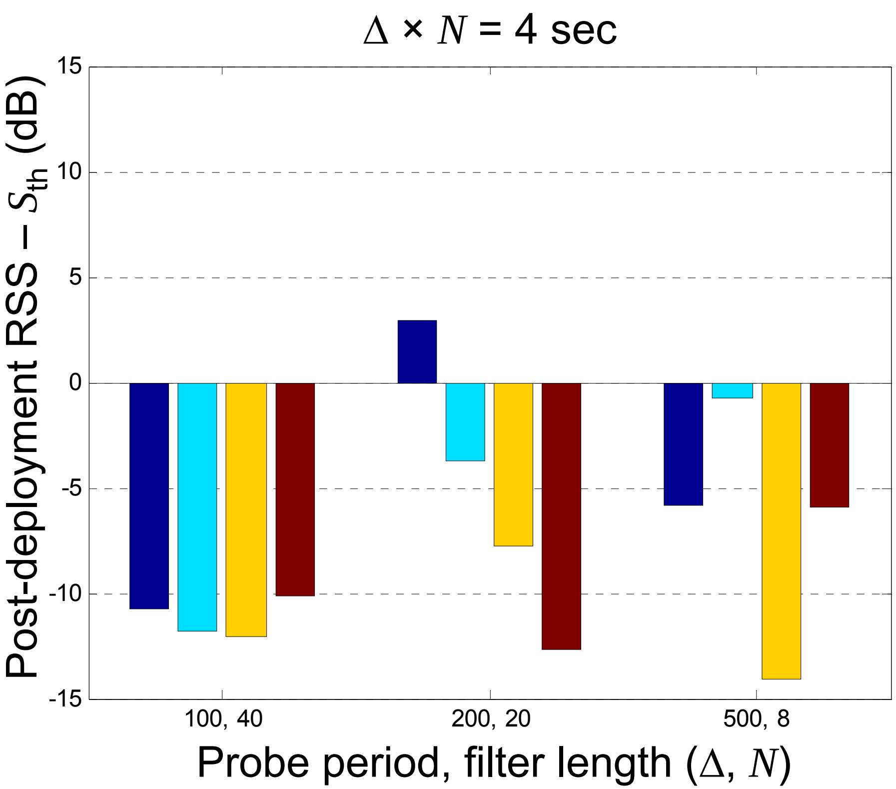
Red: DRM track with simple position correction at RFID “waypoints.”

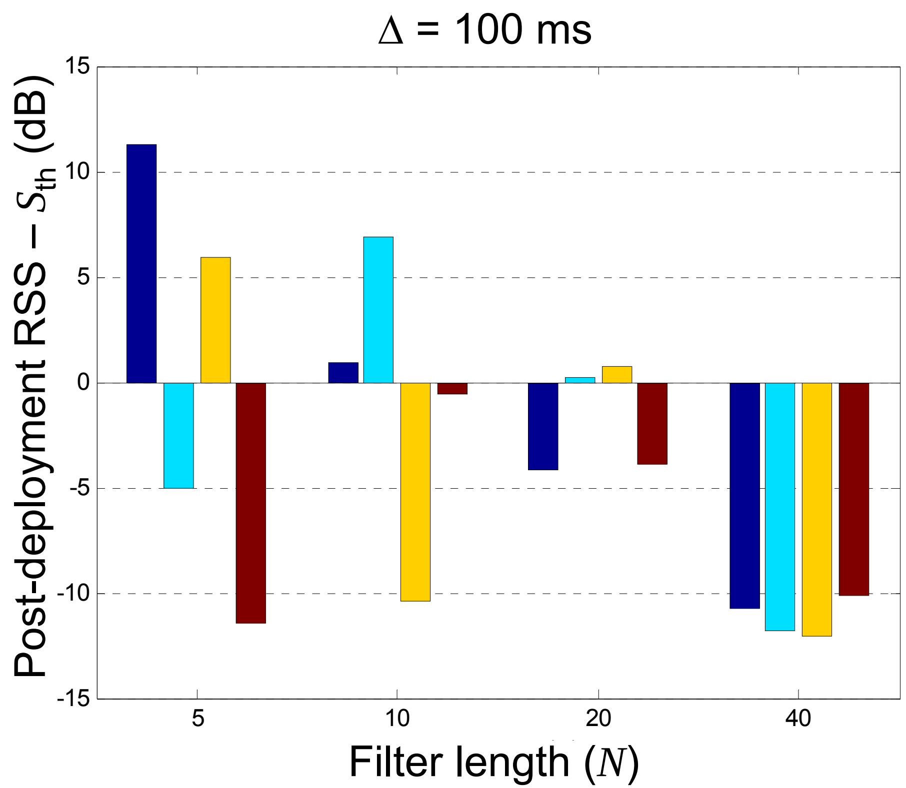
Extra Slides

Deployment Algorithm Tradeoffs

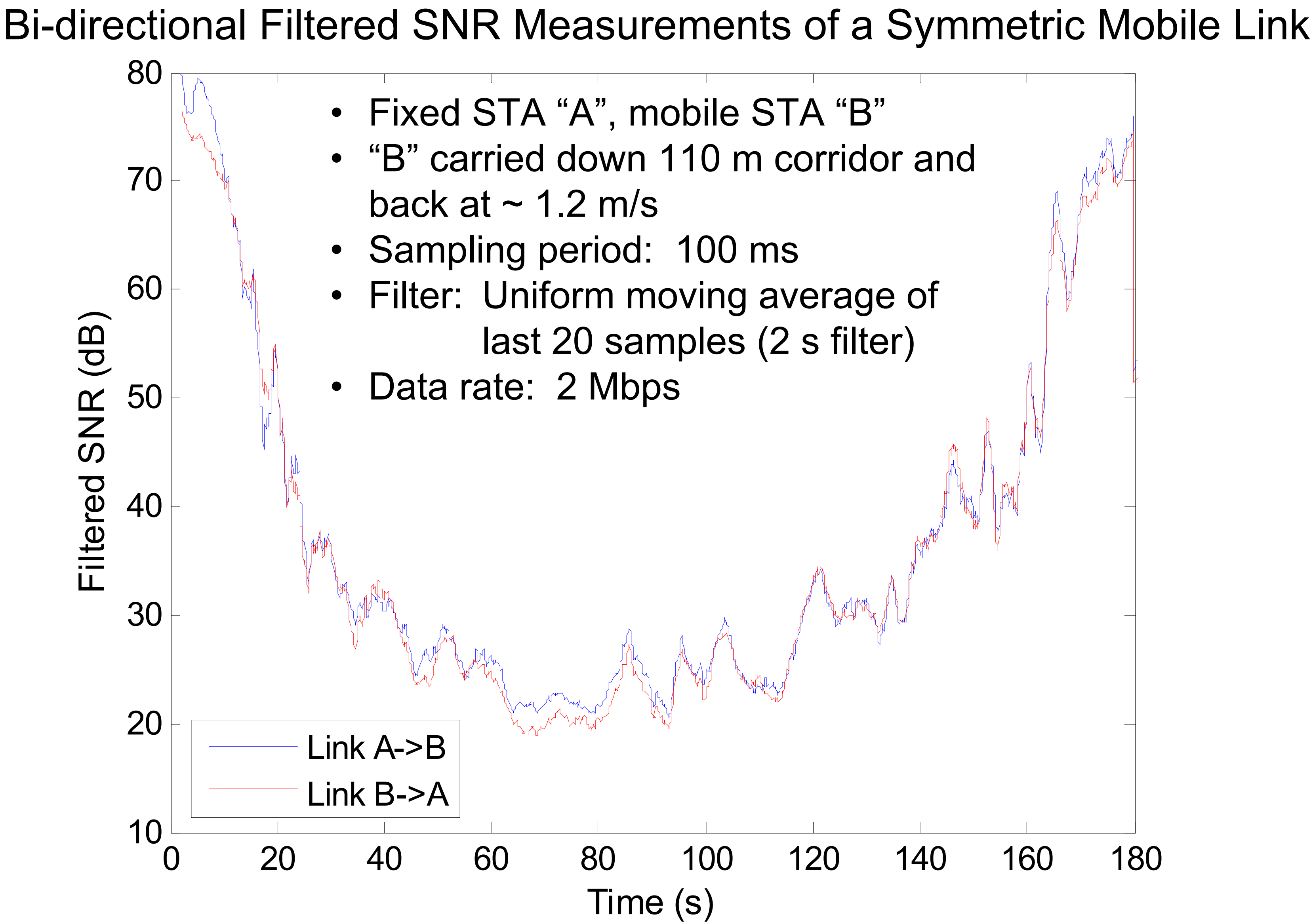
Deployment Parameters

Δ	Probe period
N	Averaging filter length
S_{th}	Threshold RSS

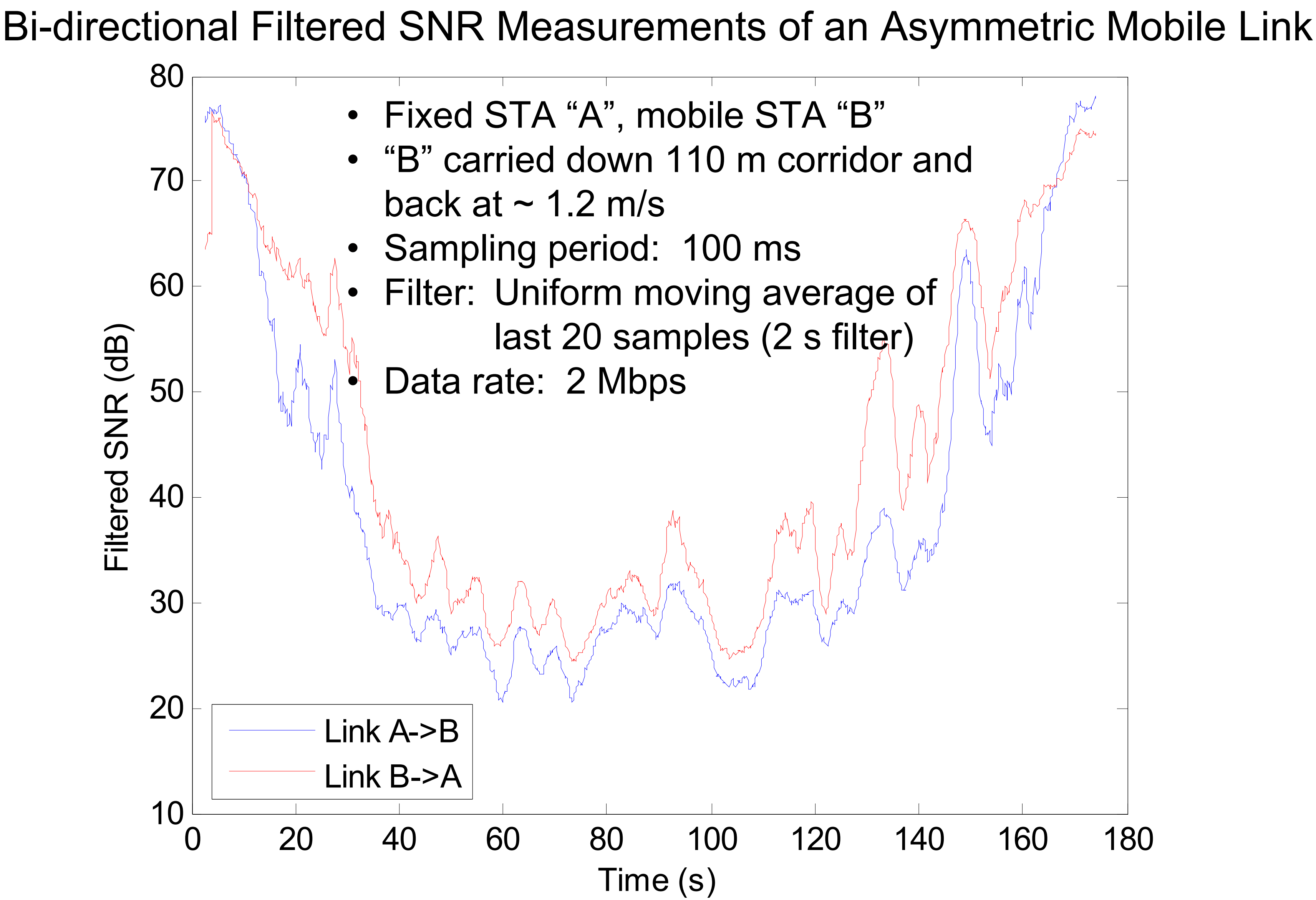




2.4 GHz Symmetric Link Measurements



2.4 GHz Asymmetric Link Measurements



Similarities with LANdroids

LANdroid Capability	NIST Breadcrumb
Self-Configuration	○
Self-Optimization	○
Self-Healing	○
Tethering	○
Intelligent Power Management	
Placement-by-Indicator	●
Geolocation	○

○ Partial support

● Full support