Notes from the Wireless Frontier

Upamanyu Madhow

Dept. of Electrical and Computer Engineering

University of California, Santa Barbara

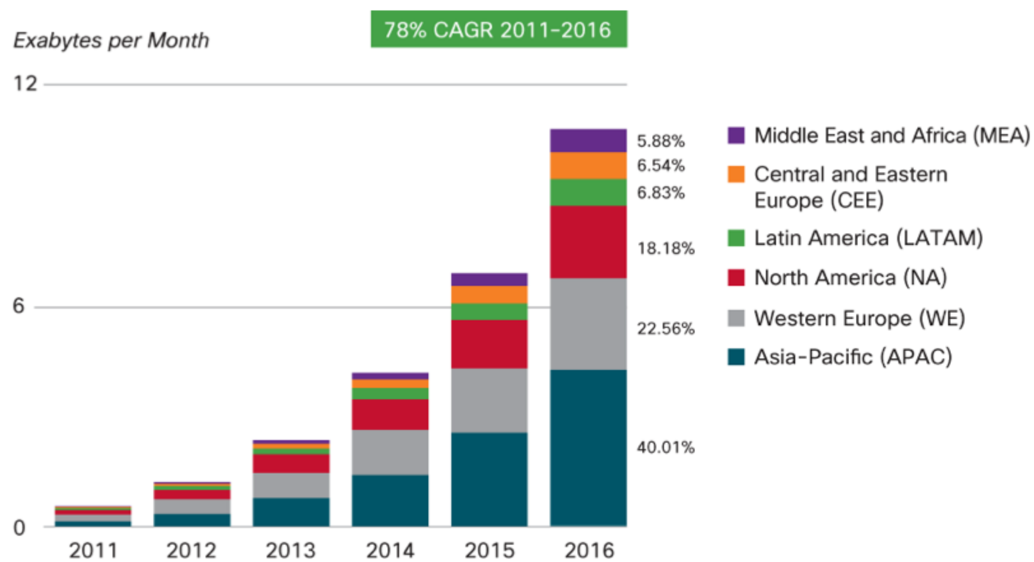
Presentation at UC, Irvine Oct 12, 2012

20 good years for wireless

- Digital cellular started in the 1990s
  - 6B mobile phone subscribers today!
  - Connects the most remote locations to the global economy
- WiFi is no slouch either
  - Huge growth in carrier and enterprise markets
  - Huge potential in residential markets in developing nations
- Technology is converging
  - MIMO, OFDM part of all modern standards
- Is there any more research to be done?
  - Yes, for at least another 20 years

Speed: Exponential Growth in Wireless Data

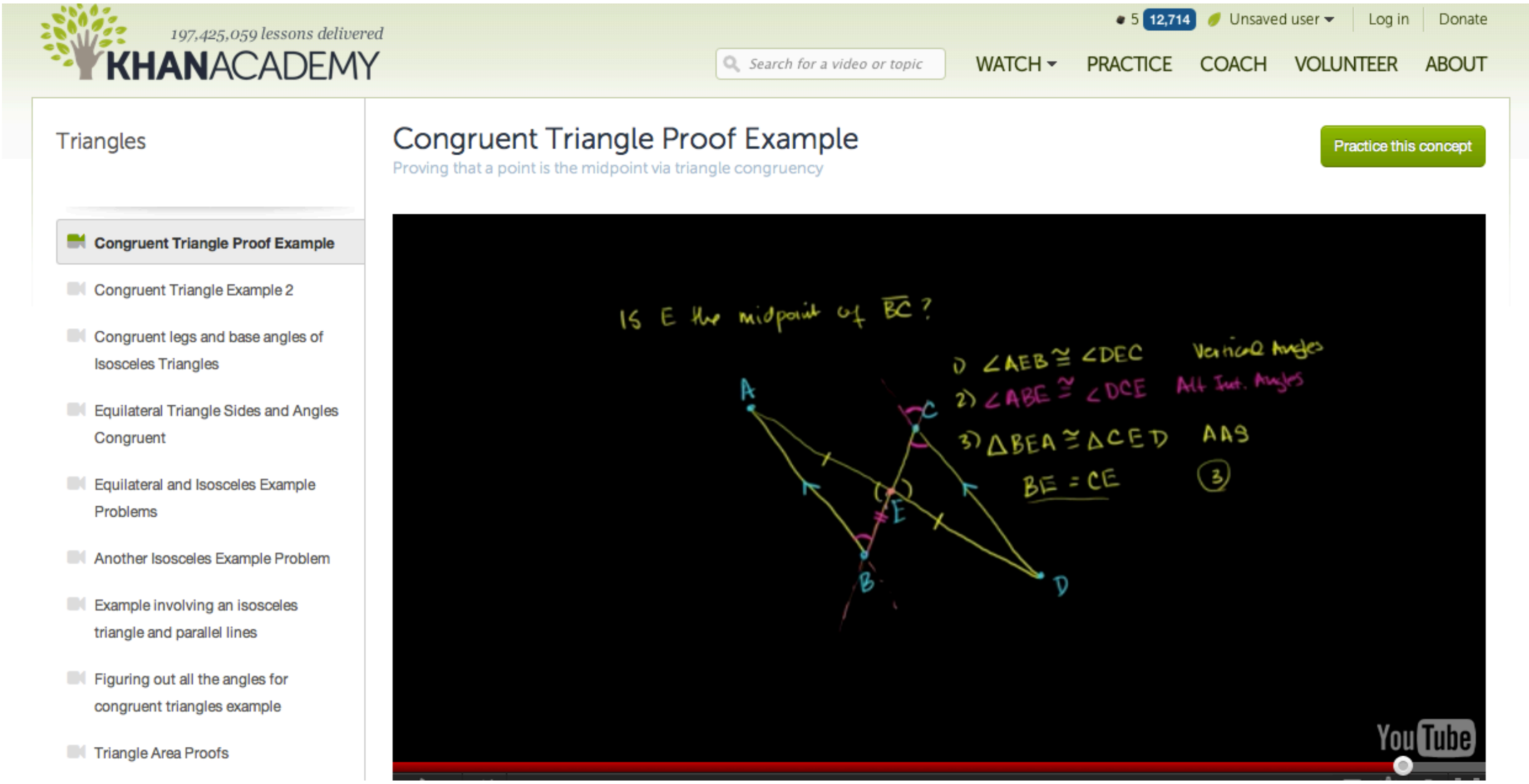
Figure 2. Global Mobile Data Traffic Forecast by Region



Source: Cisco VNI Mobile, 2012

NEED EXPONENTIAL INCREASE IN CELLULAR NETWORK CAPACITY!
(without breaking the bank)

Ubiquity: Broadband Everywhere

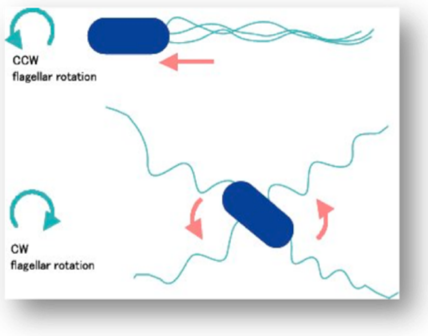


NEED TO GET THIS TO THE REMOTEST CORNERS OF THE WORLD!

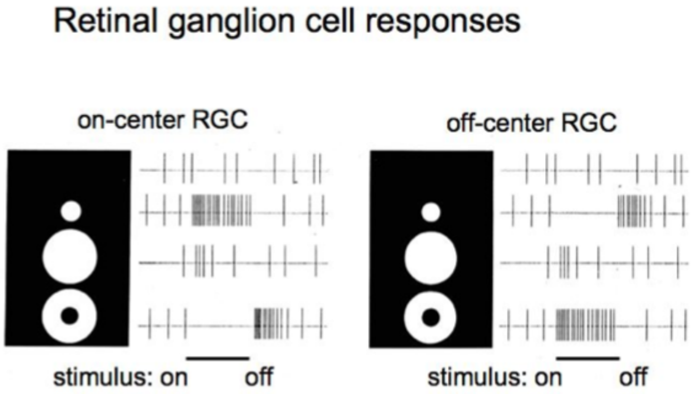
Intelligence: Wireless-enabled multi-agent systems

- Very large scale sensor and robot networks
- Bio-inspired design for inference and automation at scale
- Features: Minimalism, feedback, stigmergy, redundancy, hierarchy
- Biology as an initial idea generator
  - Must still do all the hard work of engineering

Swarming (stigmergy)



Chemotaxis



Simple sensing building blocks (center-surround response)

What are our options?

- Millimeter wave communication
  - Huge amounts of bandwidth (7 GHz unlicensed at 60 GHz)
  - Low-cost RFICs and packaging becoming available
  - Tiny carrier wavelengths requires comprehensive rethinking of design approaches
- Distributed MIMO
  - Multiple antennas can provide large gains in range/rate tradeoffs
  - Large carrier wavelengths (e.g., white space) propagate better, but multiple antennas too bulky
  - Cooperative clusters of nodes can form virtual arrays
  - Synchronization is the key bottleneck
- Bio-inspired designs
  - Inference and control for large-scale multi-agent systems
  - Learning from bacteria, sardines and neuroscience

Millimeter wave communication (FASTER)

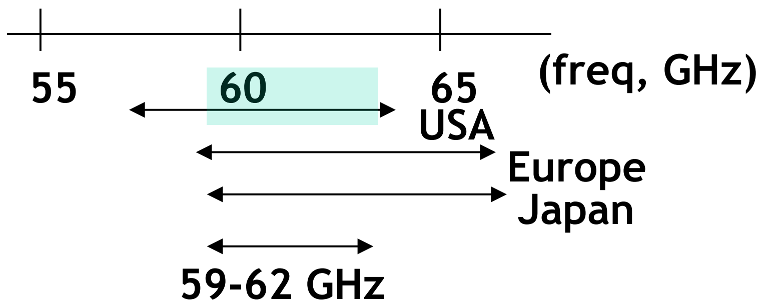
Prof. Mark Rodwell (hardware, system concepts)

Profs. Elizabeth Belding and Heather Zheng (networking)

Eric Torkildson, Munkyo Seo, Colin Sheldon, Sumit Singh, Jaspreet Singh, Sandeep Ponnuru, Hong Zhang, Raghu Mudumbai

The end of spectral hunger (at short ranges)

60 GHz: 7 GHz of unlicensed spectrum in US, Europe, Japan



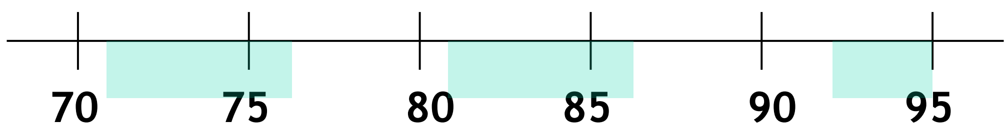
Common unlicensed spectrum

Oxygen absorption band

Ideal for short-haul multihop

(reduced interference)

E/W bands: 13 GHz of spectrum in US with minimal licensing/registration



Avoids oxygen absorption

Good for long-haul P2P

Bands beyond 100 GHz will become accessible as RFIC and packaging technology advances

What's different?

- Need highly directional links
  - λ^2 scaling of path loss unacceptable: too expensive to produce power at mm wave frequencies
- Can realize highly directional electronically steerable links
  - 1000 element antenna array can fit in our palm
- Blockage kills
  - Obstacles look bigger at small wavelengths
  - Need to steer around, not burn through
- Cannot count on carrier sense for MAC
  - Highly directional links make it hard to snoop on neighbors
  - Can we still use distributed coordination mechanisms?
- Can exploit reduced spatial interference to simplify MAC
- Spatial multiplexing available even for LoS environments
  - Small path length differences enough to provide full rank MIMO channel

Current industry focus: indoor 60 GHz networks

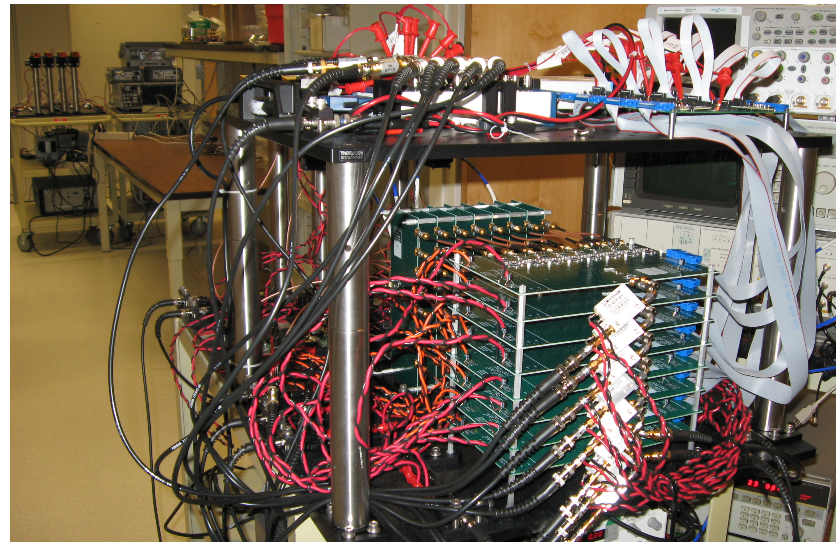
- WiGig spec/IEEE 802.11ad standard: up to 7 Gbps
- Support for moderately directional links
- 32 element antennas that can steer around obstacles

www.technologyreview.com

Progress due to push for WiGig

- 60 GHz CMOS RFICs ✓
  – WiFi-like economies of scale if and when market takes off
- Antenna array in package ✓ (32 elements)
  – Good enough for indoor consumer electronics applications
- MAC protocol supporting directional links ✓
  – Good enough for quasi-static environments
  – Does not provide interference suppression
  – Does not scale to very large number of elements
- Gigabit PHY ✓
  – Standard OFDM and singlecarrier approaches
  – Does not scale to 10 Gbps at reasonable power consumption (ADC bottleneck)

LoS MIMO can produce 2-4X increase in data rates



UCSB 4x4 LoS-MIMO prototype

5m

14 Gbps
on a WiGig
channel

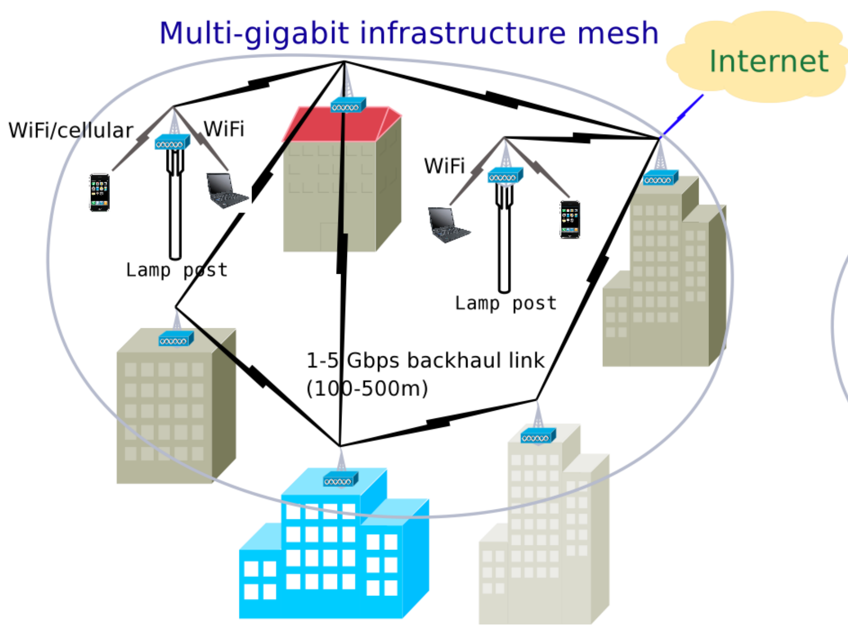
10m

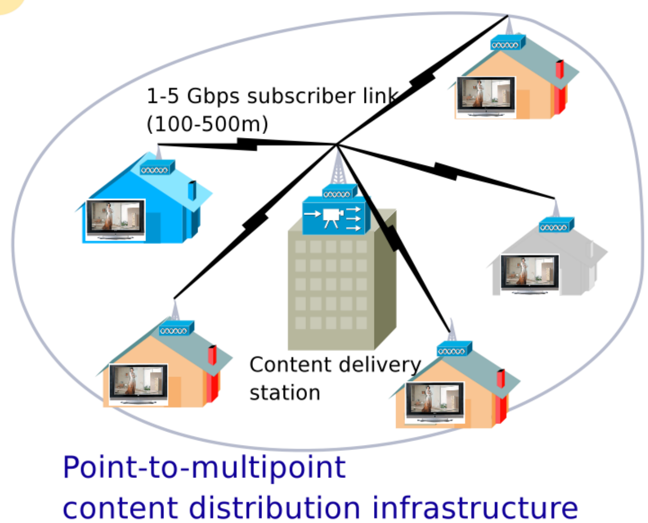
28 Gbps on a
WiGig channel

Not our emphasis today

Today: mm wave to the rescue of mobile operators

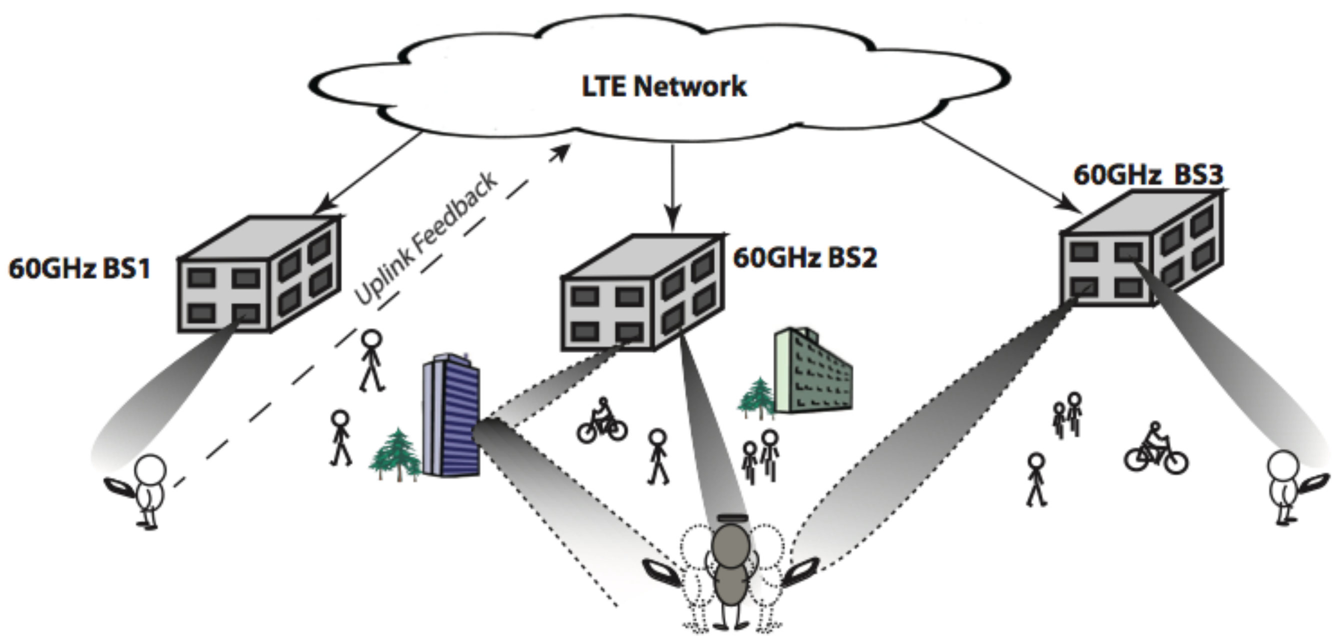
- Increase cellular capacity by drastically increasing spatial reuse
  - Base stations on lampposts, 200 m cell size
  - 4G to mobile, mm wave between base stations
- MultiGigabit wireless mesh backhaul enables dense picocell deployments
- Key challenges: highly directional networking, five nines reliability





Going one step further: 60 GHz to the mobile

- Base stations on lampposts
  - Both LTE and 60 GHz to the mobile
  - Downlink 60 GHz offload with uplink LTE feedback
  - Can leverage WiGig radio on mobile device in receive-only mode
- Key challenges: channel tracking with very large transmit arrays



mm-wave: technical topics today

- Highly directional networking (mm wave backhaul)
  - Using learning and memory to overcome deafness
- Very large arrays (60 GHz to the mobile)
  - Compressive adaptation

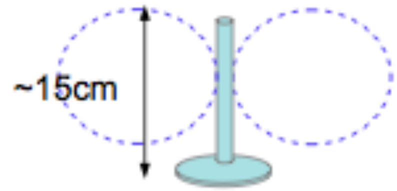
Highly Directional Networking

MultiGigabit mesh backhaul for picocellular networks

Coordination rather than interference is the challenge

Omni-coverage yet highly directional nodes

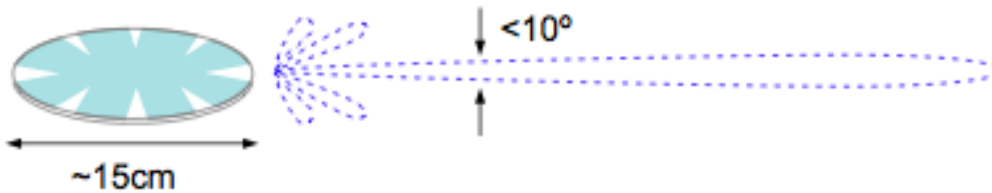
2.4 GHz
Wi-Fi antenna
D= 5dBi

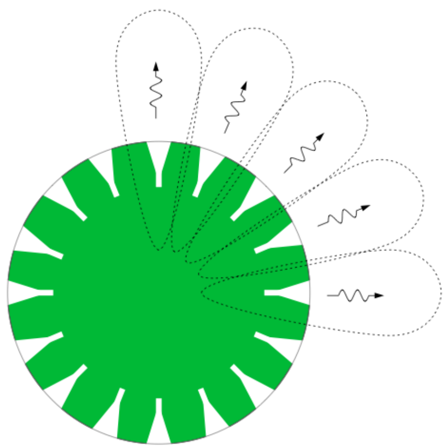


$$D \equiv \frac{\text{Max. power density}}{\text{Average power density}} = \frac{\pi}{\lambda^2} A_{eff} \propto f^2$$

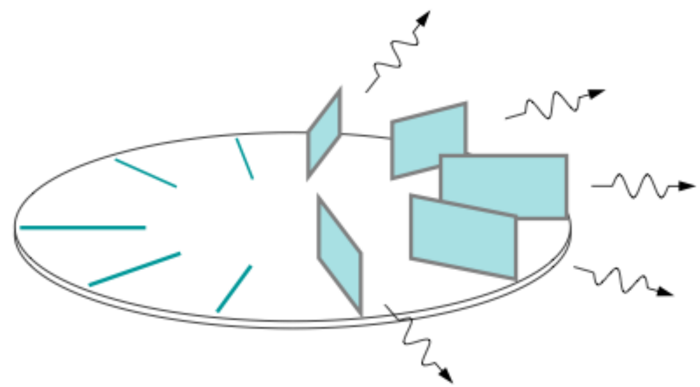
$$D \approx \frac{40{,}000}{\theta_{azimuth}\theta_{elevation}}$$

Circular array antenna
for a 60 GHz mesh network
D=30dBi



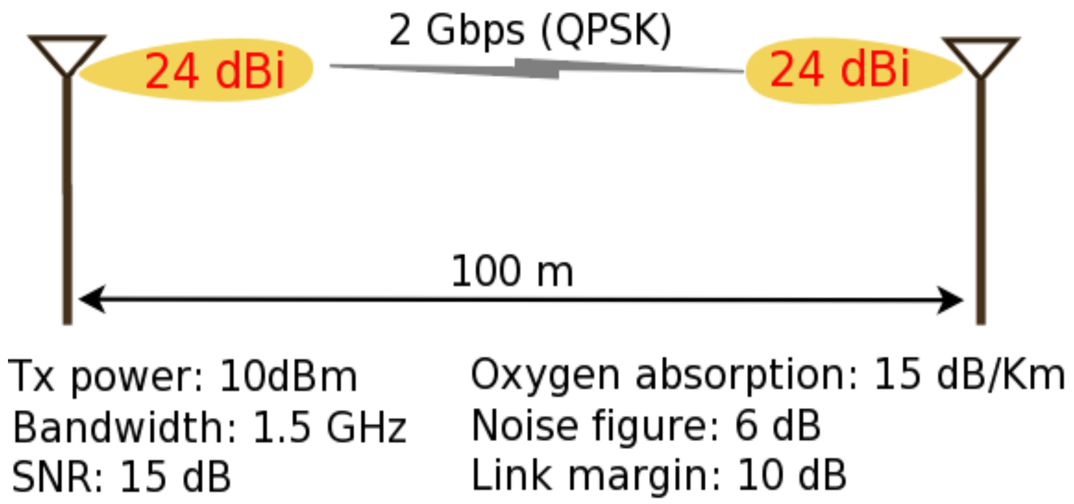


TOP VIEW



Reconfigurable circular array
Total 10 angular slots; 5 slots installed

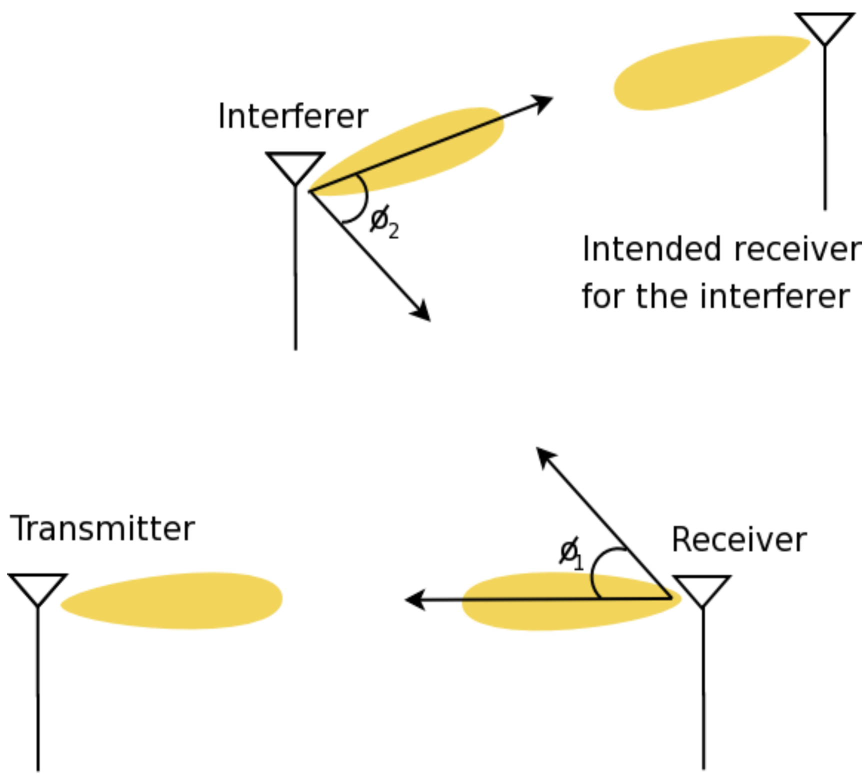
Nominal Link



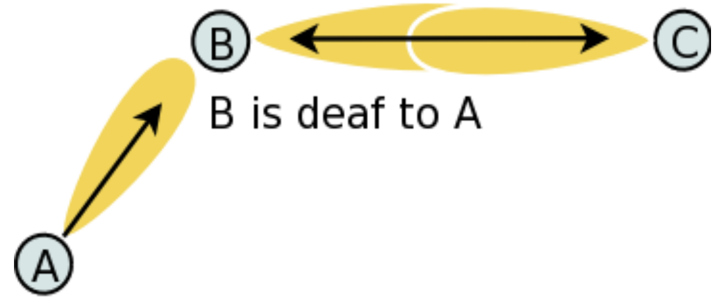
Caveat: can have significant fading due to ground and wall reflections
(but can provide quasi-deterministic diversity)
Can get higher range and rate by using higher directivities
(need hardware architectures for steerable arrays with large number of elements)
Can go to higher carrier frequencies to get spatial multiplexing gains

Interference and Deafness

Interference with directional links



Deafness

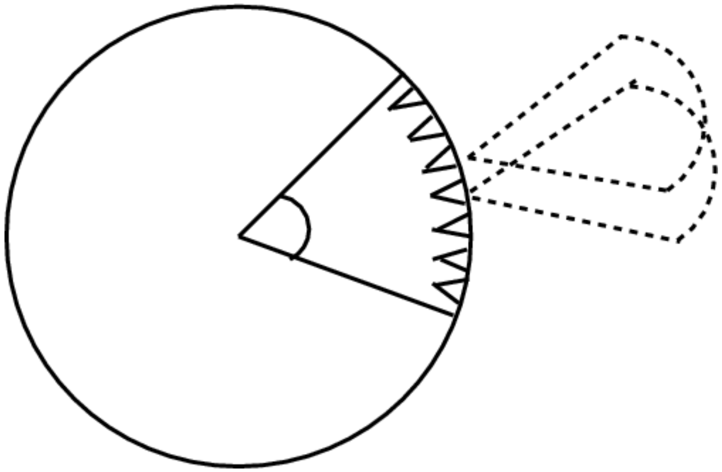


Key design issues

- No ``omnidirectional mode'' for MAC
  - Must use directionality to attain link budget
  - Directional only mode also simplifies PHY
- Are directional links like wires?
  - A qualified yes
- How do we exploit ``wire-like'' characteristics for MAC?
  - Carrier sense is out, but interference is much reduced
- Many other details
  - Network discovery
  - Synchronization maintenance
- Step 1: Understand spatial interference

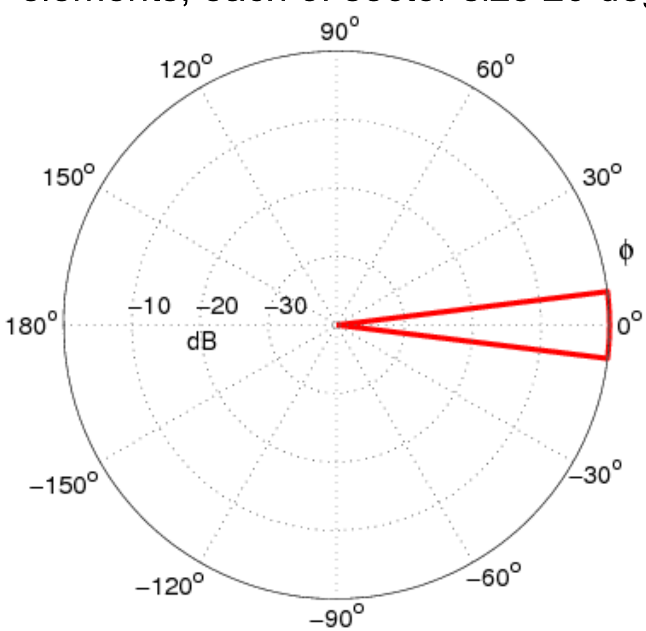
Mudumbai, Singh, Madhow: Infocom 2009, ToN 2011

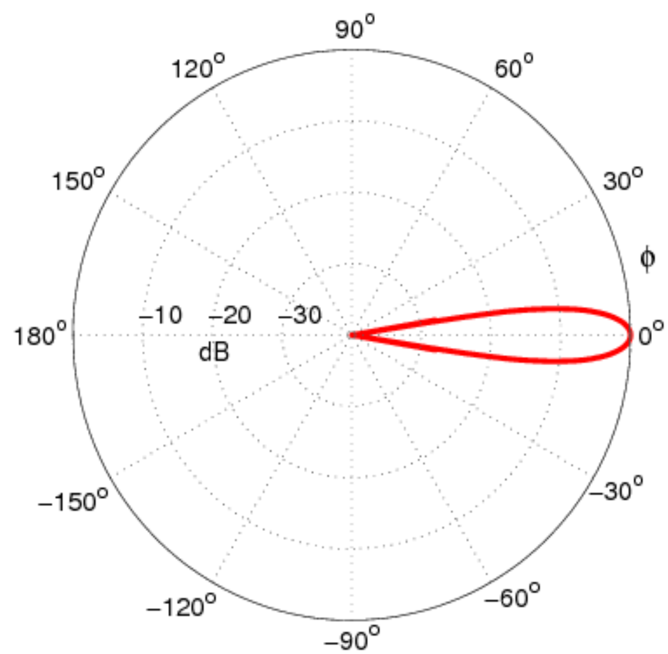
Modeling beam patterns



Approximating a circular array of slot antennas as a uniform linear array of flat-top elements.

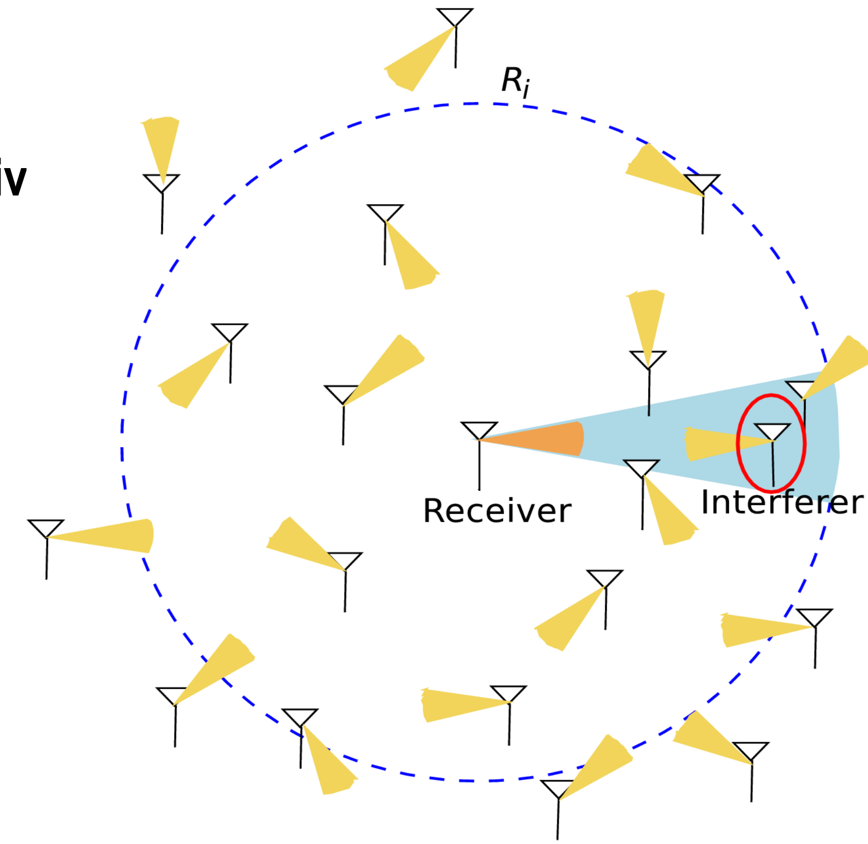
Gain pattern for a flat-top antenna (beam angle 14.4 degrees) and a 12 element linear array of flat-top elements, each of sector size 20 degrees. Antenna gain in both cases: 24 dBi





Interference under the protocol model

- Flat top antenna, randomly placed transmitters, random orientation wrt desired receiver
- Collision iff there exists at least one interferer
  - within the interference range
  - within the receiver beamwidth
  - pointing in the direction of the receiv



Collision Probability $1 - e^{-\lambda \beta A_c}$

$$A_c = \frac{(R_0 \Delta\Phi)^2}{4\pi} e^{-\alpha(R_i - R_0)}$$

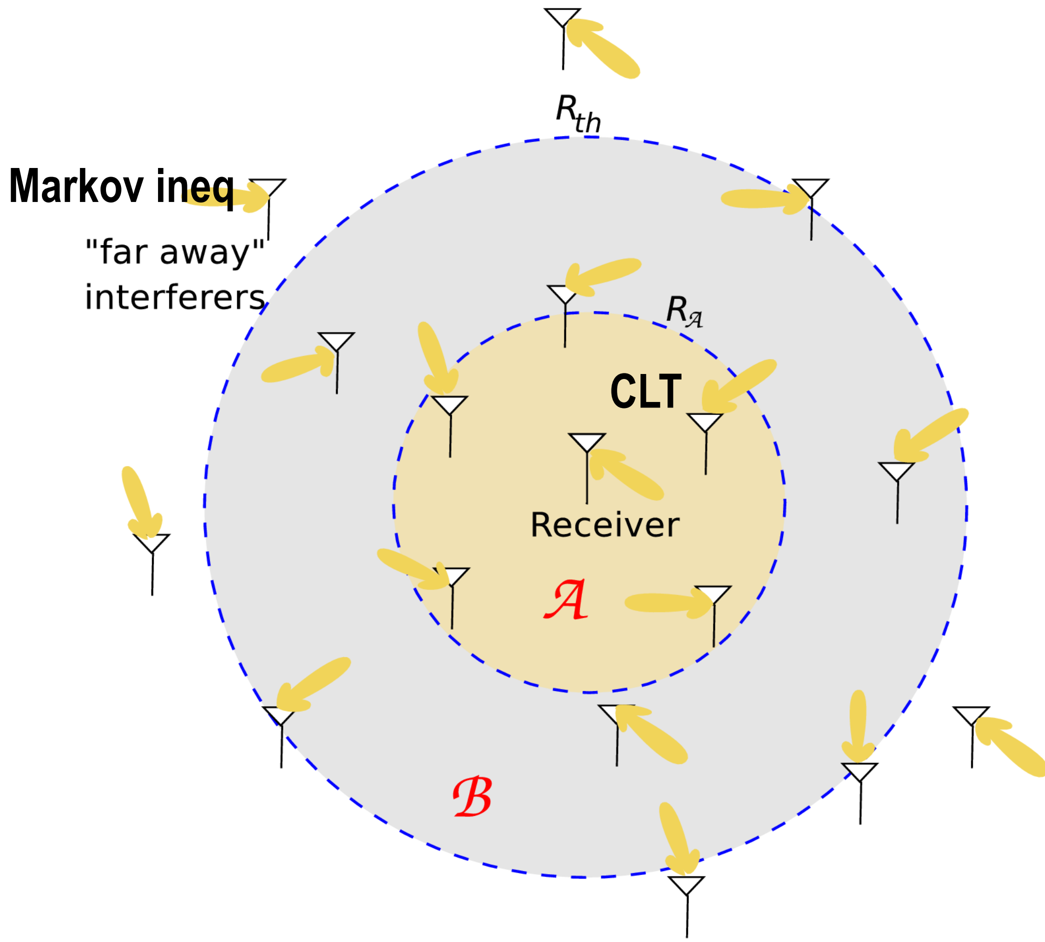
β : SINR threshold
λ : density of transmitting nodes
ΔΦ: (azimuthal) beamwidth
R_0 : nominal link range
R_i : interference range
α : atmospheric absorption coefficient

Physical model

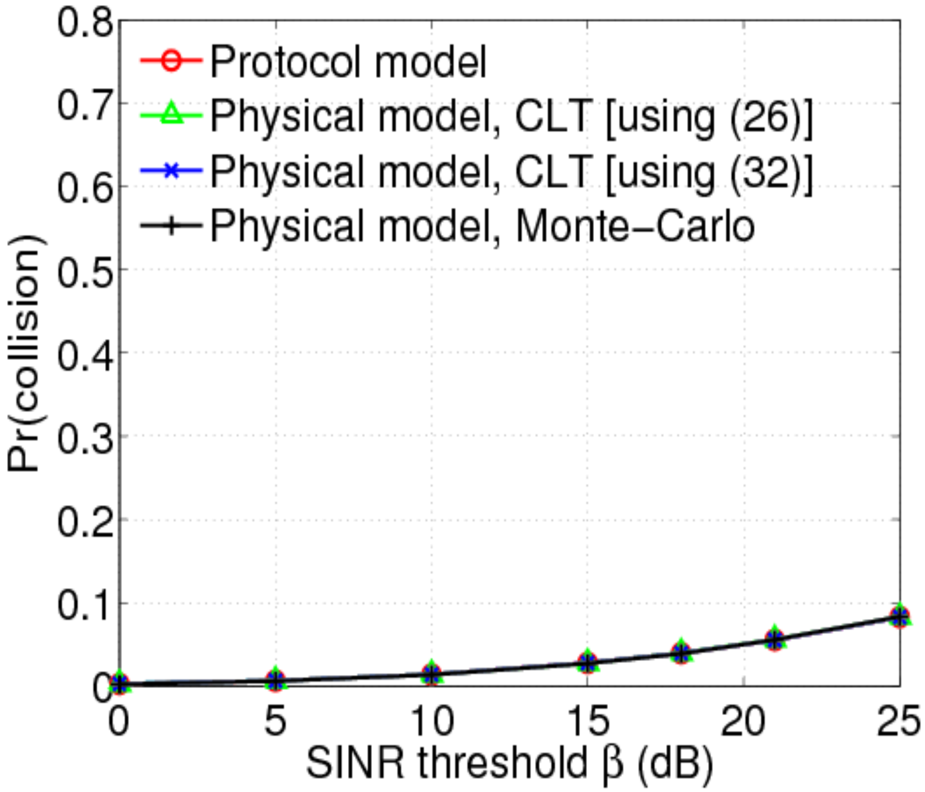
Collision prob = P[sum interference exceeds threshold]

Approach:

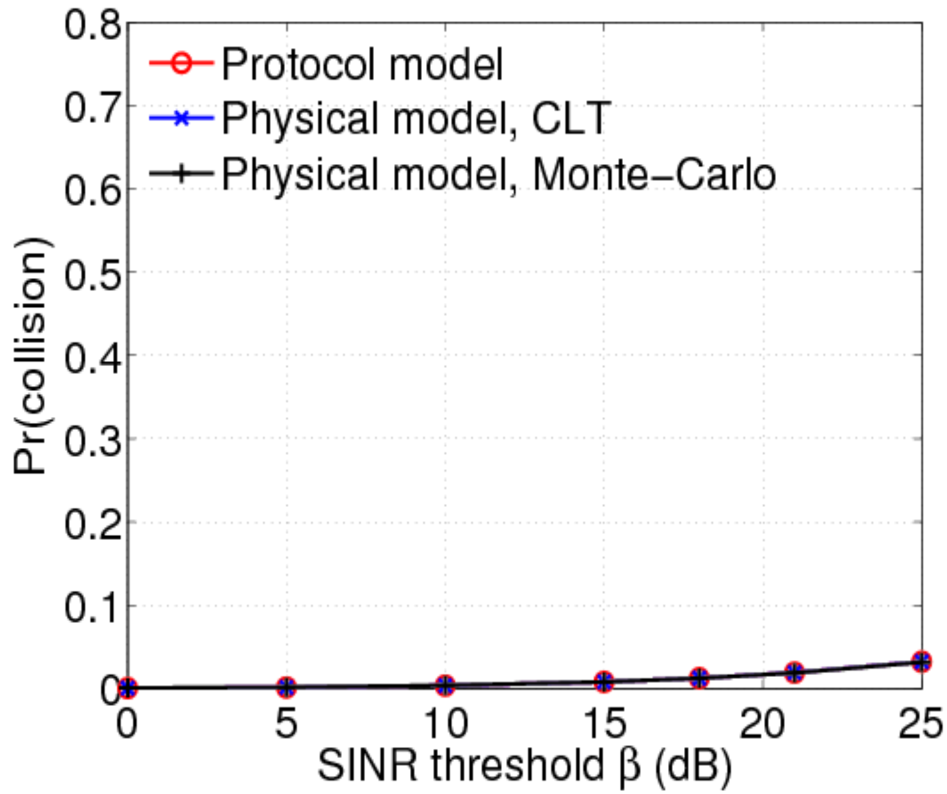
1) Exploit oxygen absorption to bound effect of far-away interferers using Markov ineq
2) Use CLT or Chernoff bound plus protocol ...del for nearby interferers



Collision probabilities (sparse network)



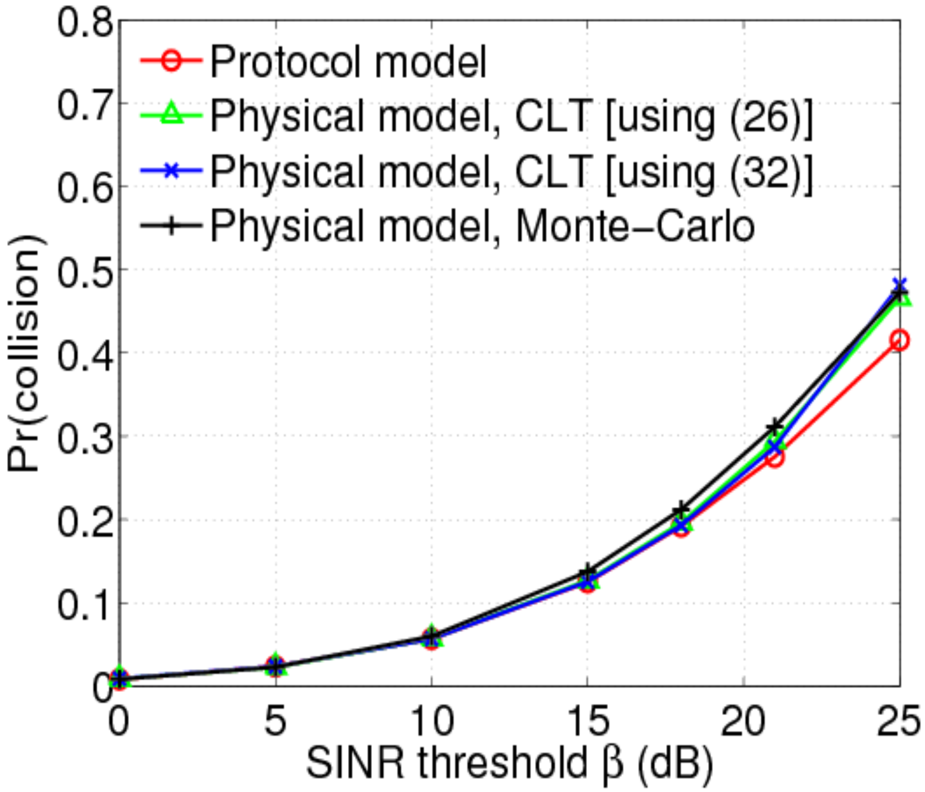
Flat-top antenna



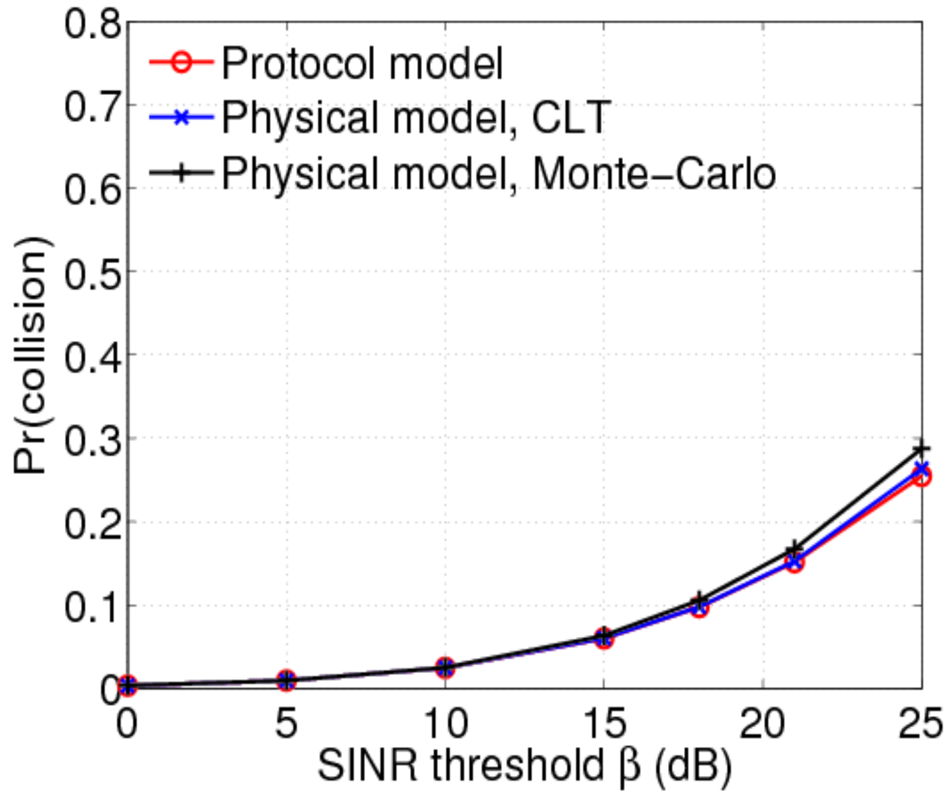
Linear array

Link range R =200m, $\pi\rho R^2=\pi$

Collision probabilities (dense network)



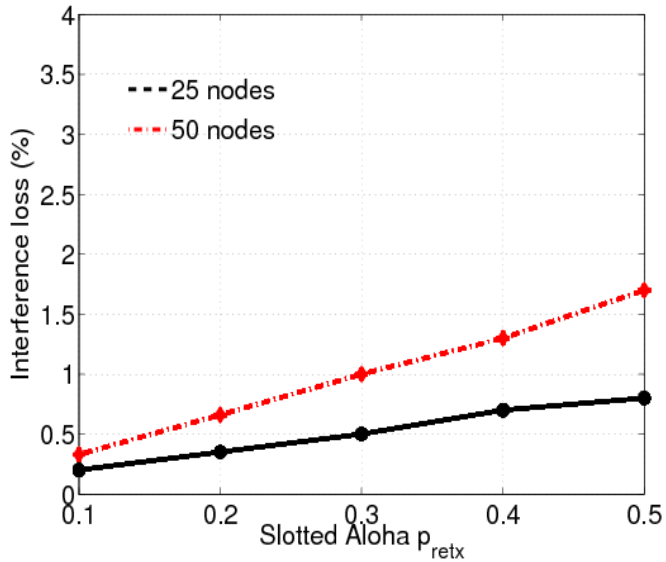
Flat-top antenna

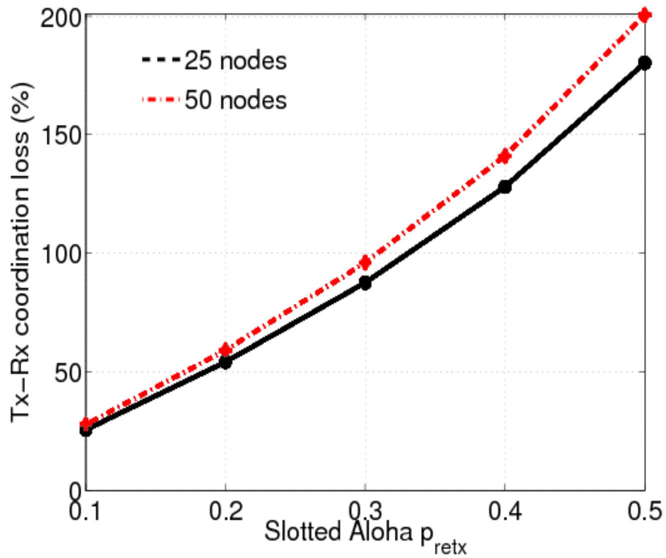


Linear array

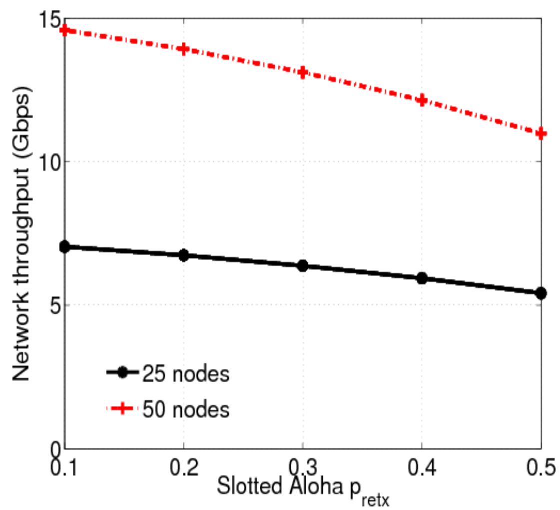
Link range R =100m, $\pi\rho R^2$=5.2 (Pr(connected network) = 0.99)

Coordination is the bottleneck





Collision losses order of magnitude smaller than losses due to failed coordination



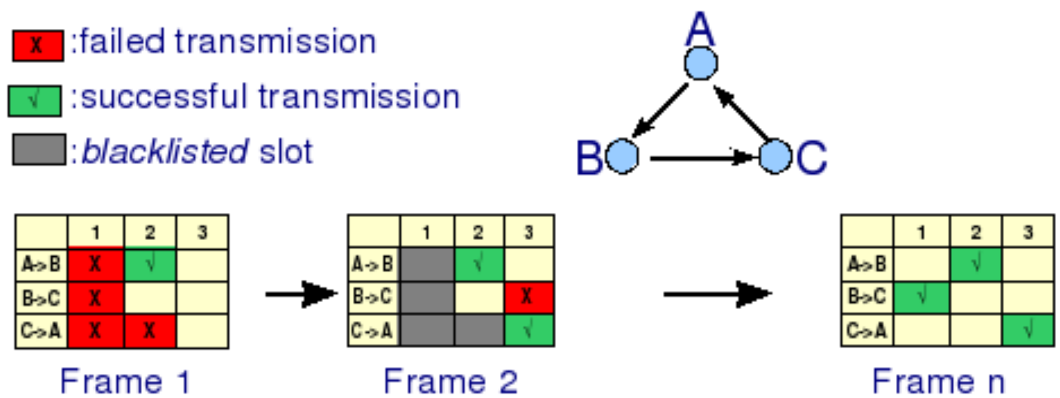
Recap of MAC Design Criteria

UCSB

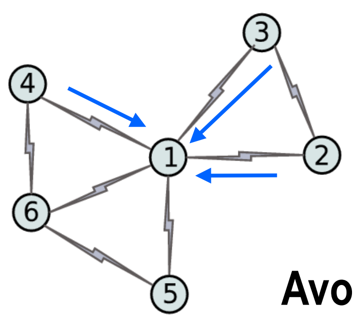
- Different transmitters do not coordinate with each other
  - *Wire-like* links, *deaf* neighbors
- Transmitter tries to coordinate with intended receiver
  - Half-duplex constraint
  - Receiver can only receive successfully from one node at a time
- Benchmarks: slotted Aloha and TDM
- How to do better than slotted Aloha while staying simple?
- How to approach the performance of globally computed TDM schedules?
  - Use learning and memory
- How to maintain slotting in lightweight fashion?
  - Work in progress

Memory-guided directional MAC (MDMAC)

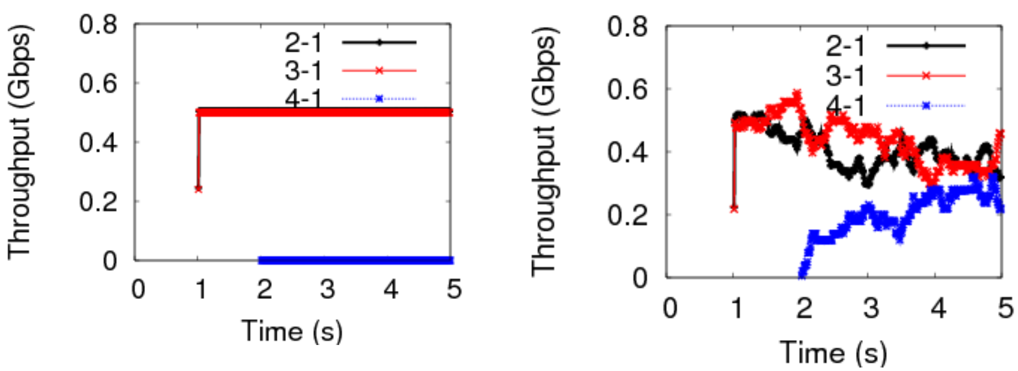
Stigmergic evolution of TDM-like schedule



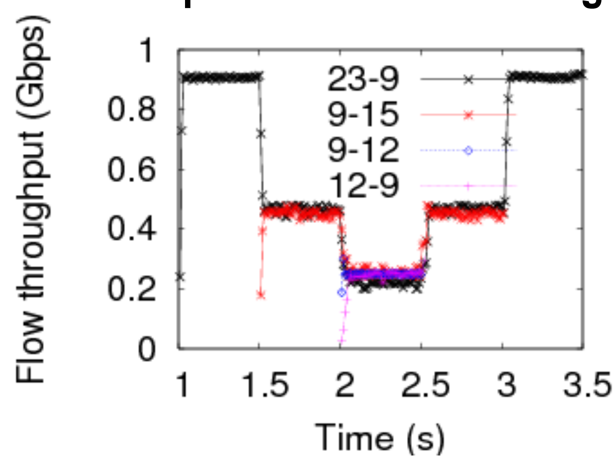
Overall schedule evolution



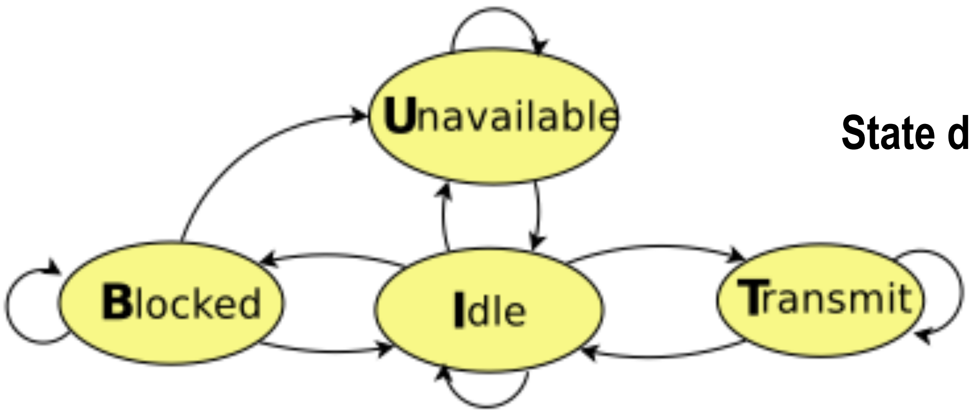
Avoiding lockout via randomization



Adaptation to traffic changes



Design guidelines from fixed point analysis



State diagram for a typical outgoing link

Randomized holding time for slot governs P[Transmit → Idle] and P[Unavailable → Idle]
Randomized holding time for blacklisted slot governs P[Blocked → Idle]

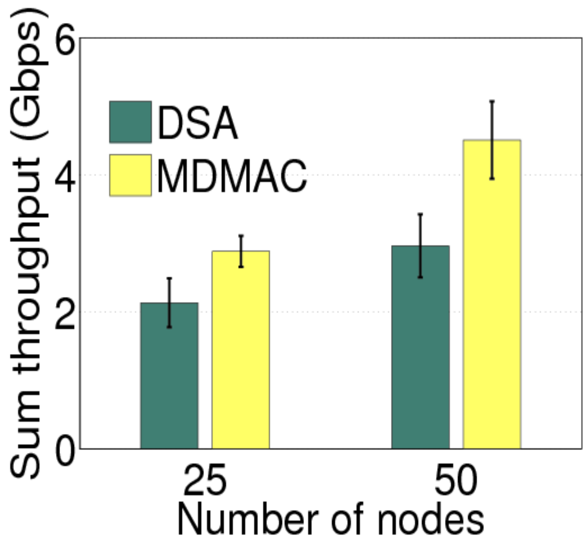
$$P_{IT} = p_{tx}\left(\frac{P_I}{P_I + P_B}p_l + \frac{P_B}{P_I + P_B}\right)$$

$$P_{IU} = \frac{p_{tx}p_l P_I}{P_I + P_B}, P_{BU} = \frac{p_{tx}P_I}{P_I + P_B}, P_{IB} = \frac{p_{tx}^2 P_I}{P_I + P_B}$$

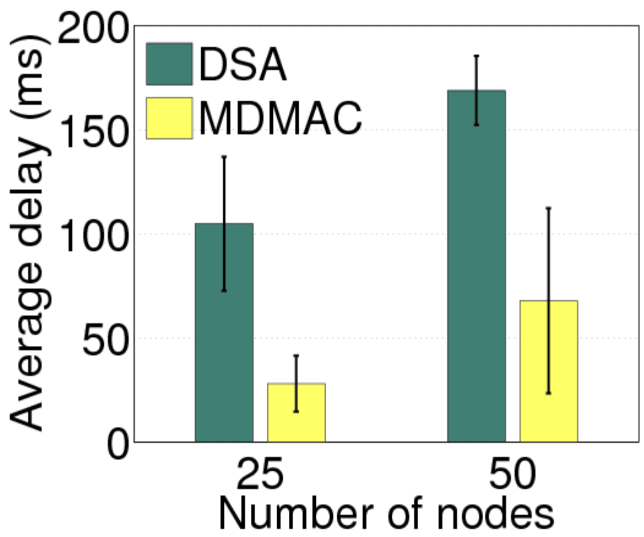
Transition probs for a 2-node network

TDM-like performance on a mesh network

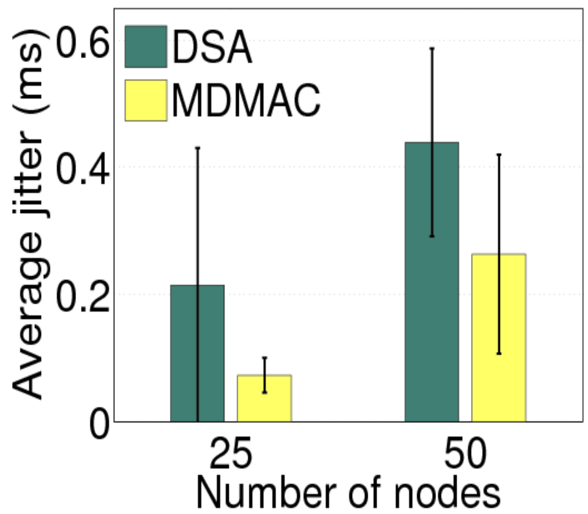
4-5% “missed transmit opportunities”
Significantly better than benchmark directional slotted aloha



Aggregate network throughput



End-to-end delay



Delay-jitter

Highly directional mesh networks: take-aways

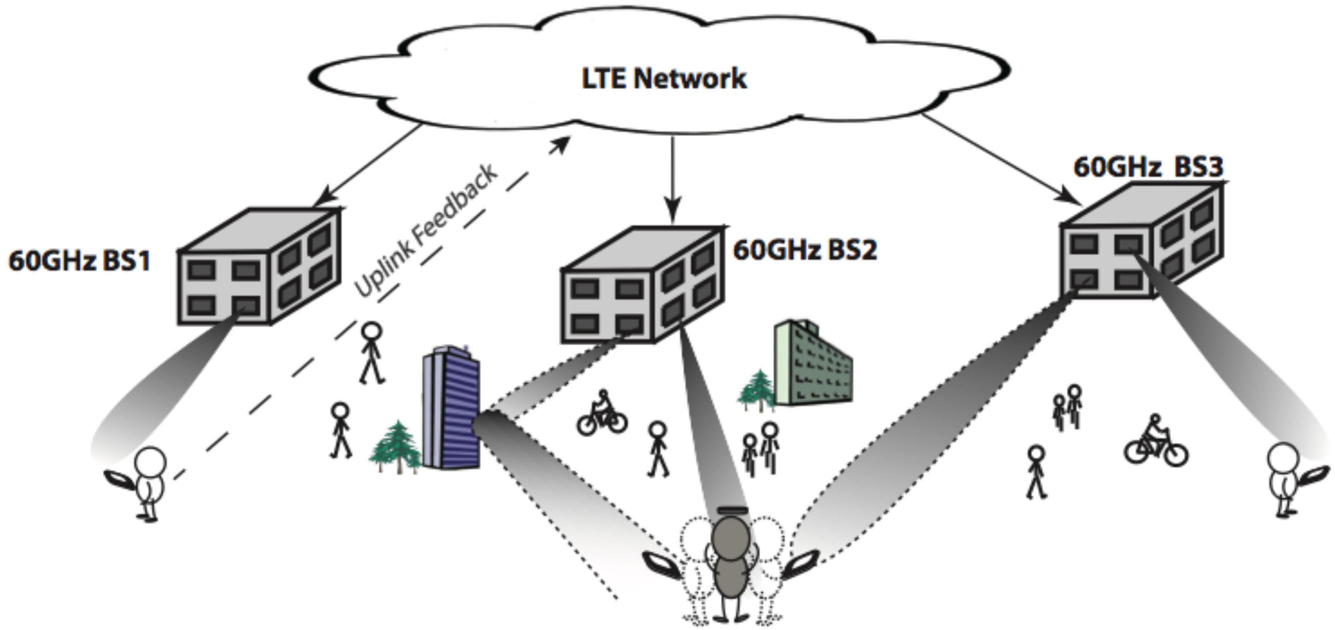
- Need to rethink design
  - Pseudowired abstraction
  - Emphasis shifts from interference management/avoidance to scheduling
  - Promising results approaching TDM performance
- Omni-coverage yet highly directional nodes are an interesting hardware challenge
  - Interplay of form factor, antenna design, partitioning of RF/IF/baseband functionalities
  - May have significant cross-fertilization with indoor WiGig

Adapting electrically Large but physically small arrays

Why? 60 GHz downlinks, wireless data centers,…

How do we adapt them?

Electrically large arrays for 60 GHz to the mobile

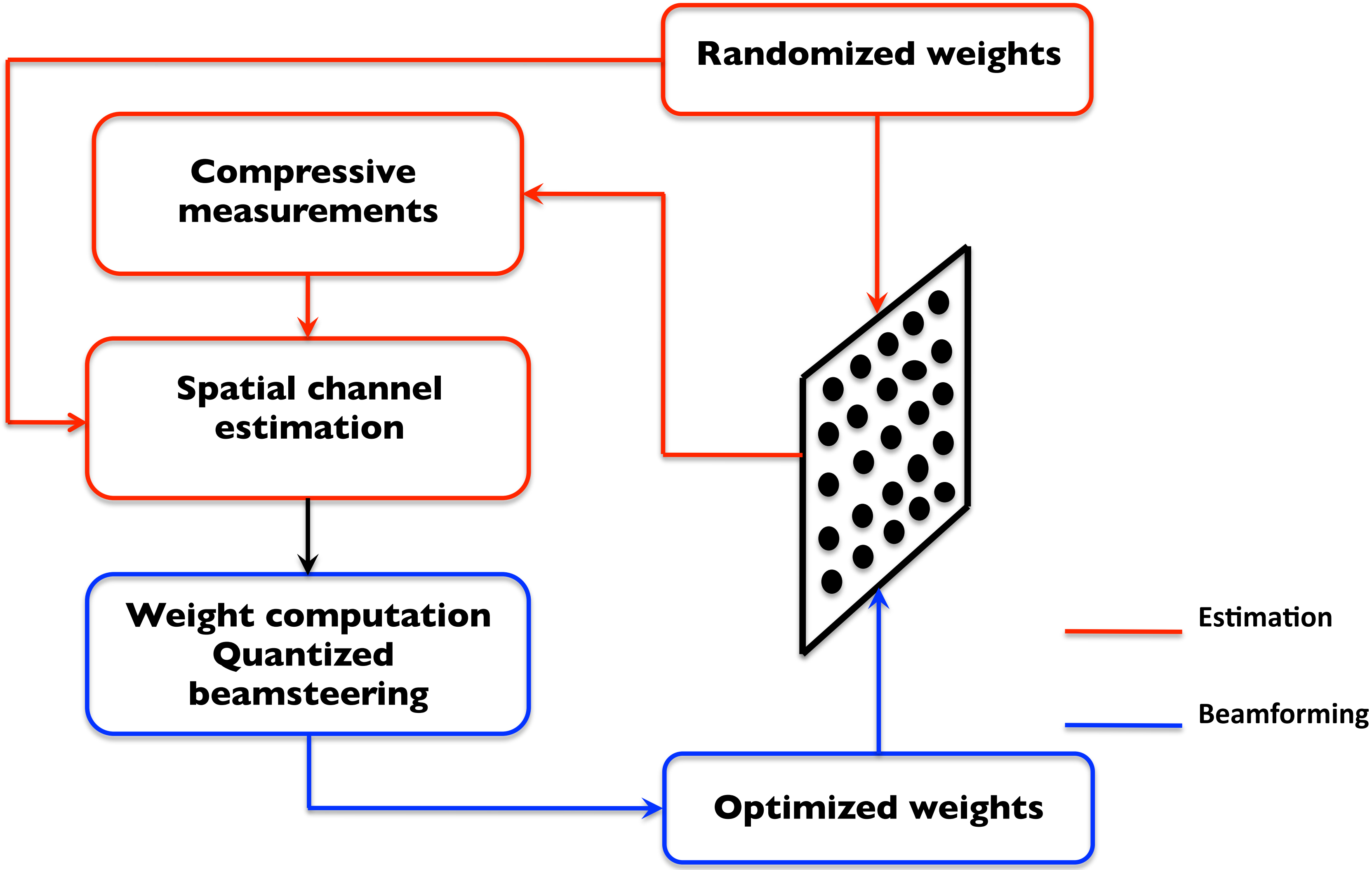


90 degree vertical coverage
100 degree horizontal coverage

10 degree by 10 degree beam: 90 elements
5 degree by 5 degree beam: 360 elements

How do we adapt large arrays?

Compressively…

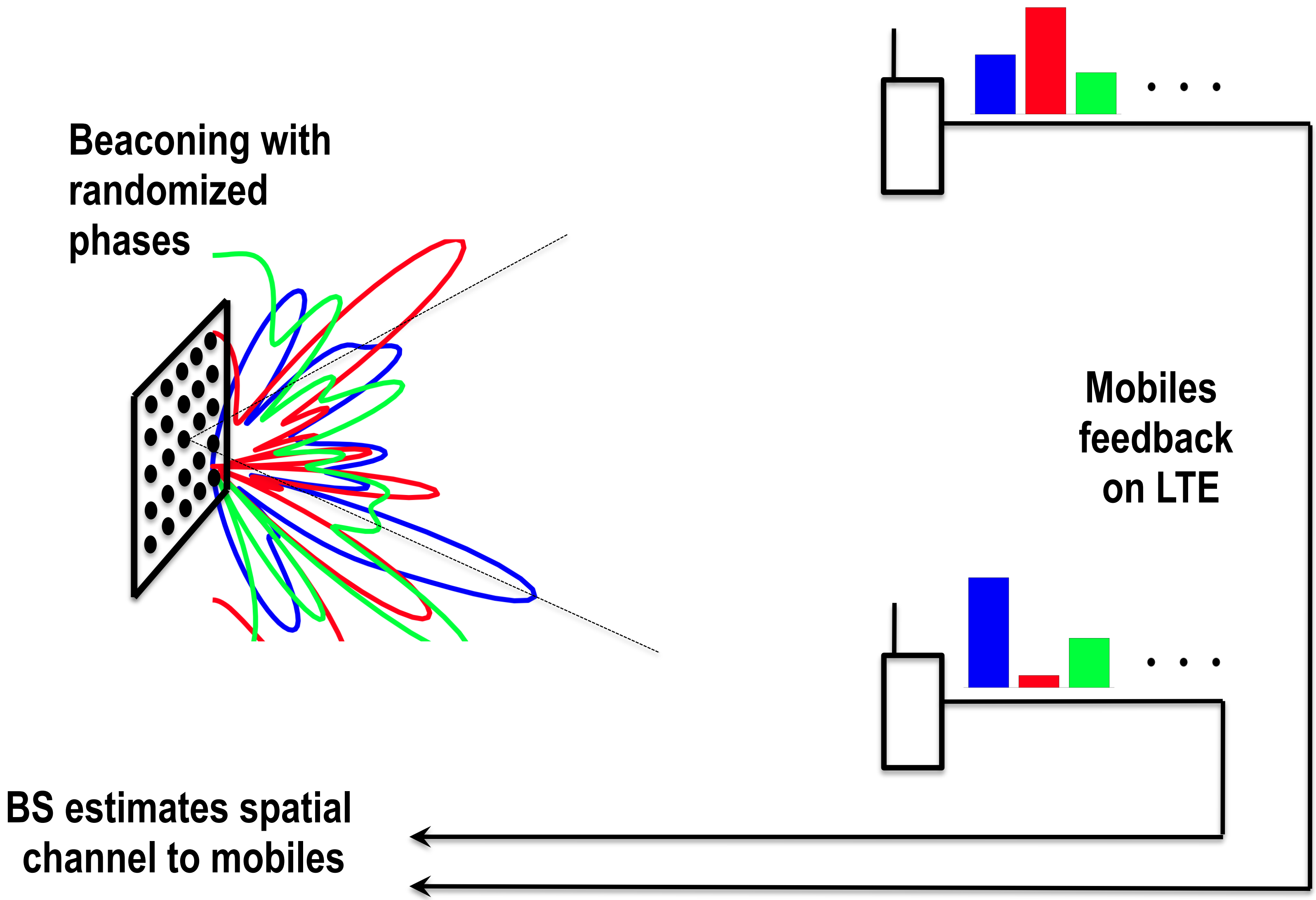


Ramasamy, Venkateswaran, Madhow, ITA 2012, Allerton 2012, Asilomar 2012

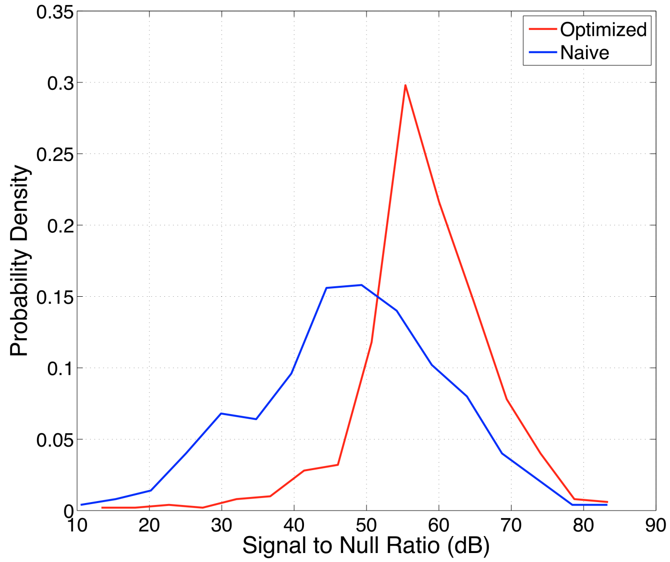
Key design concepts

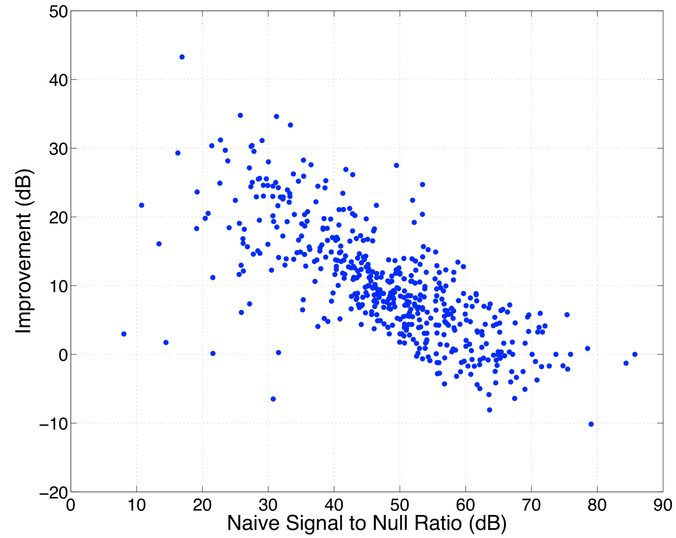
- RF beamforming
  - Scalability requires coarse control of each element
- Exploit channel sparsity
  - Small number of randomized projections capture all the relevant information
  - Compatible with heavily quantized phases
- Exploit channel continuity to further reduce tracking overhead
- Explicitly compute weights for coarsely quantized phases
  - Can steer nulls as well as beams
  - Naïve quantization of zero-forcing solution followed by sequential optimization

Compressive Beaconing with Coarse Phase Control



Beam & null steering with coarse phase control





Mean signal-to-null ratio 58 dB
10 dB mean improvement over naïve quantization
Big improvements (~30 dB) improvement when it really counts!

60 GHz to the mobile: take-aways

- Need large arrays with 100s-1000s of elements
  - Recent breakthroughs in compressive array adaptation can be employed for beamsteering and nullsteering
  - Follows from more general compressive estimation framework
- Link budgets easily attainable using CMOS
  - Tiny transmit powers per element (well below 0 dBm)
- Asymmetric architecture provides WiGig extension to outdoor mobile environments
- Opens up essentially indefinite spatial reuse

mm waves: exploring further

Survey

U. Madhow, S. Singh, *60 GHz communication,* chapter in *Handbook of Mobile Comm.* (ed. J. Gibson), 2012.

MIMO techniques and channel modeling

Sheldon, Seo, Torkildson, Madhow, Rodwell*, A 2.4 Gb/s millimeter-wave link using adaptive spatial multiplexing,* APS-URSI 2010.

Ramasamy, Venkateswaran, Madhow, *Compressive adaptation of large steerable arrays,* ITA 2012.

Torkildson, Madhow, Rodwell, *Indoor millimeter wave MIMO: feasibility and performance,* IEEE Trans. Wireless Comm., Dec 2011. (see also mmCom 2010)

Zhang, Venkateswaran, Madhow, *Channel modeling and MIMO capacity for outdoor millimeter wave links,* WCNC 2010. (see also mmCom 2010)

Torkildson, Ananthasubramaniam, Madhow, Rodwell, *Millimeter wave MIMO: wireless links at optical speeds,* Allerton 2006.

Compressive adaptation

Ramasamy, Venkateswaran, Madhow, *Compressive adaptation of large steerable arrays* ITA 2012.

Ramasamy, Venkateswaran, Madhow, *Compressive tracking with 1000-element arrays…,* Allerton 2012.

Ramasamy, Venkateswaran, Madhow, *Compressive estimation in AWGN…,* Asilomar 2012.

Networking with highly directional links

Singh, Mudumbai, Madhow*, Interference analysis for highly directional 60-GHz mesh networks: the case for rethinking medium access control,* IEEE/ACM Trans. Networking, October 2011.

Singh, Mudumbai, Madhow, *Distributed coordination with deaf neighbors: efficient medium access for 60 GHz mesh networks,* IEEE Infocom 2010.

Singh, Ziliotto, Madhow, Belding, Rodwell, *Blockage and directivity in 60 GHz wireless personal area networks,* IEEE JSAC, October 2009.

Singh, Ziliotto, Madhow, Belding, Rodwell, *Millimeter wave WPAN: cross-layer modeling and multihop architecture,* IEEE Infocom 2007 mini-symposium.

ADC Bottleneck: Analog multitone, TI-ADC, low-precision ADC

Distributed MIMO
(FARTHER)

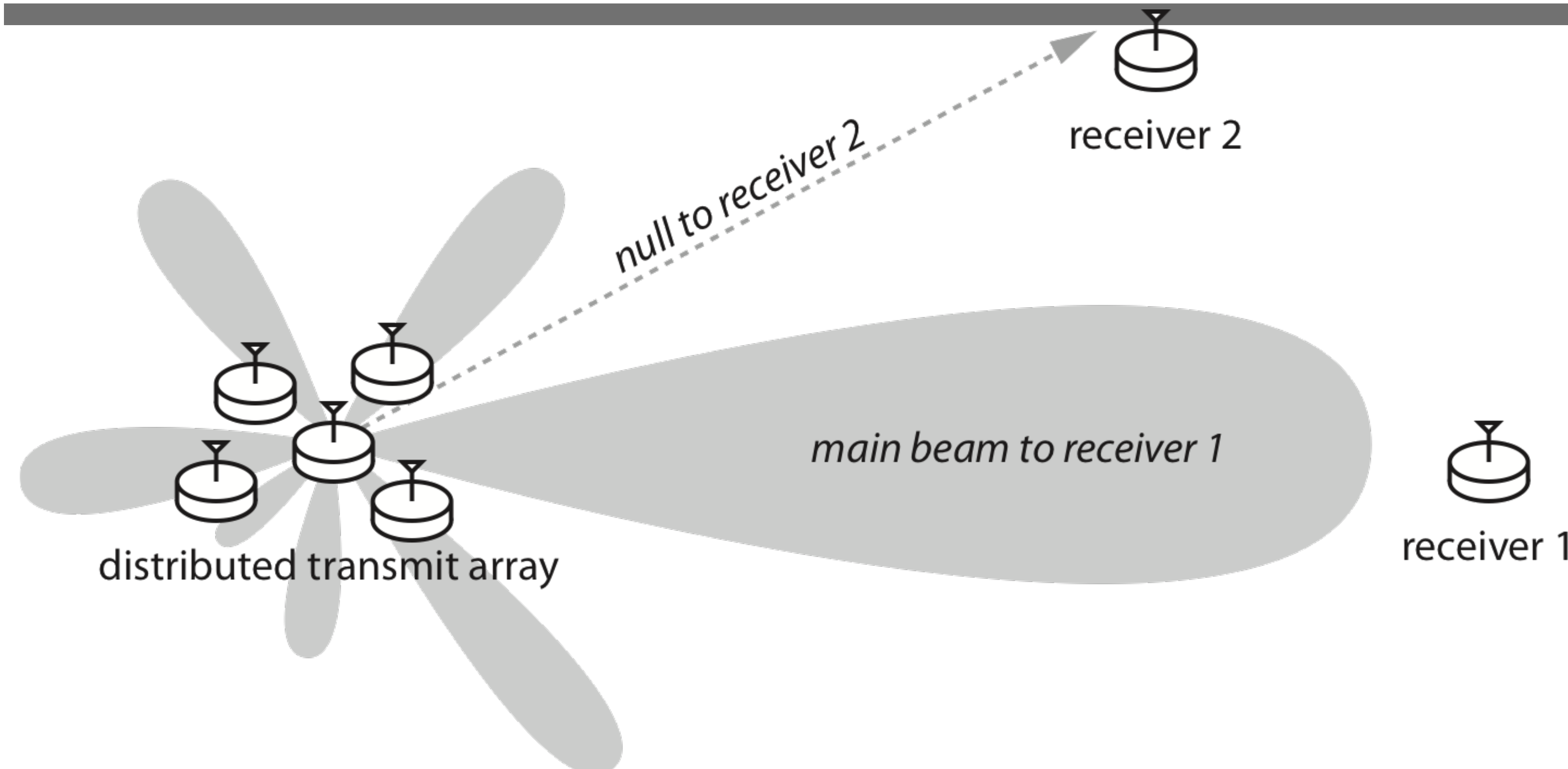
Dr. Francois Quitin and Andrew Irish (UCSB)

Profs. Raghu Mudumbai, Prof. Soura Dasgupta, Mahboob Rahman (U Iowa)

Prof. Rick Brown (WPI)

Dr. Pat Bidigare and others (BBN/Raytheon)

The promise of distributed MIMO

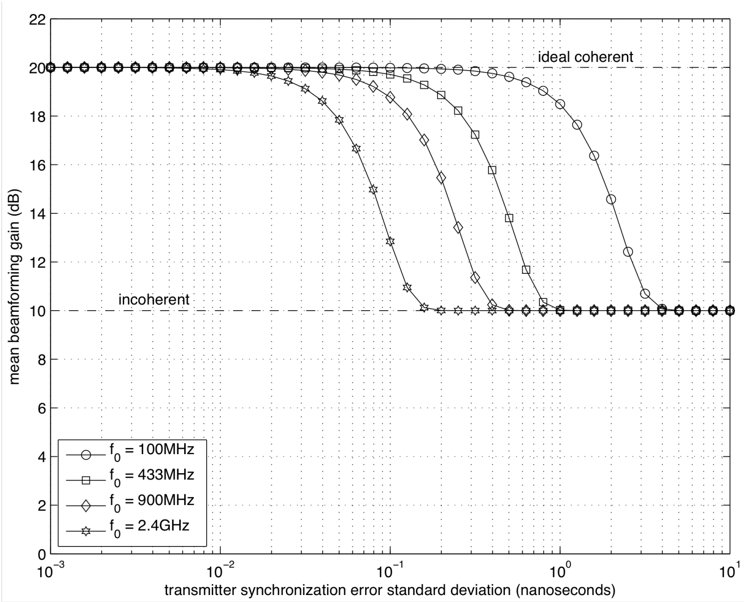


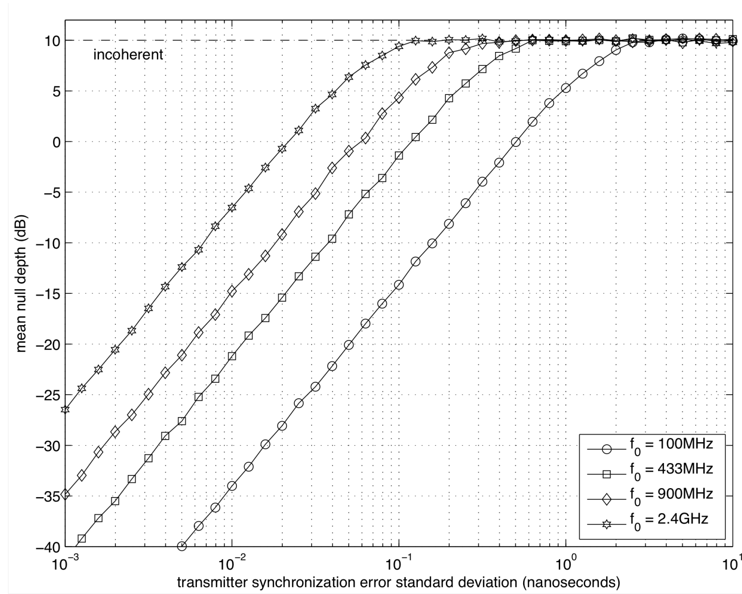
Vision: Opportunistic MIMO without form factor constraints

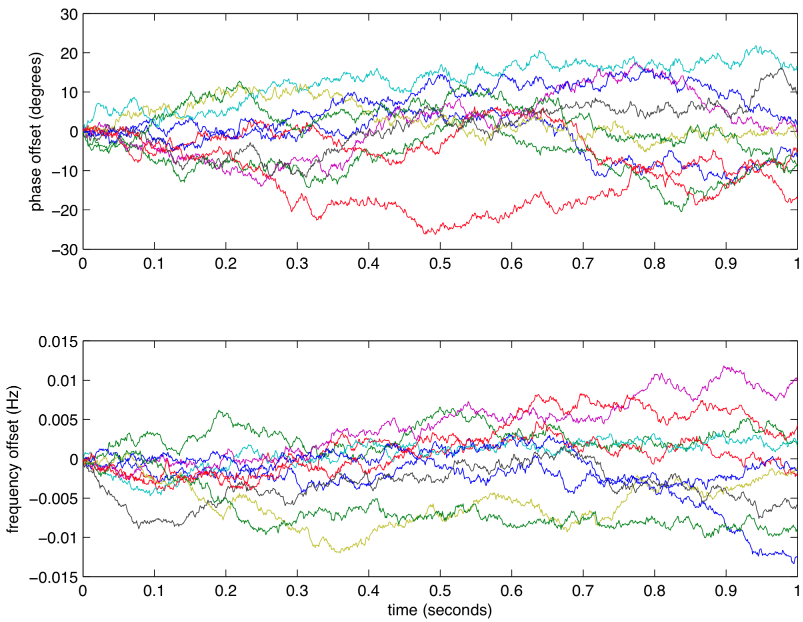
Synchronization-enabled protocols to support distributed realization of any MIMO scheme: beamforming, nulling, SDMA, spatial muxing, interference alignment,…

MANY APPLICATIONS: DISTRIBUTED BASE STATION, DISTRIBUTED 911, SENSOR NETWORKS,…

The synchronization bottleneck





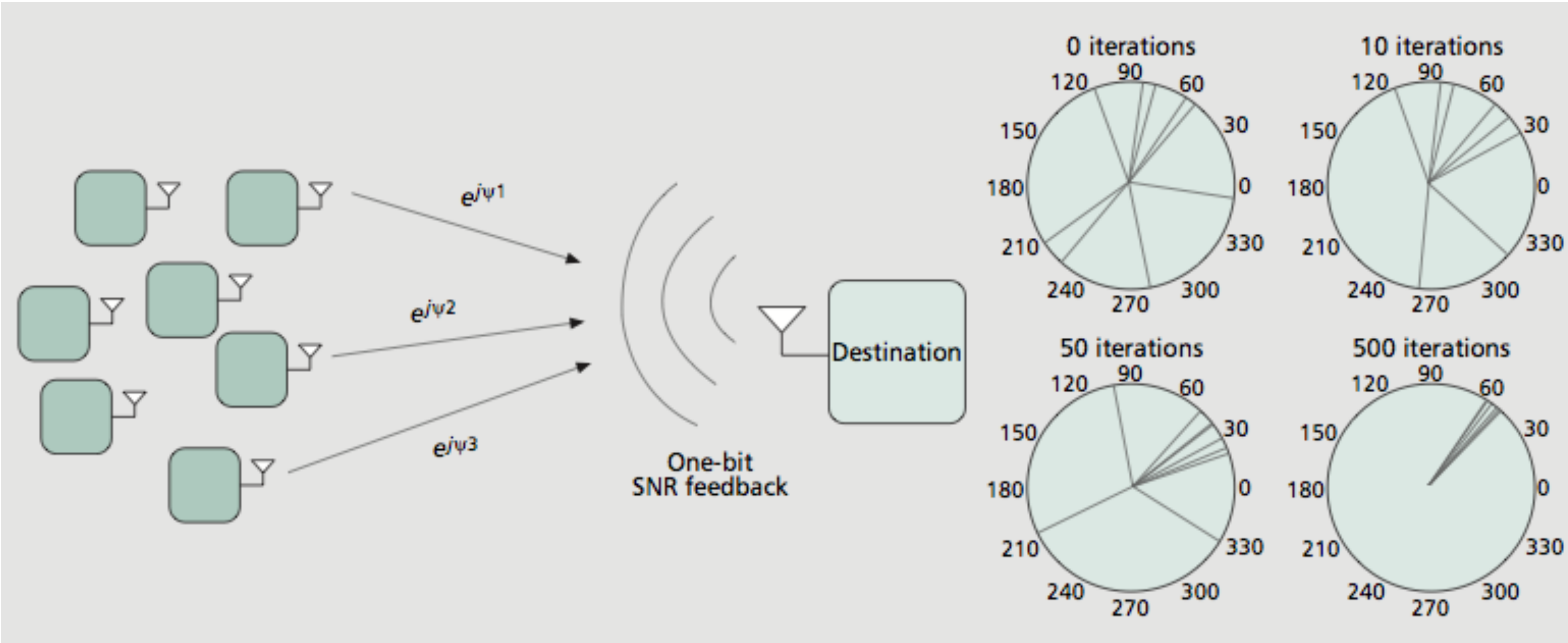


Stringent phase/freq sync requirements

But even good oscillators drift

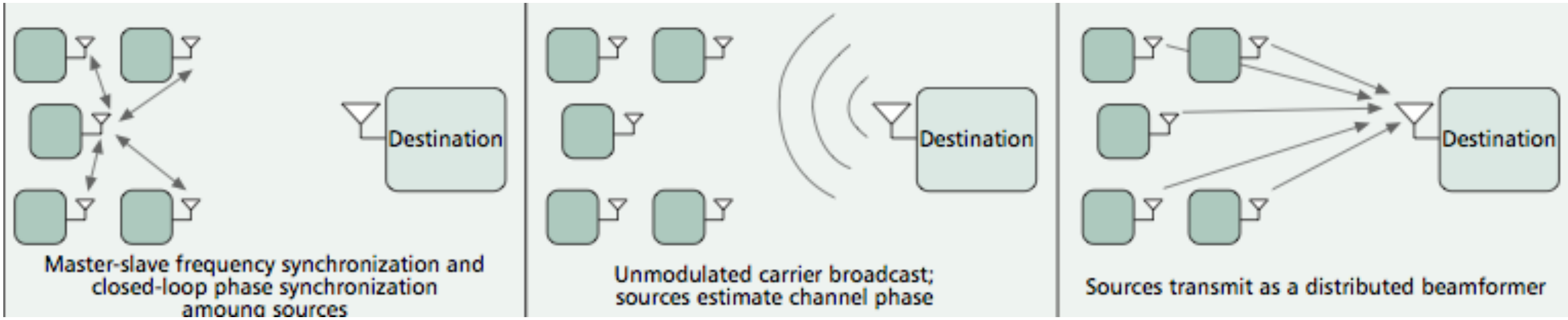
And mobility causes Doppler shifts

One approach: explicit feedback



Decentralized randomized ascent based on one bit feedback

Another approach: pre-synchronization

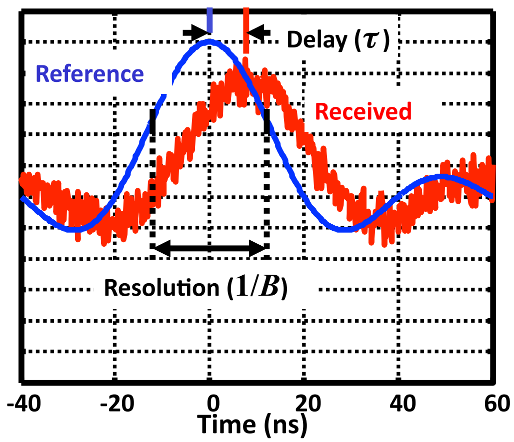


Can pre-synchronize distributed array in phase and frequency
Then use implicit feedback (reciprocity)

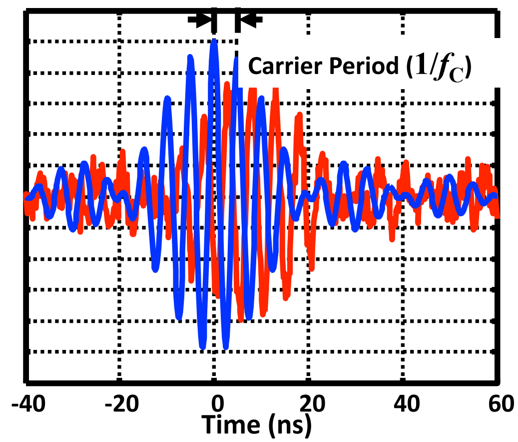
Reaching fundamental limits in timing sync

Accuracy within *small fraction of carrier period* with sufficient SNR

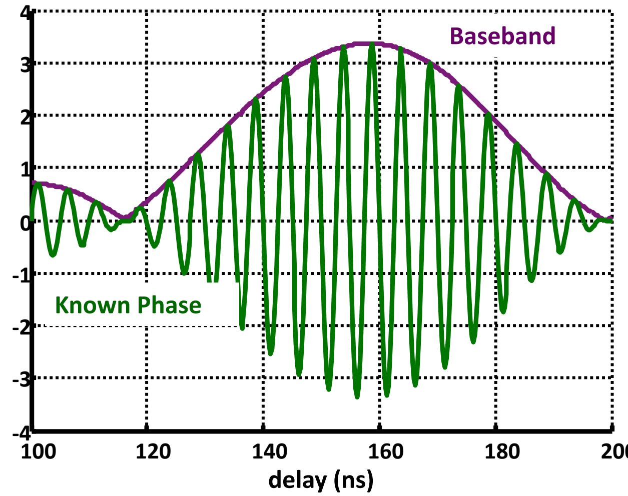
Baseband Waveform



Waveform on Carrier



Likelihood Function



Baseband CRLB:

$$\mathrm{var}_{BB}(\hat{\tau}) \ge \frac{3/\pi^2}{BT\,SNR\,B^2}$$

Post-Integration SNR | Square Bandwidth

Known Phase CRLB:

$$\mathrm{var}_{NB}(\hat{\tau}) \ge \frac{1/8\pi^2}{BT\,SNR\,f_C^2}$$

Post-Integration SNR | Square Frequency

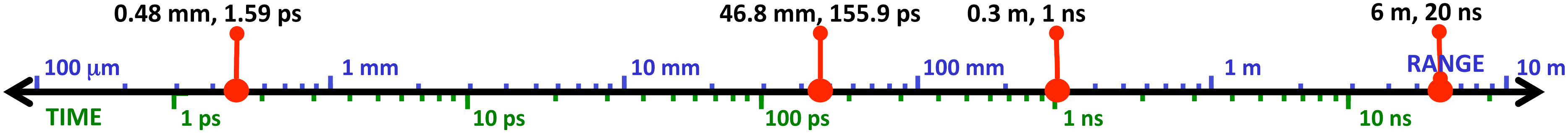
Example: f_C = 1 GHz, B = 50 MHz, T = 10 μs, SNR = 10 dB

Known Phase CRLB
0.48 mm, 1.59 ps

Baseband CRLB
46.8 mm, 155.9 ps

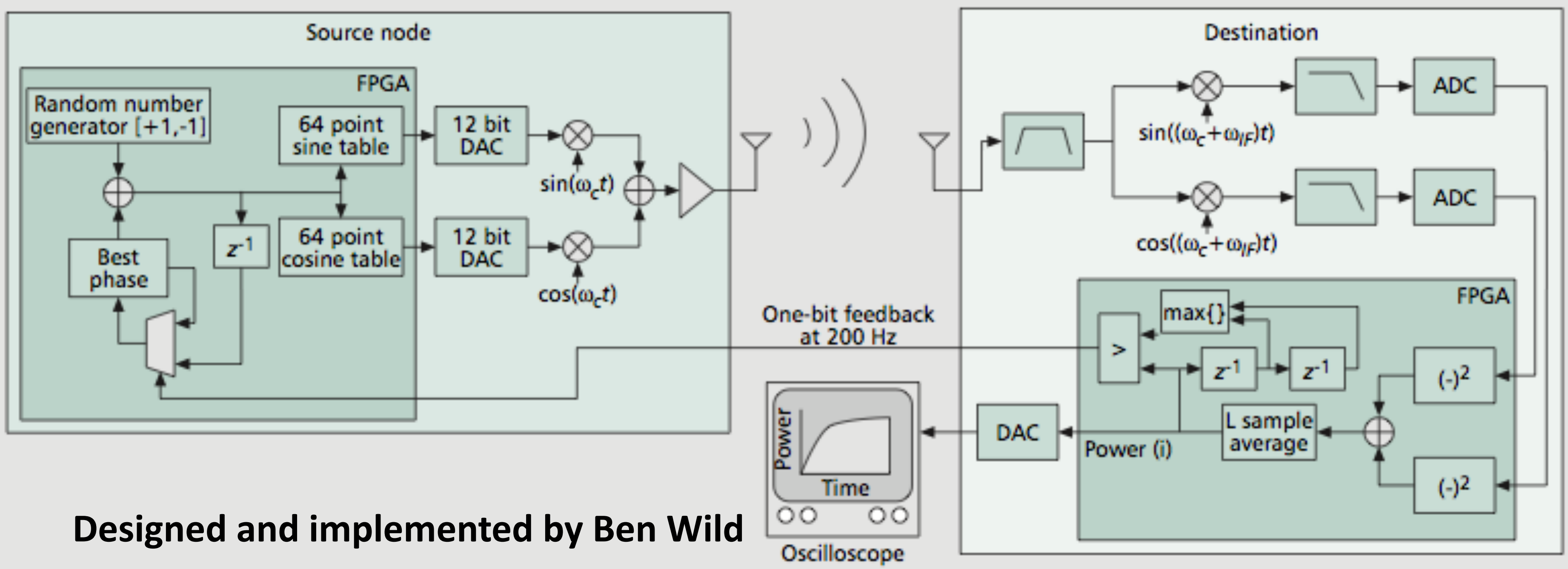
Carrier Period
0.3 m, 1 ns

Resolution
6 m, 20 ns

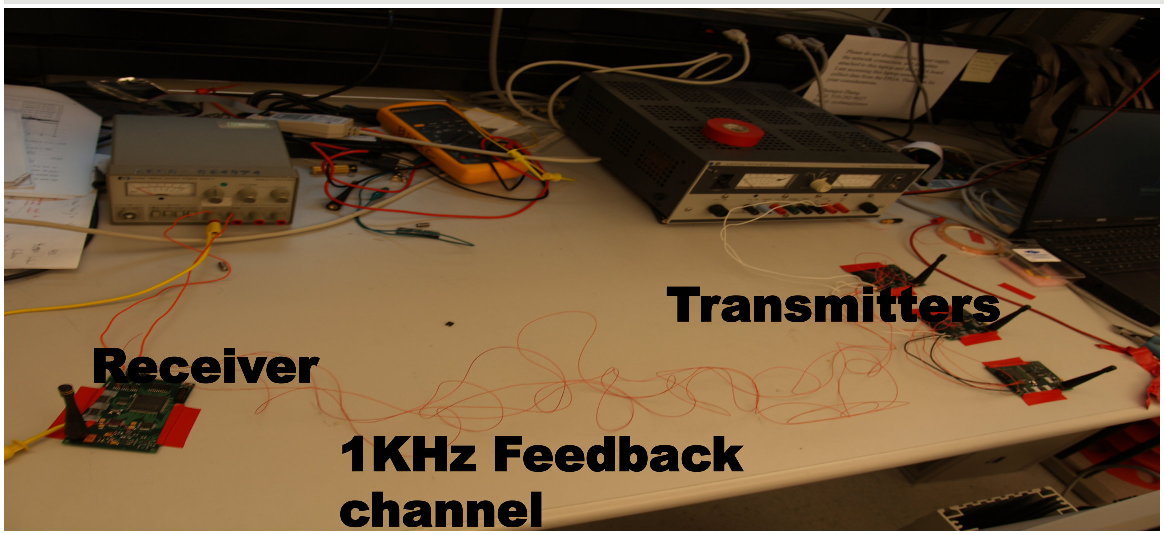


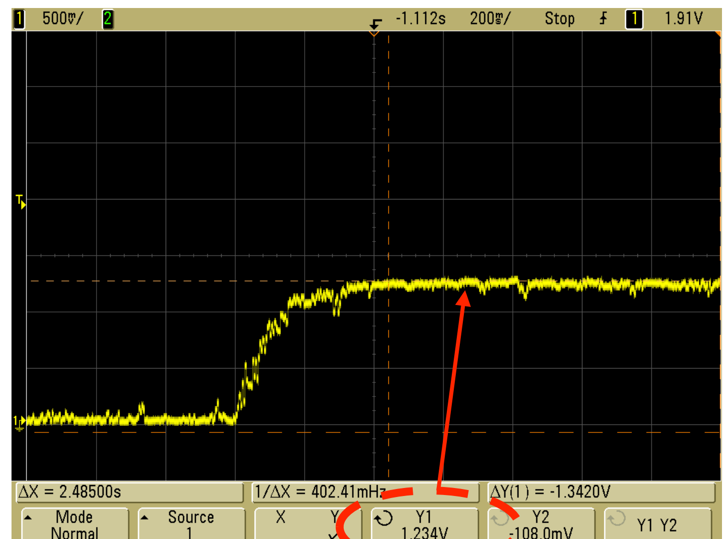
Weinstein & Weiss, *Fundamental Limits in Passive Time Delay Estimation – Part I: Wide-Band Systems* IEEE Trans ASSP-32 No. 2

Early prototype with wired feedback

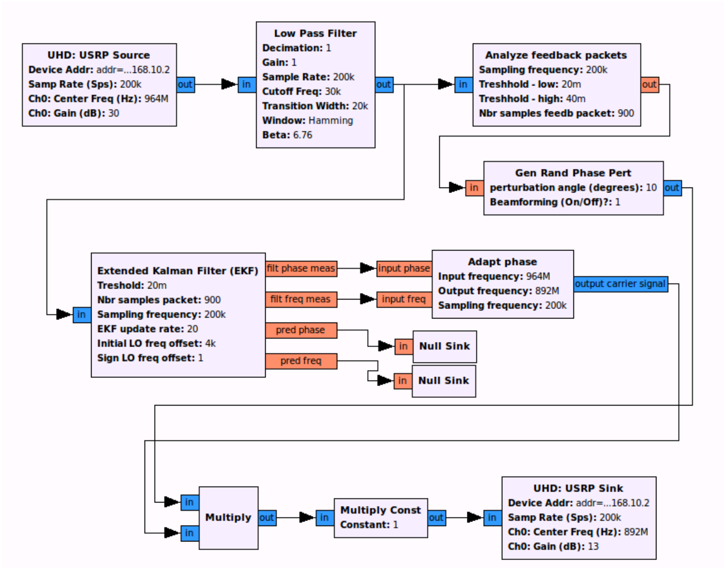


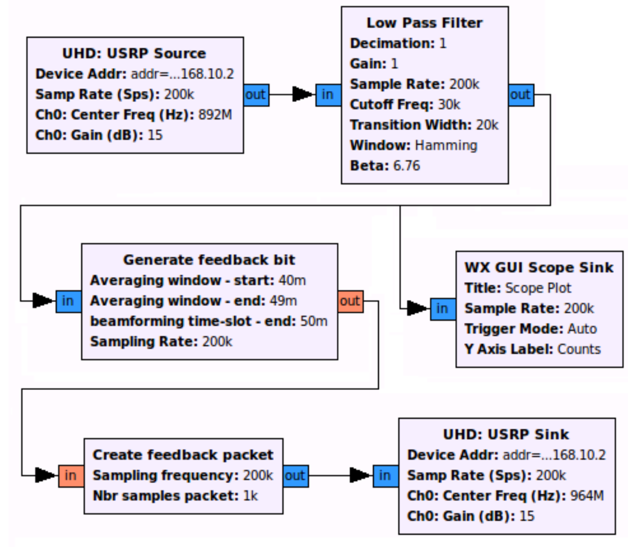
Designed and implemented by Ben Wild





Today: all-wireless demo (software-defined radios)

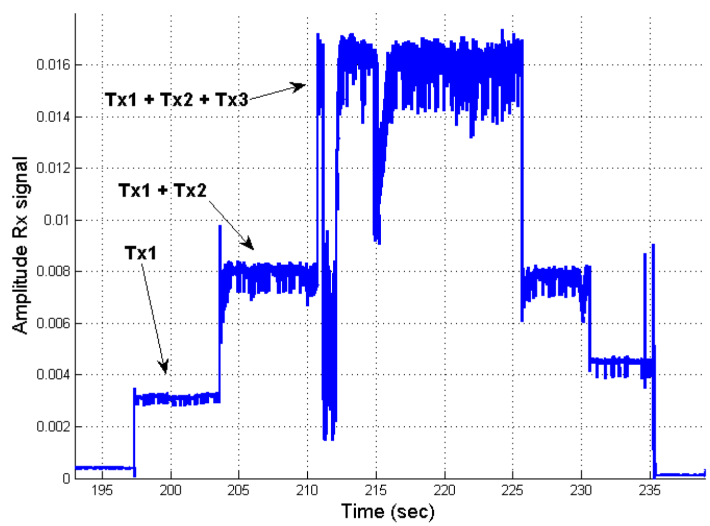




Transmitter synchronize freq to receiver's using EKF
Use fb to adjust phase

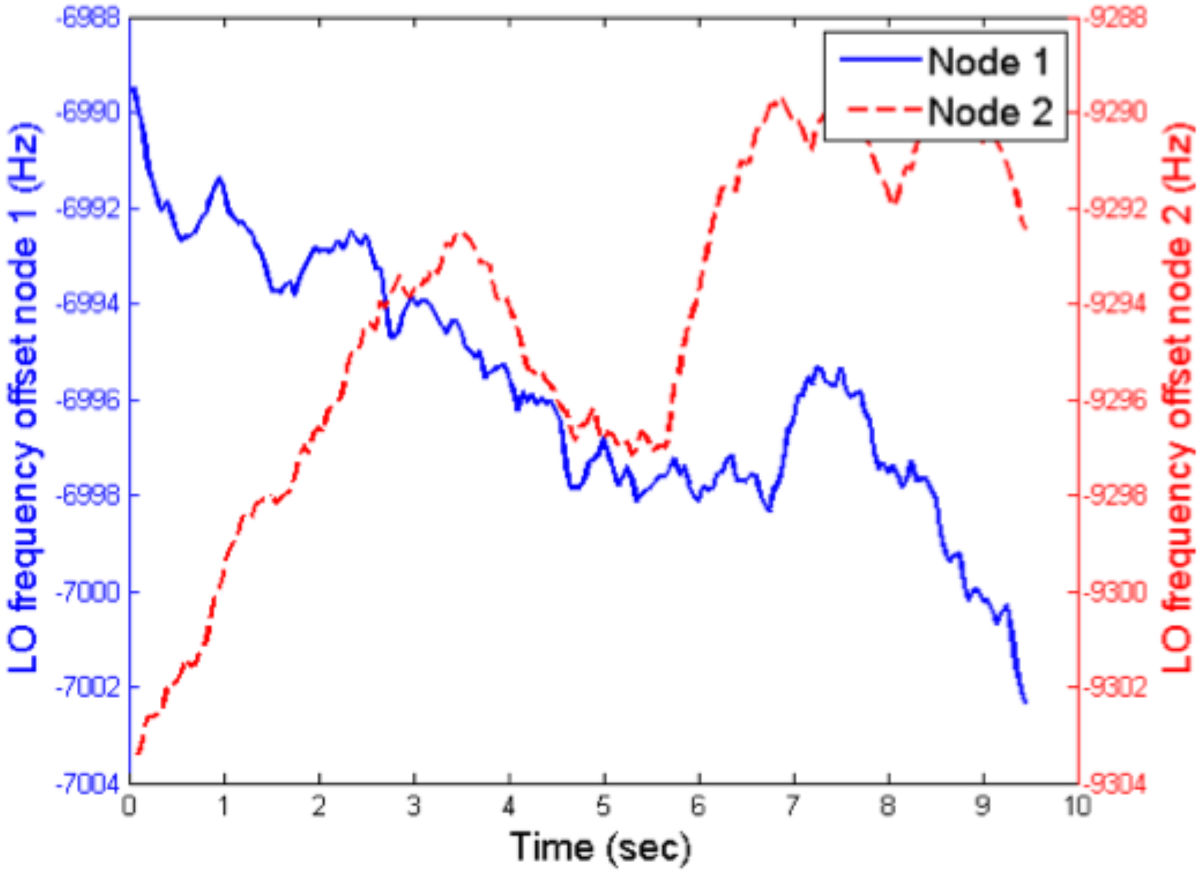
Receiver sends 1-bit fb packets

LIVE DEMO AT WoWMoM 2012



Close to ideal beamforming despite poor quality LOs

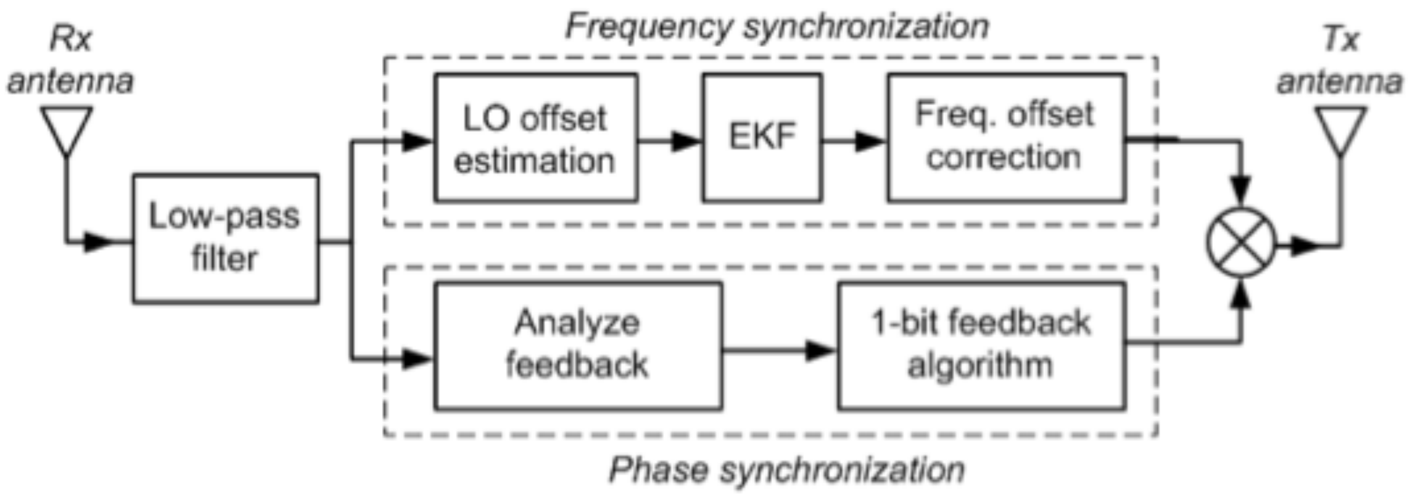
The problem: terrible LOs

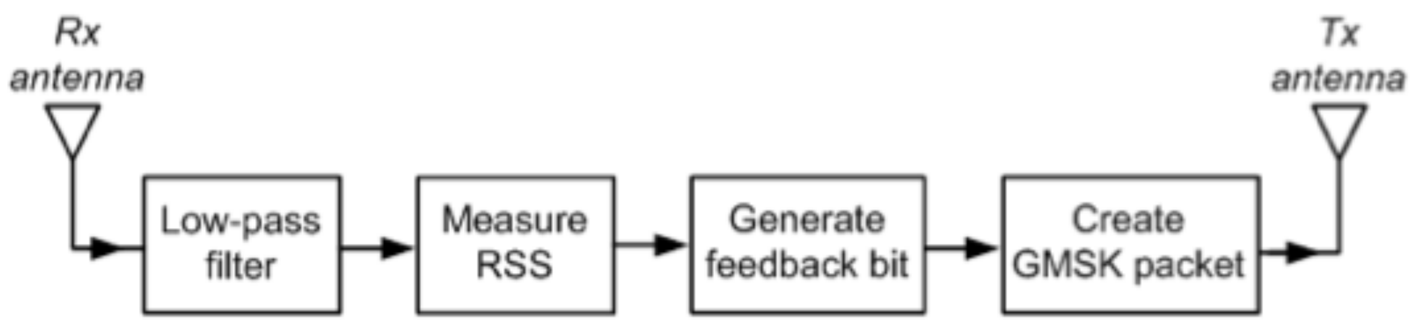


Distributed transmission: key ideas

- USRP radios have bad oscillators
  - Large offsets, rapid frequency drift
  - Must do frequency sync frequently
  - Extended Kalman filter for robustness to phase unwrapping errors
- One bit feedback for phase sync
  - Works if frequencies have been synchronized
- Use feedback packet waveform for frequency estimate
  - Sync frequencies to that of destination node

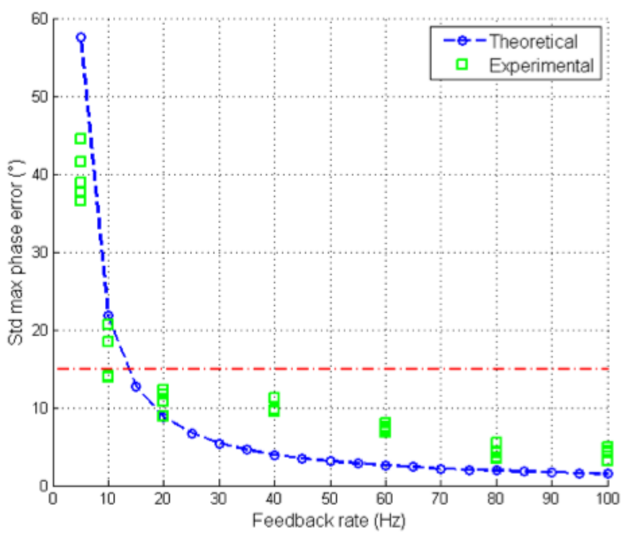
Architecture



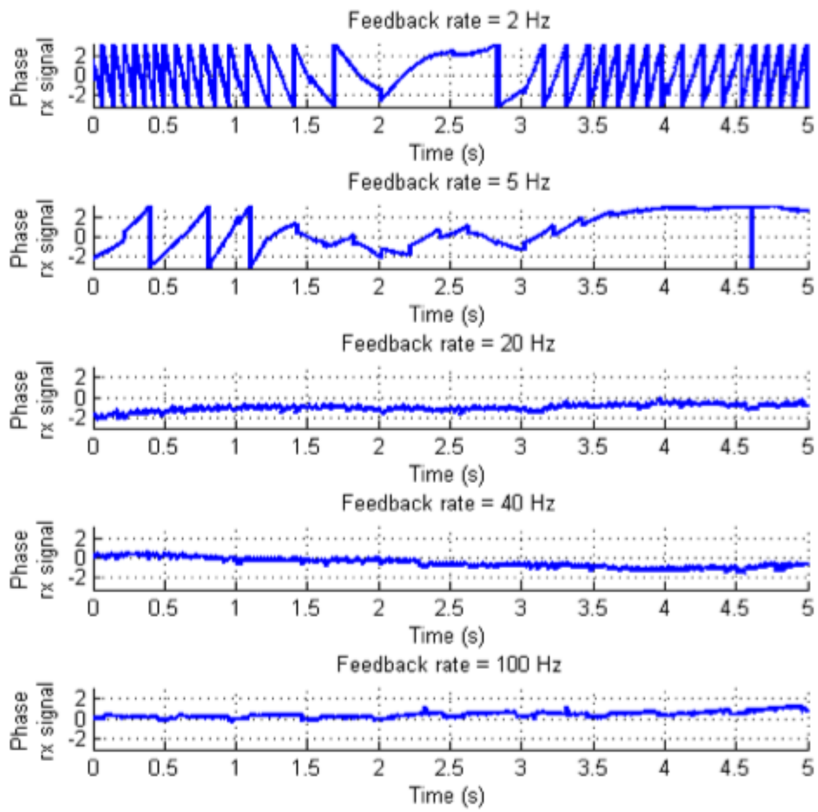


Determining feedback rate

Based on clock modeling

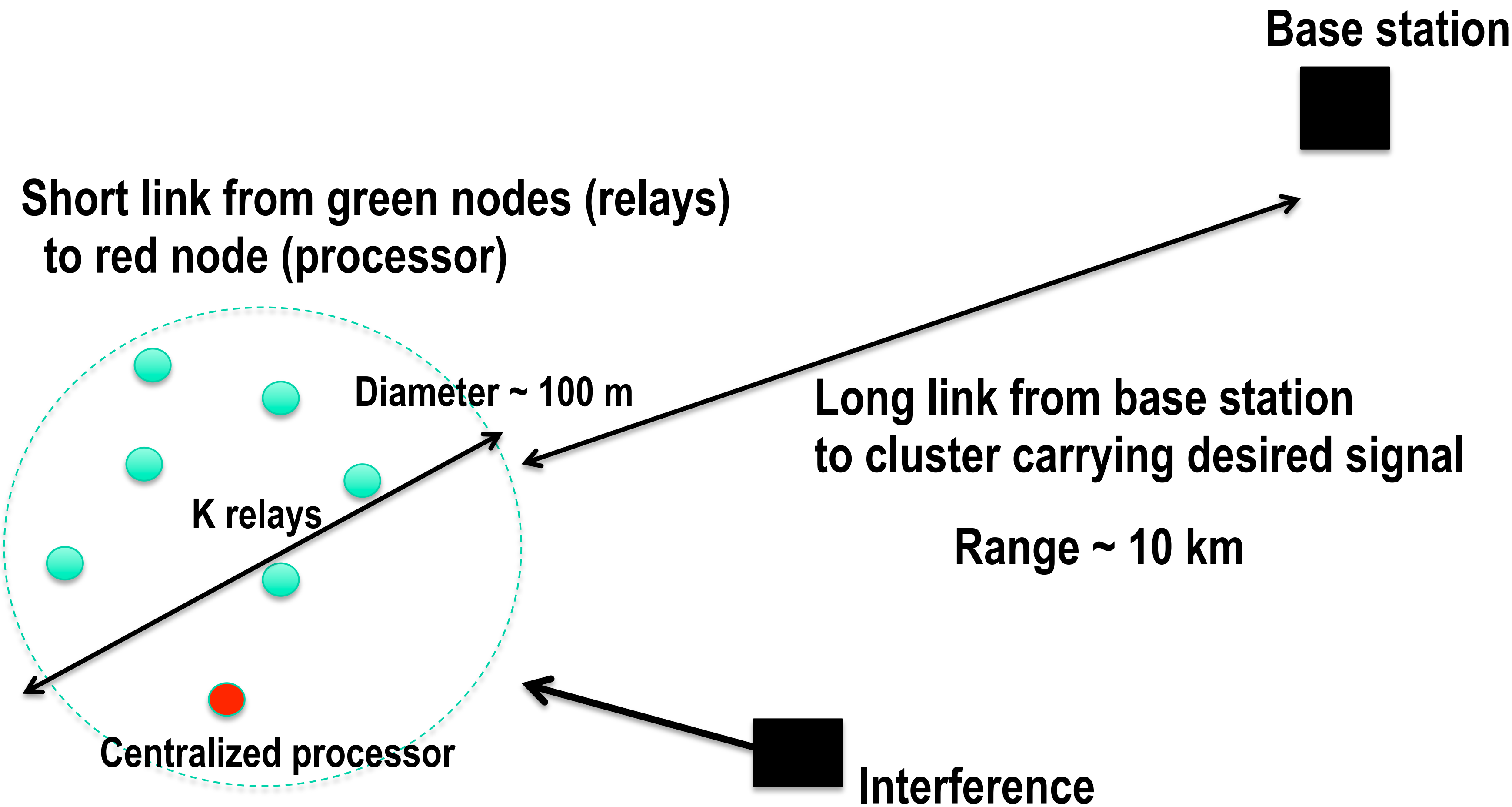


Eyeballing experimental results on freq sync



Clock model provides guidance on feedback rate for freq sync

Distributed reception: system model



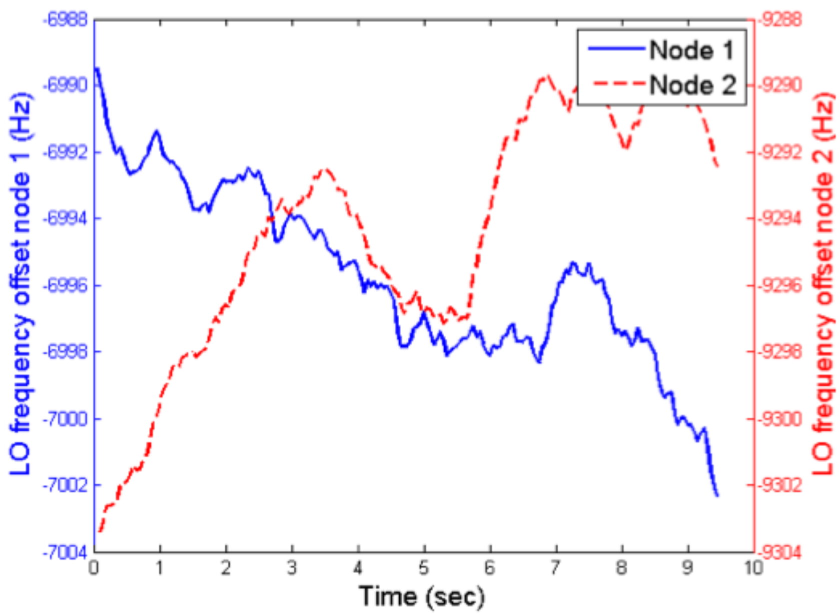
Feedback broadcast from red node (processor) to green nodes (relays)
Can use TDD or FDD for long link/short link multiplexing at relays

How to scale distributed reception?

- Separately sending received signals to centralized processor does not scale
- Key idea: All receiving nodes transmit simultaneously for “in air” linear combining
- Turns distributed receive beamforming on long link into distributed transmit beamforming on short link
- In other words, amplify-and-forward (generalizes to filter-and-forward)
  - Lots of papers, nothing on synchronization!

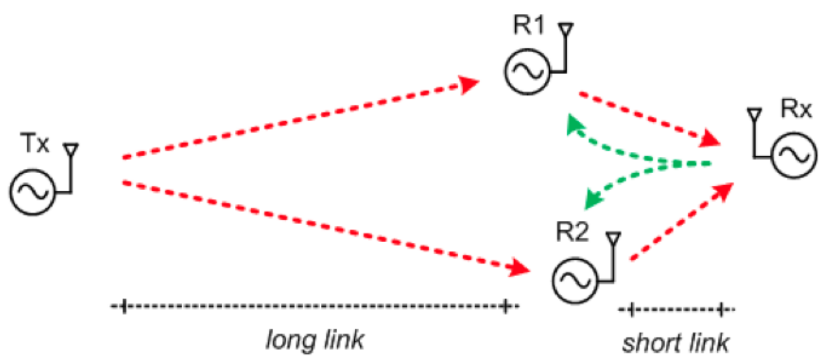
Freq sync not needed for D-RX?

- Base station to relay, relay to processor
  - Relay LO offset cancels out in TDD systems
- What happens with low-quality oscillators?

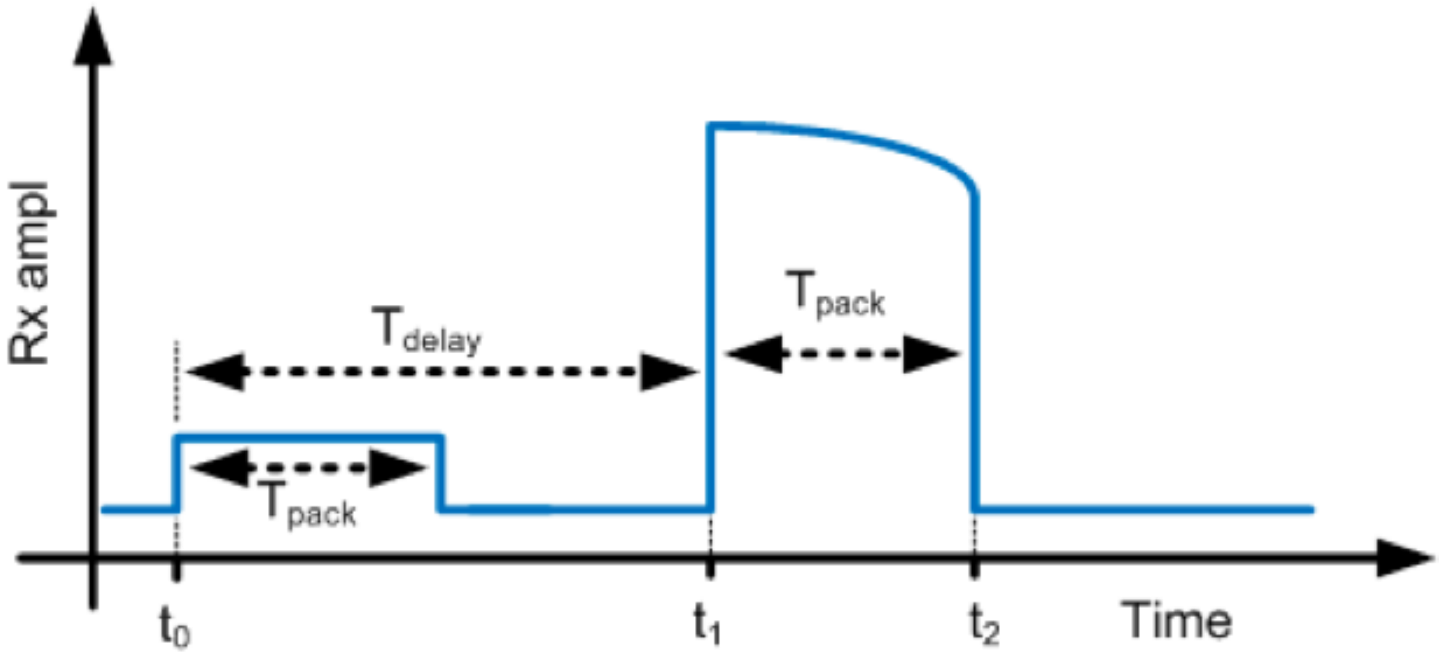


Simple approach to coherence

- No frequency sync at relays
  - Need to account for frequency drift in design
  - Make relaying delay short enough
- Implicit timing sync
  - Use timing of packets received over long link to transmit over short link
- Phase sync using one bit feedback using side channel over short lin'-

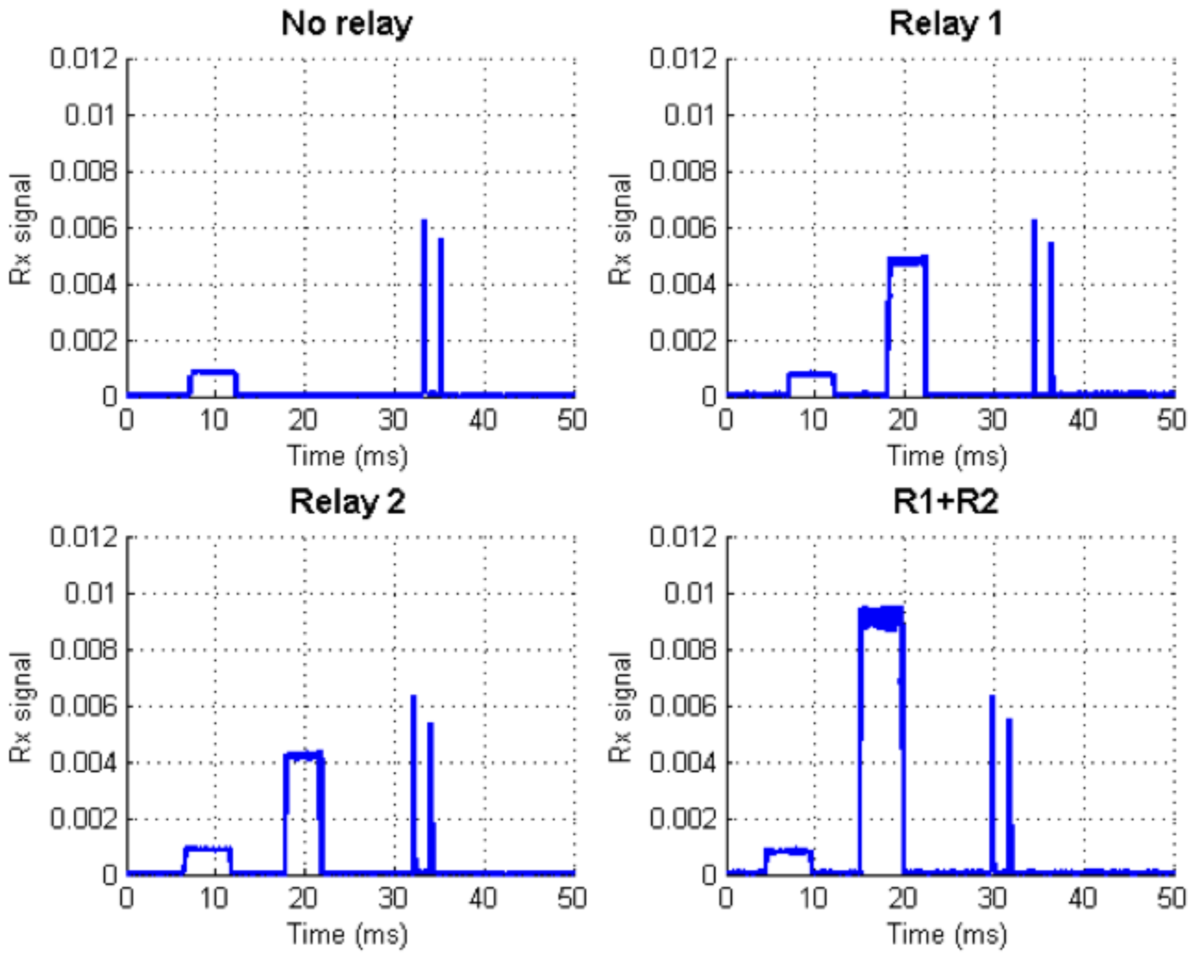


The effect of relaying delay

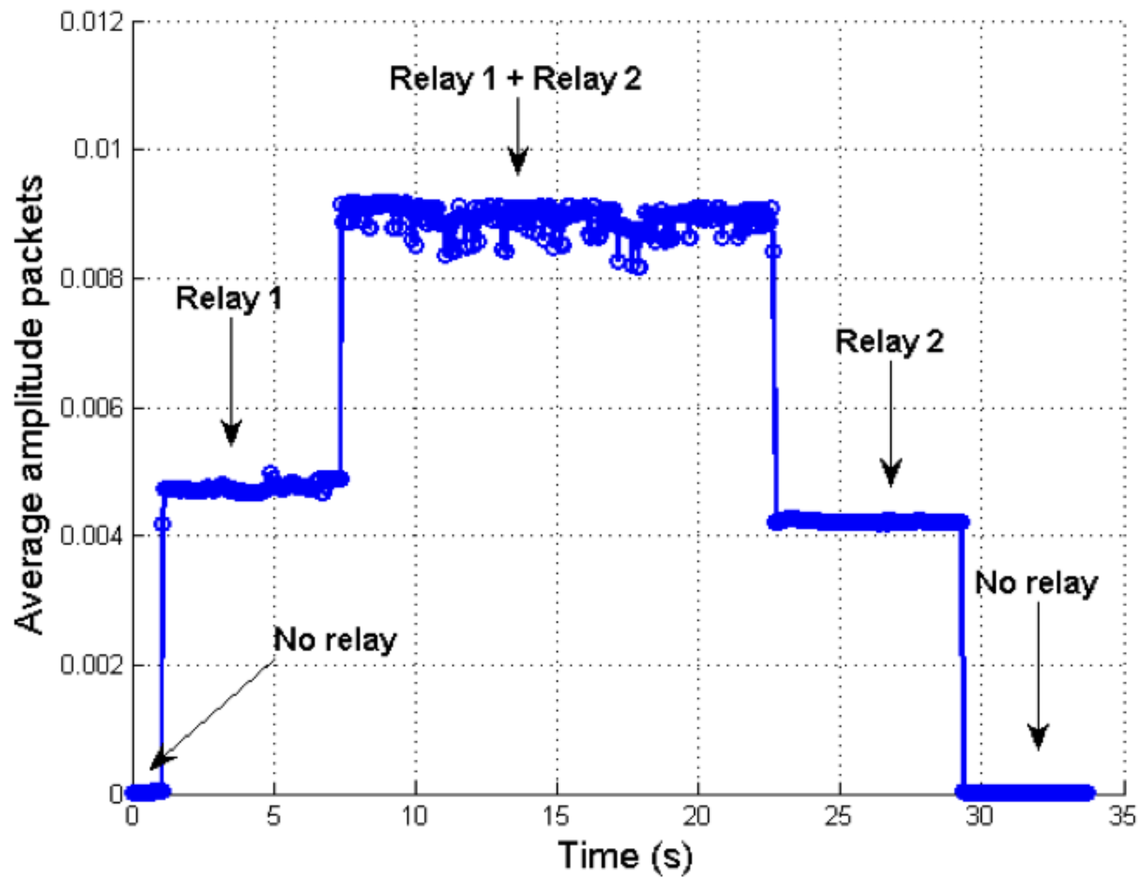


Even with USRP oscillators, can afford as much as 100 ms delay without compromising receive beamforming

Typical frames



Demo: D-RX for windowed sinusoid



Evolution of received amplitude of relayed packets over multiple frames

D-MIMO Take-aways

- Potential for making MIMO truly ubiquitous
- Significant progress in theory and practice
  - Distributed transmit beamforming
  - Distributed receive beamforming
  - All-wireless demos
  - Picosecond timing sync
- Huge effort still needed before transition out of the lab
  - Wideband signaling over dispersive channels
  - Rapid mobility
  - Cross-layer protocols
  - System design (e.g., DBS, D911)
  - Pushing further with SDR testbed

D-MIMO: exploring further

One-bit algorithm fundamentals
Mudumbai et al, *Distributed transmit beamforming using feedback control,* IEEE Trans. Information Theory, Jan 2010.
SDR Testbed
Quitin, Rahman, Mudumbai, Madhow, *Distributed beamforming with software-defined radios: frequency synchronization and digital feedback,* Globecom 2012.
Quitin, Rahman, Mudumbai, Madhow, *Demonstrating distributed transmit beamforming with software-defined radios,* live demo at WoWMoM 2012. **(live demo, BEST DEMO AWARD)**
Achieving fundamental limits of timing sync
Bidigare et al*, Attaining fundamental bounds on timing synchronization,* ICASSP 2012.
Bidigare et al, *Initial over-the-air performance assessment of ranging and clock synchronization using radio frequency signal exchange,* SSP 2012.
Per-user feedback based schemes
Brown et al, *Receiver-coordinated distributed transmit beamforming with kinematic tracking,* ICASSP 2012.
Brown et al, *Receiver-coordinated distributed transmit nullforming with channel state uncertainty,* ICASSP 2012.

Wireless-enabled multi-agent systems (SMARTER)

Prof. Joao Hespanha

Dr. Sriram Venkateswaran, Dr. Jason Isaacs

Dinesh Ramasamy, Aseem Wadhwa

Dr. Tien Pham, Dr. Brian Sadler (ARL)

Two examples

- Space-time localization using acoustic sensors
  - Bio-inspiration to sidestep combinatorial explosion
- Following an RF beacon to its source
  - Bio-inspiration to negotiate local optima

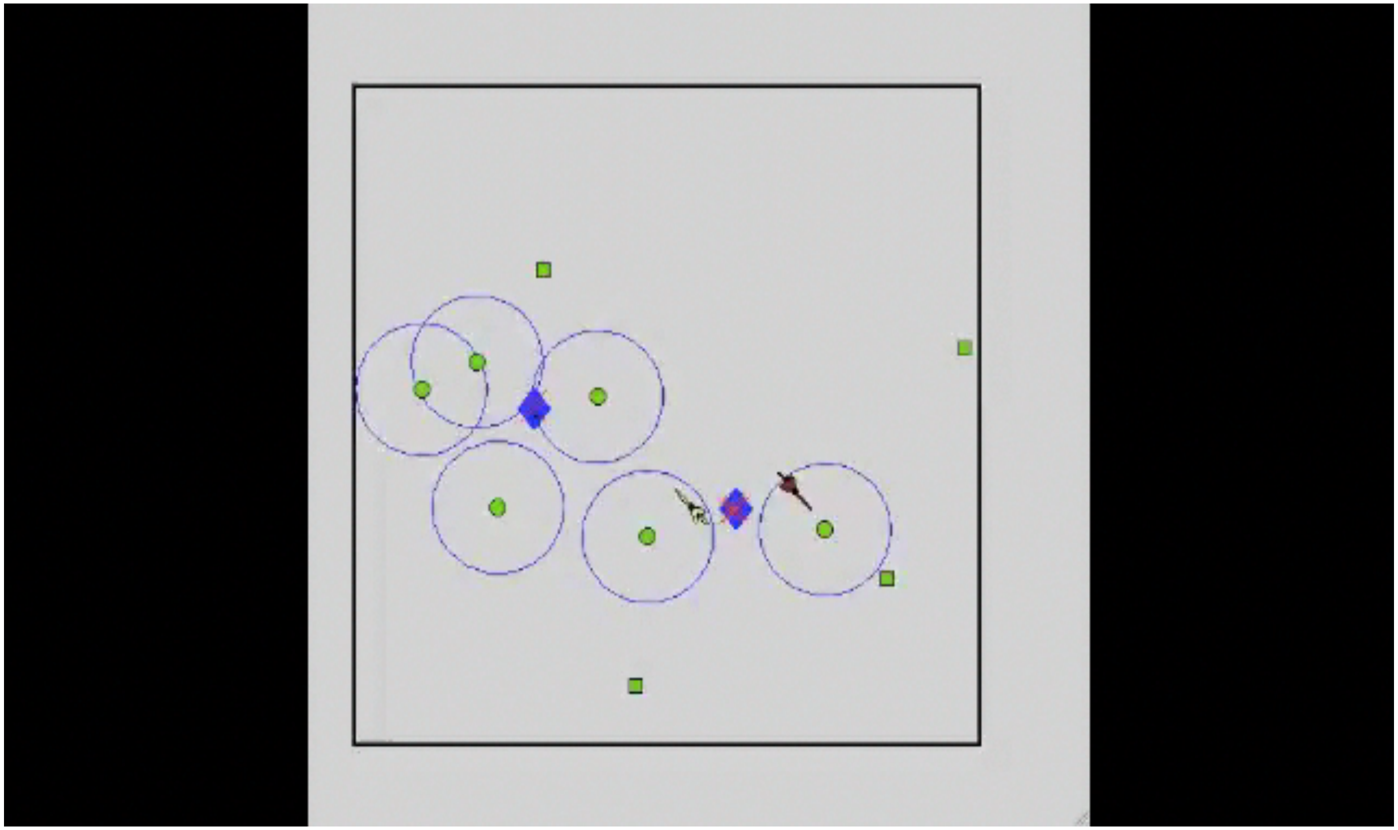
Space-time localization with UAV data mules

Real-time localization of multiple acoustic sources

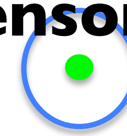
Sparse network of acoustic sensors

UAV data mule

Field demonstration

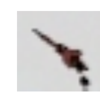


ToA Sensors



Source

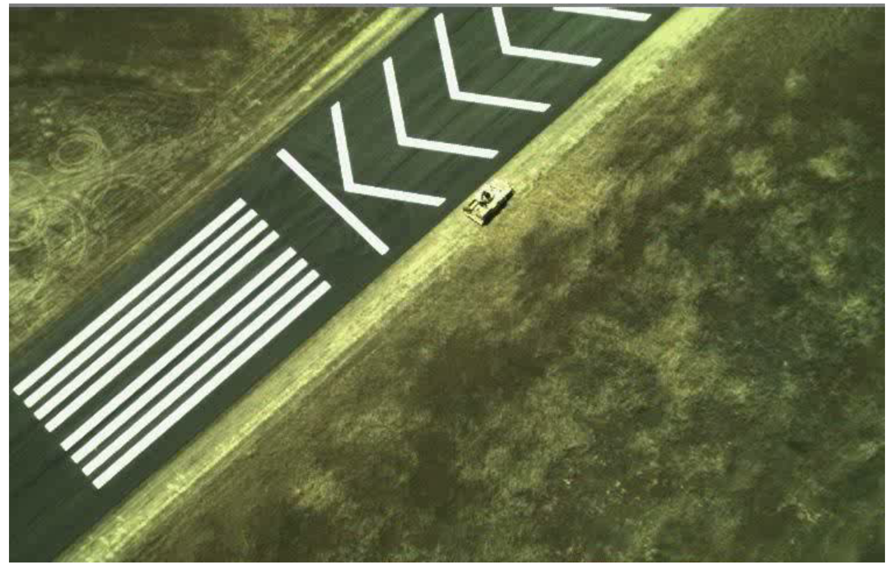
UAV



S. Venkateswaran, J. Isaacs, Prof. J. Hespanha, D. Klein UCSB
G. Collins, M. Wiatt Toyon
F. Bergamaschi, D. Conway-Jones IBM-UK
J. Burman Teledyne
T. Pham ARL
S. Quintero, A. Wadhwa UCSB

Field demonstration

Localization Performance



Cannon #1

Cannon #2

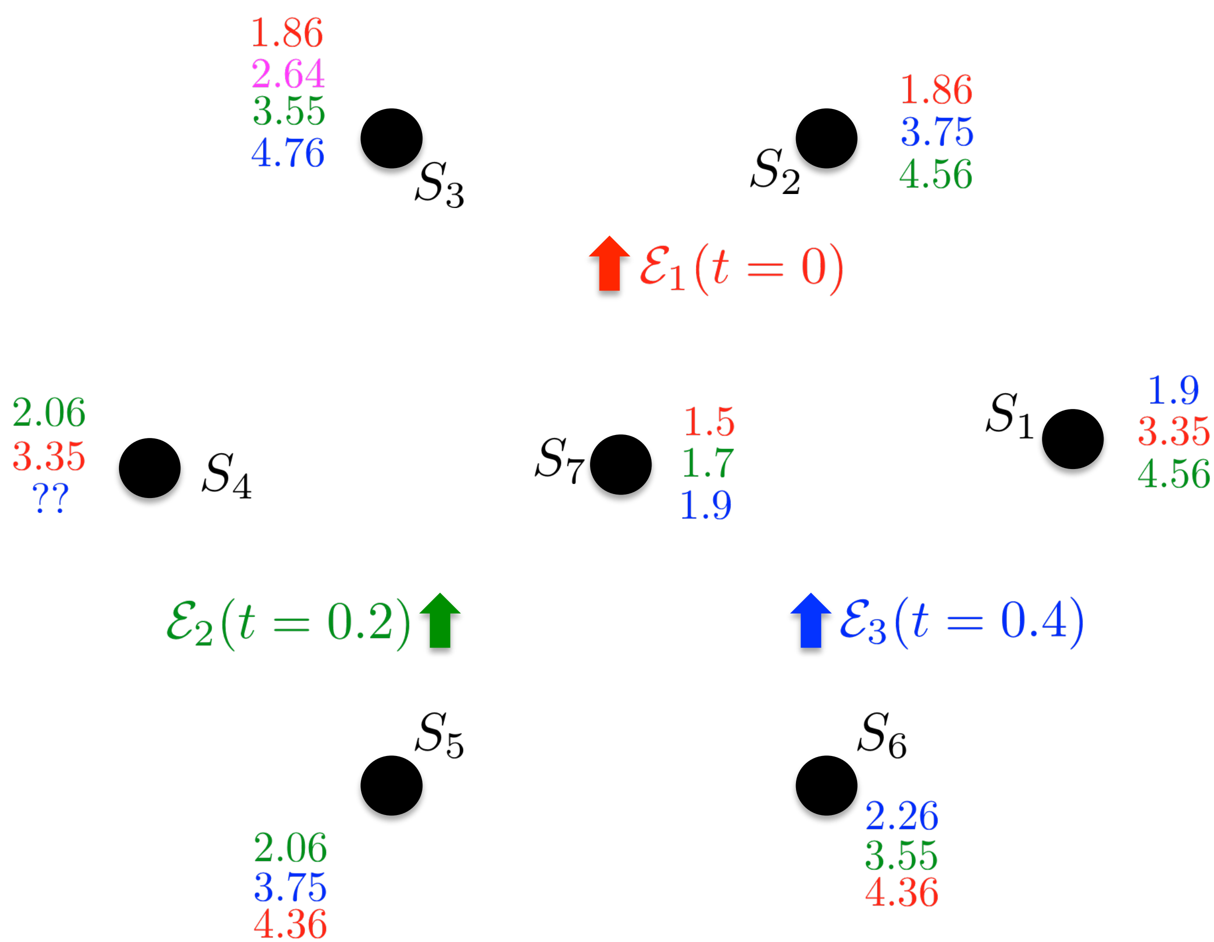
What's inside the demo

- Space-time localization using only times of arrival
  - Bio-inspired approach to processing to avoid combinatorial explosion in complexity
- UAV routing for optimizing data collection

Inside the demo
Space-time localization using ToAs

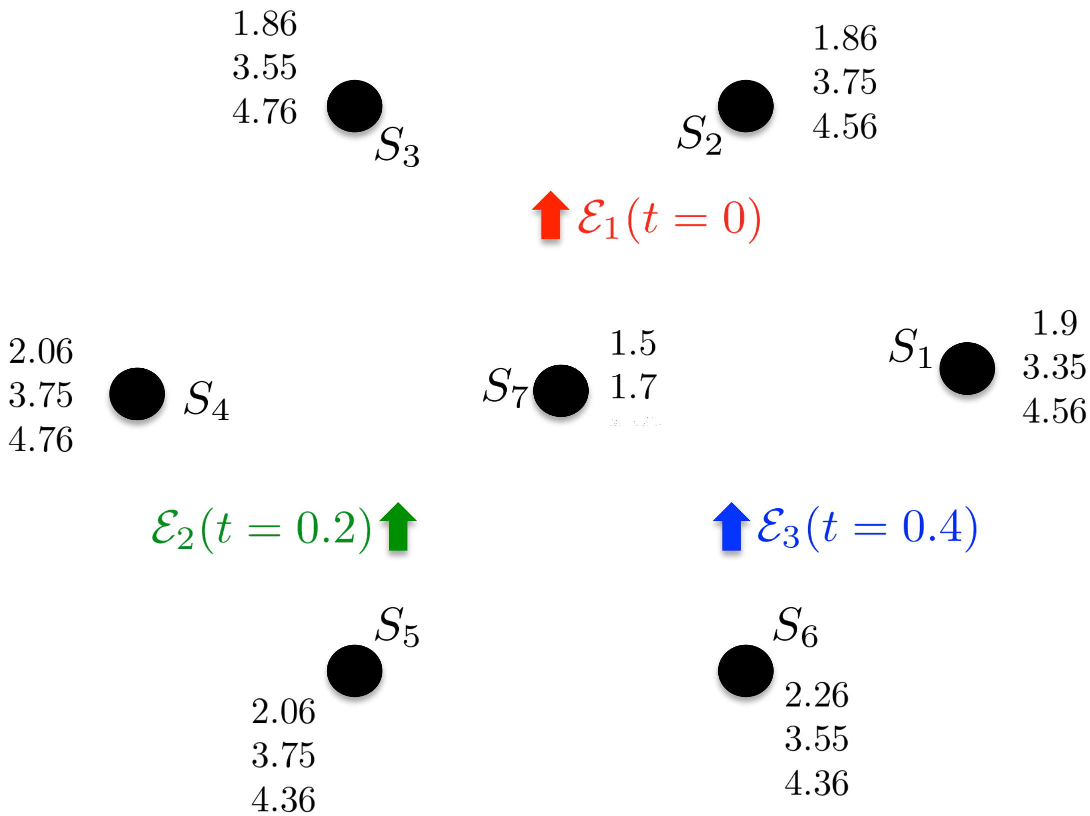
Dr. Sriram Venkateswaran

The problem with ToAs



Event orders can flip
Outliers and misses must be included in the framework

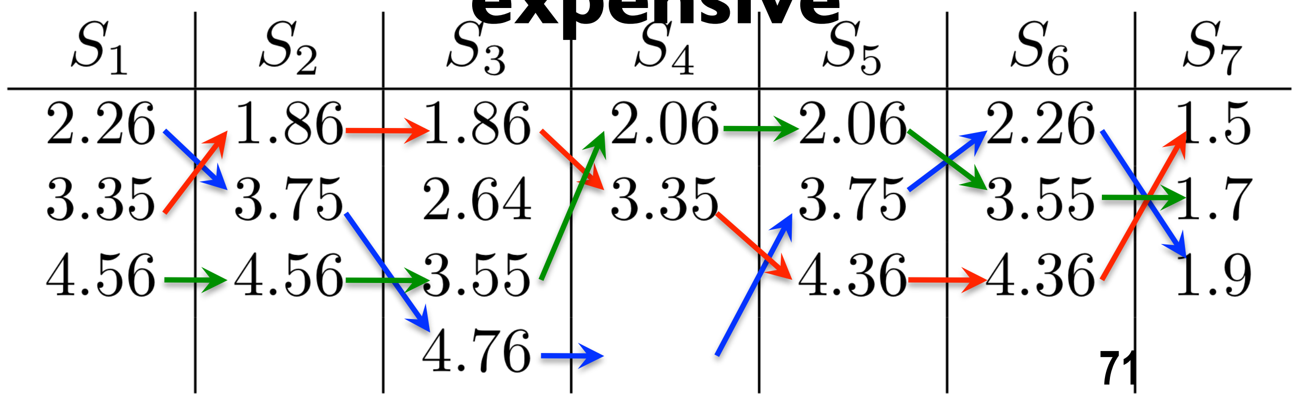
Info at the sensors: list of ToAs



What to do with a list of ToAs

S_1	S_2	S_3	S_4	S_5	S_6	S_7
2.26	1.86	1.86	2.06	2.06	2.26	1.5
3.35	3.75	2.64	3.35	3.75	3.55	1.7
4.56	4.56	3.55		4.36	4.36	1.9
		4.76				

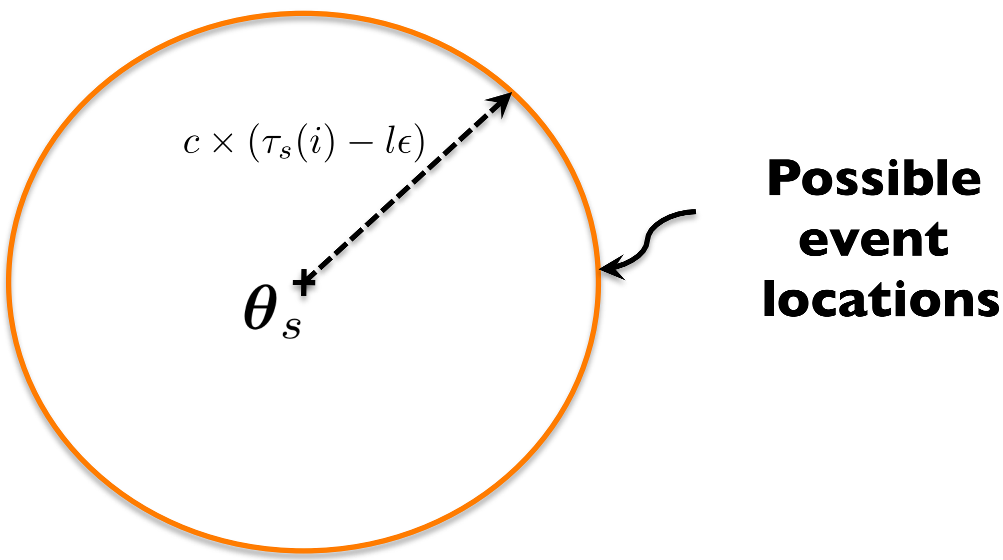
Assigning ToAs to events is the bottleneck
Must handle outliers and misses
Trying all possible combinations too expensive



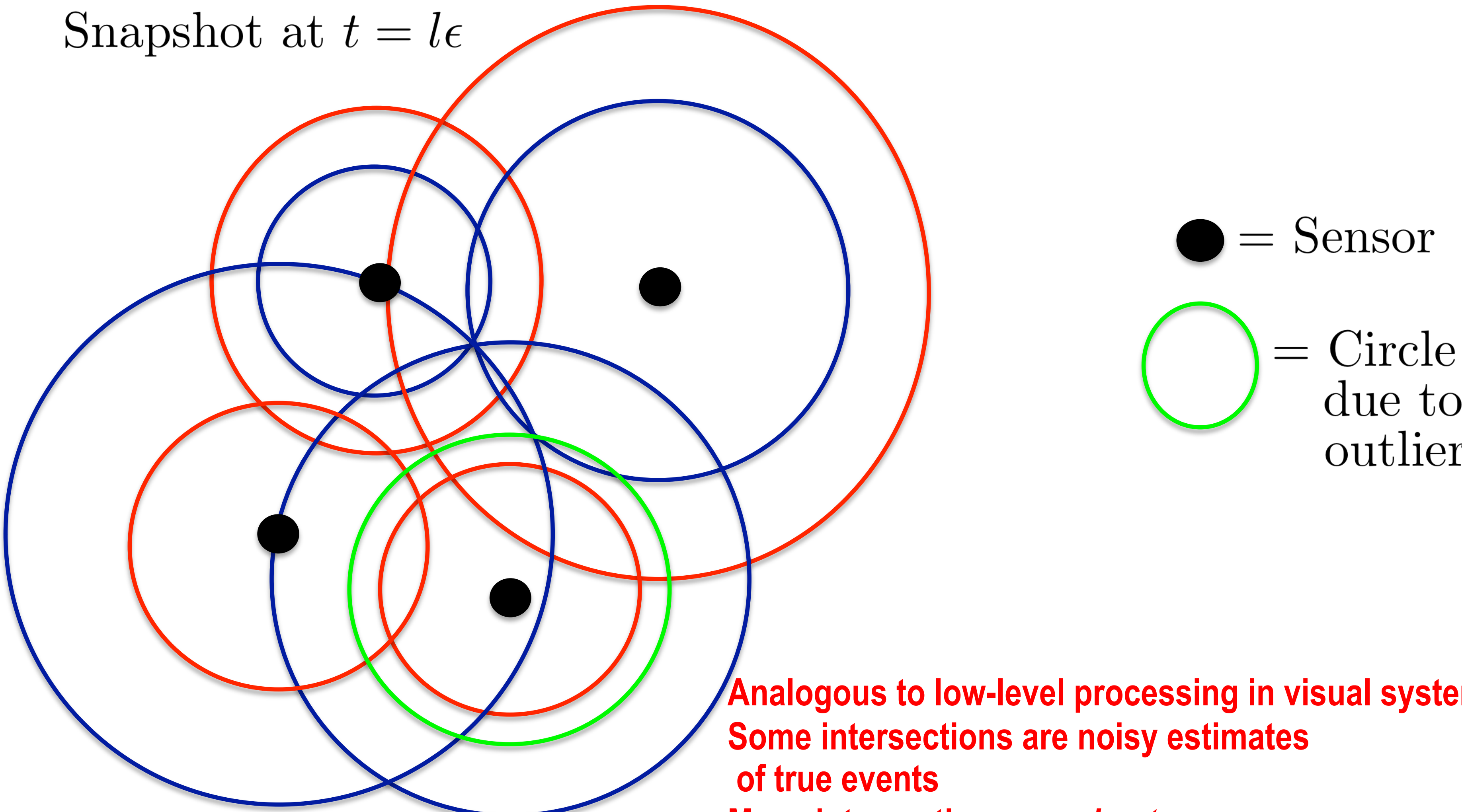
Key idea: hypothesize event times

$$\text{Possible event times}:\ (\ldots, -2\epsilon, -\epsilon, 0, \epsilon, 2\epsilon, \ldots)$$

$$\text{Event at time } l\epsilon$$
$$\text{produces } i\text{th ToA at sensor } s = \tau_s(i)$$
$$\Downarrow$$
$$\text{Propagation delay} = \tau_s(i) - l\epsilon$$



Intersect circles to generate candidates

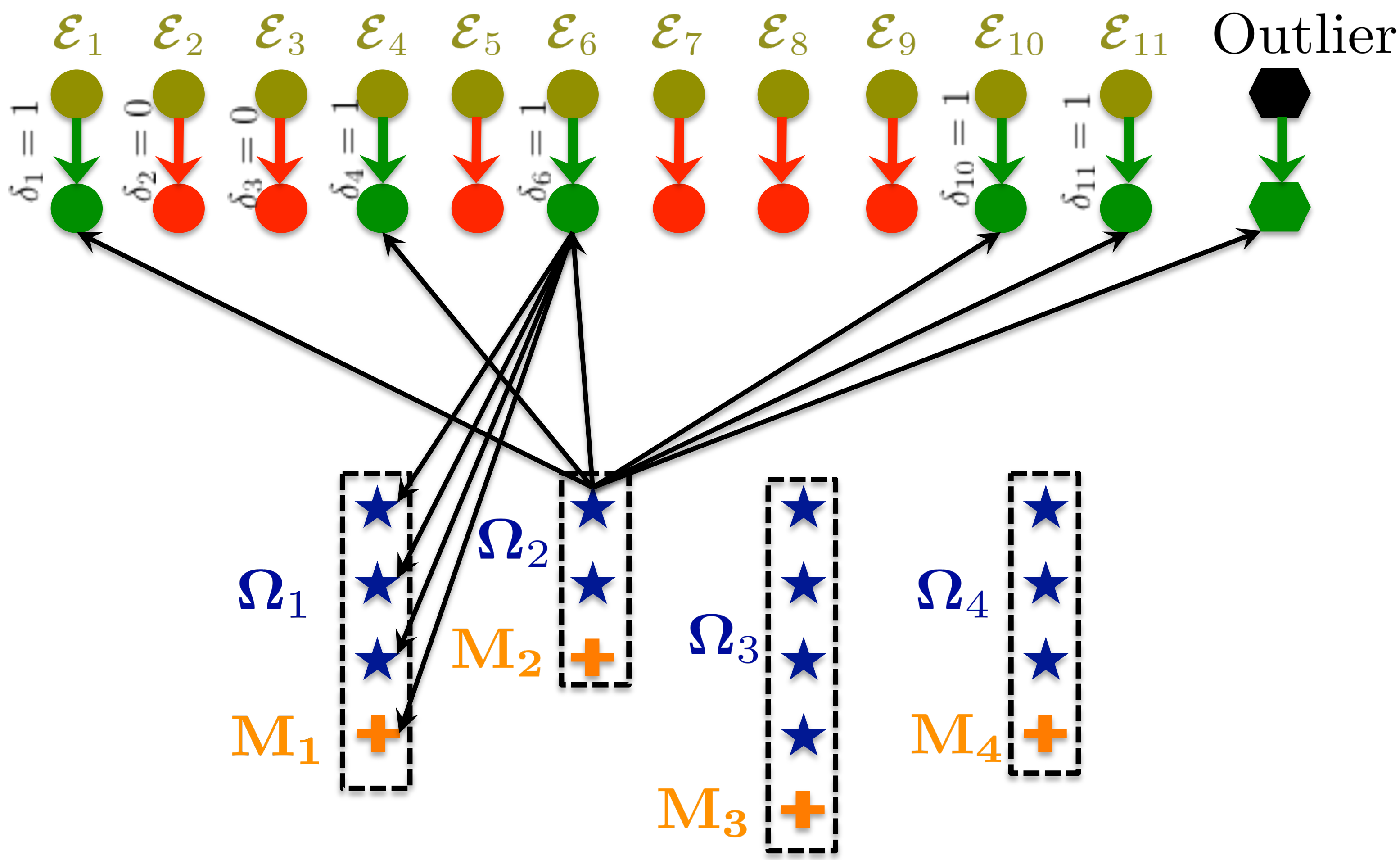


Analogous to low-level processing in visual system
Some intersections are noisy estimates of true events
Many intersections are *phantoms*

Clean-up phase

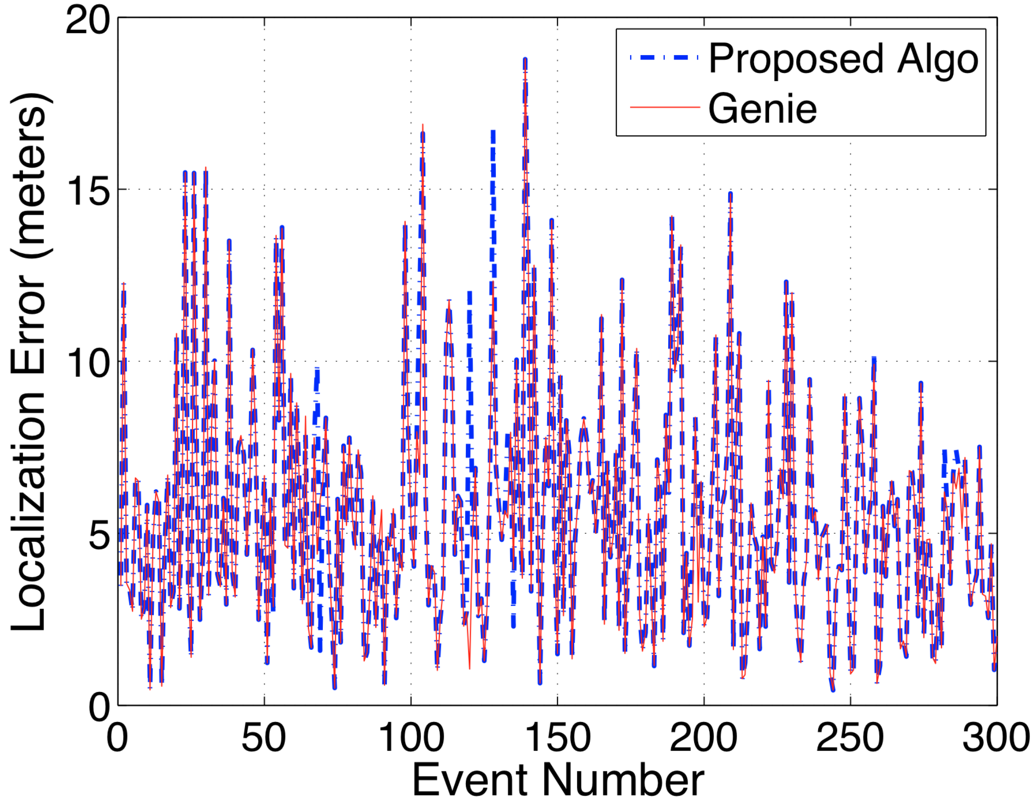
- Noisy estimates and phantoms produced by intersections involving pairs of sensors
- Now use readings on other sensors
  - Stage 1: to discard obvious phantoms
  - Stage 2: to refine space-time locations of survivors
- Then try to match with ToAs

Bayesian reconstruction



Formulate as a binary integer program
Relax and solve as a linear program

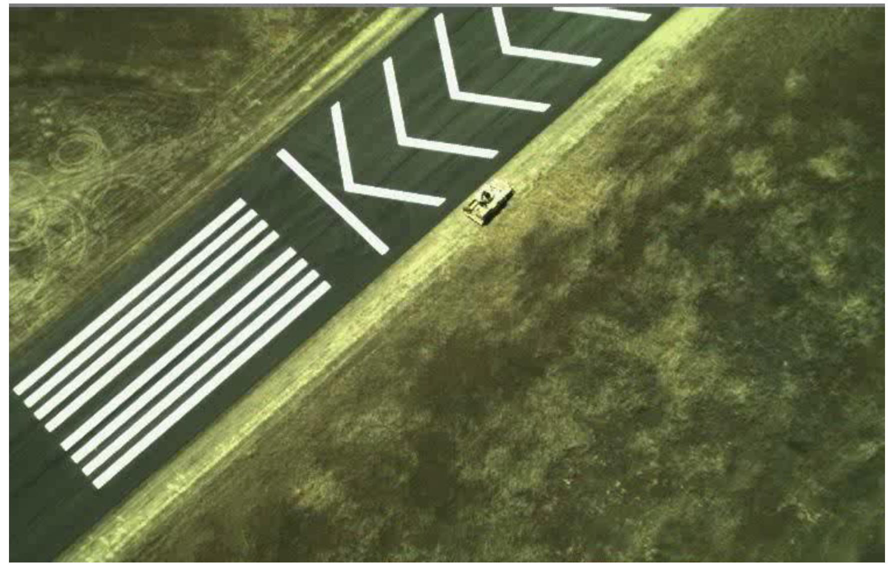
Simulated performance matches Genie



Deployment:
1 km radius

- **Always returns correct number of events (3)**
- **Localization error < 20 m, Average = 5.6 m**
- **Very close to genie, Average genie error = 5.5 m**

Leading to a working demo!



Cannon #1

Cannon #2

Following an RF beacon to its source

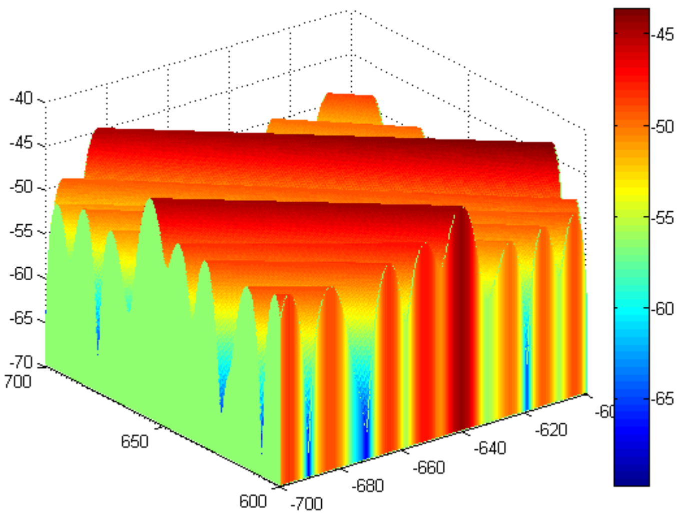
Aseem Wadhwa and Prof. Joao Hespanha (UCSB)

Dr. Brian Sadler (ARL)

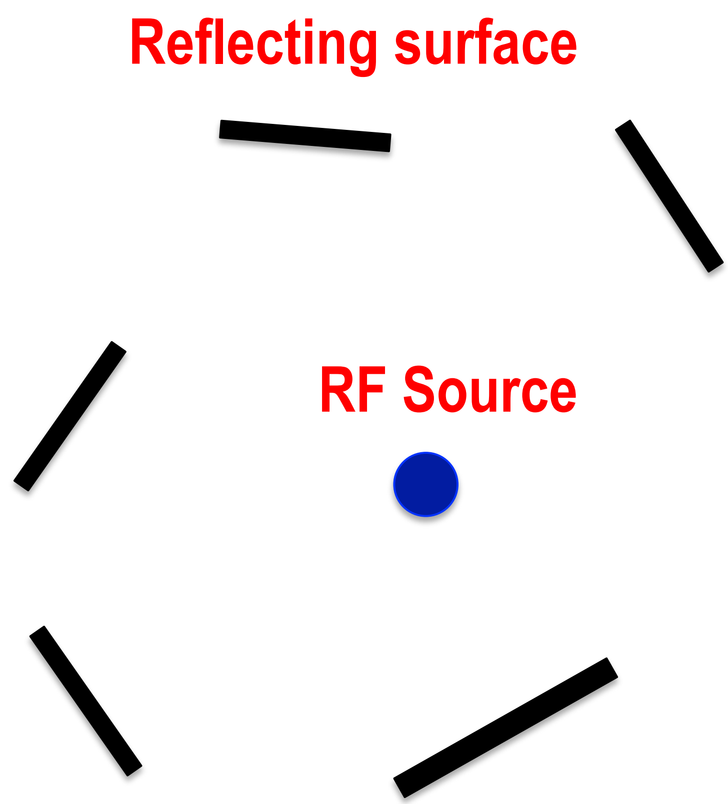
Search and rescue via RF beacons

How to navigate RSS profile towards source?
(fading swamps out path loss)

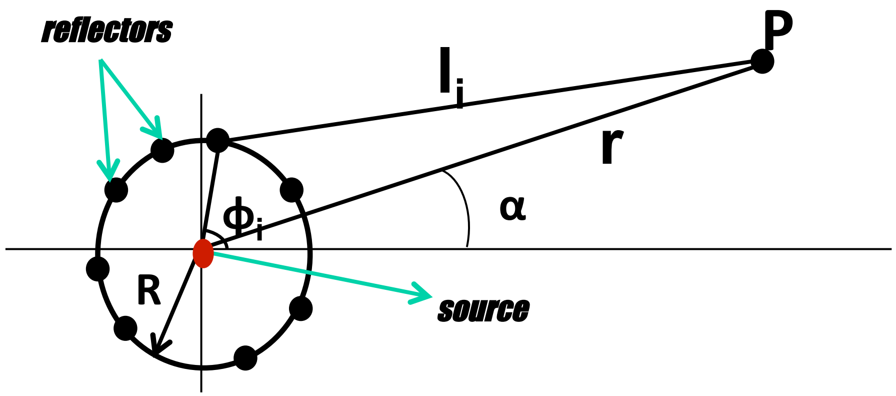
UAV



Spatial profile of
received signal strength



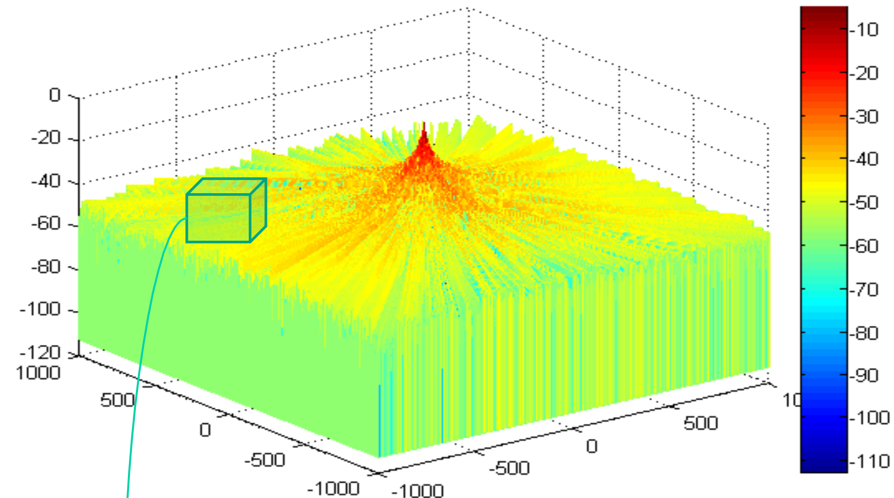
Propagation model



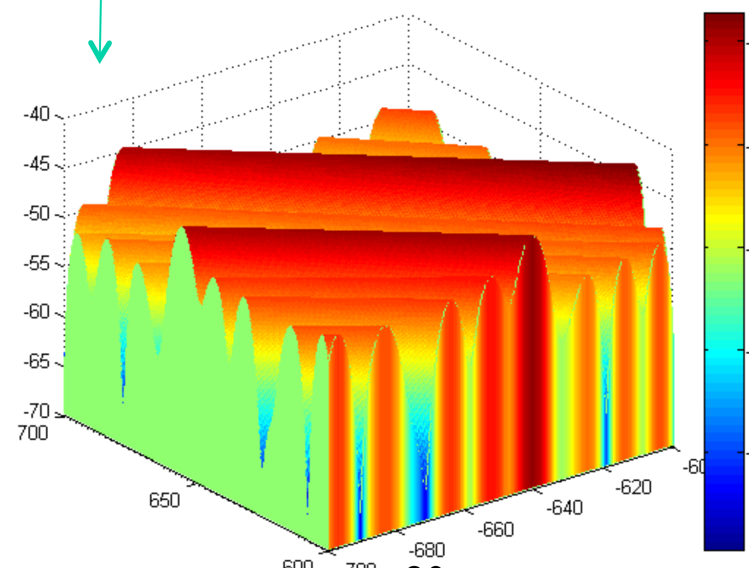
$$EF\left(r,\alpha\right) = \frac{e^{-j\beta r}}{r} + \sum_{i=1}^{T} \frac{\Gamma(i) e^{-j\beta l_i}}{l_i}$$

$$l_i = \sqrt{R^2 + r^2 - 2Rr\cos\left(\phi_i - \alpha\right)} + R$$

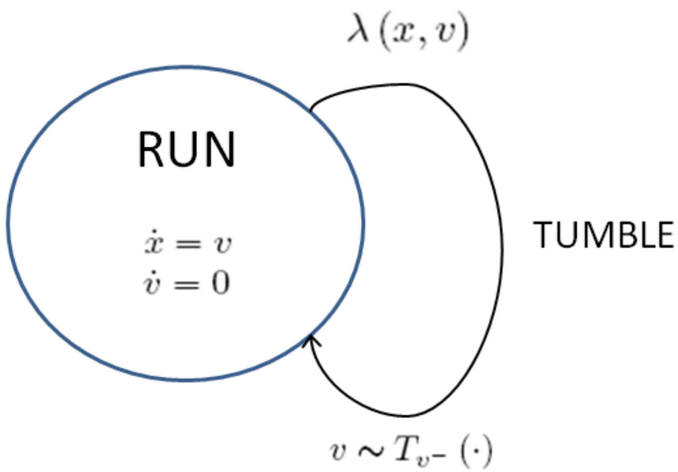
$$RSS\left(r,\alpha\right) = 20log_{10}\left|EF\left(r,\alpha\right)\right|$$

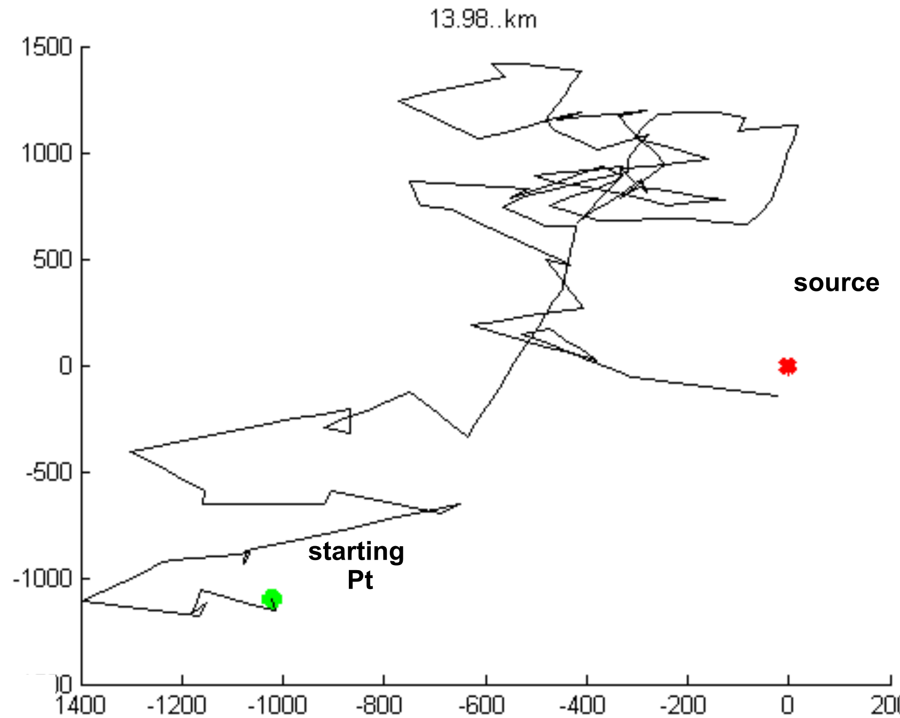


2000m X 2000m



Optimotaxis (what we learn from bacteria)





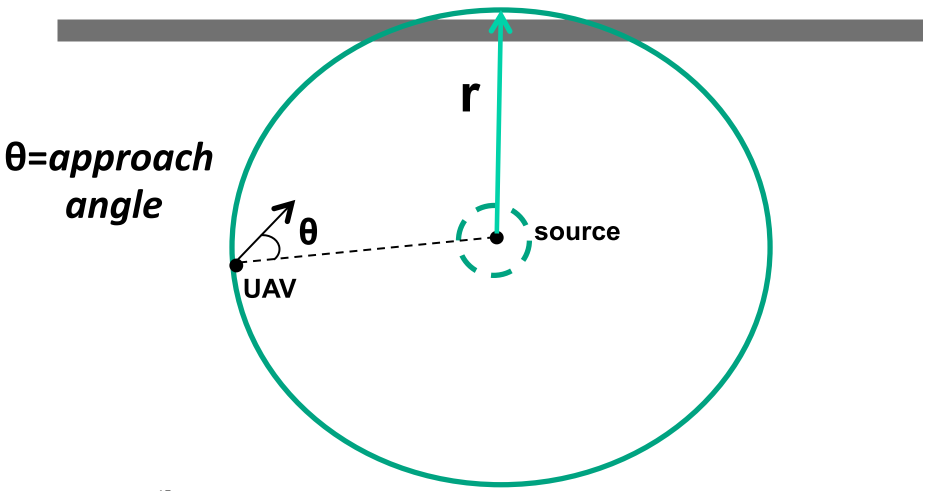
$$\frac{q(x(t), y(t))}{q(x(t_k), y(t_k))} e^{\frac{-(t-t_k)}{\eta}} \leq u, \quad t \geq t_k$$

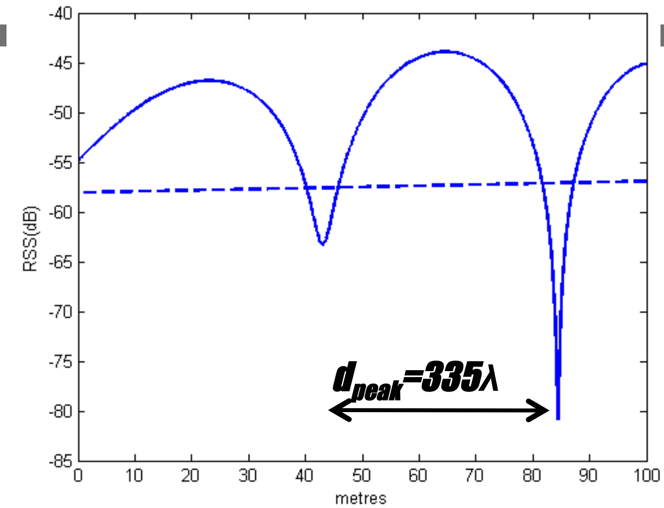
↑ [0,1] uniform random variable

Mean Path length ≈ 32km – 24 times the shortest path

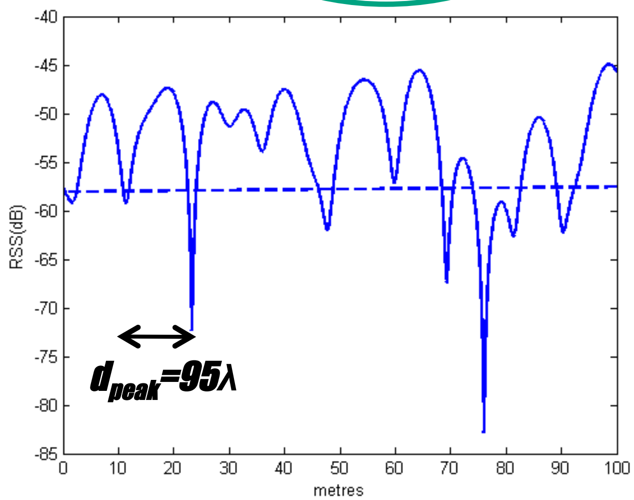
General-purpose optimotaxis too slow; need to be smarter than bacteria
Exploit problem-specific features

Adapt tumble step to spatial RSS profiles

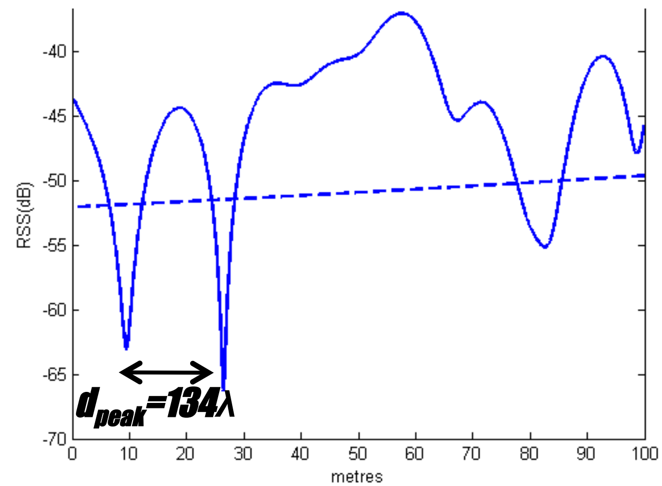




θ=10º
r=800m



θ=60º
r=800m

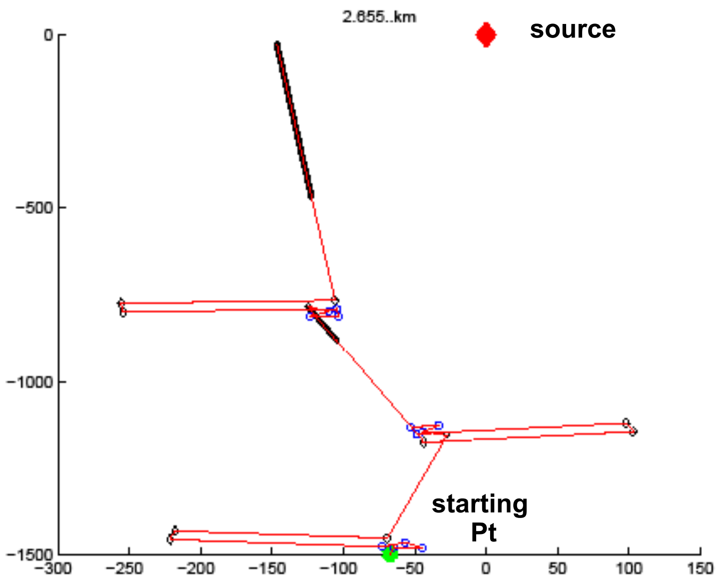


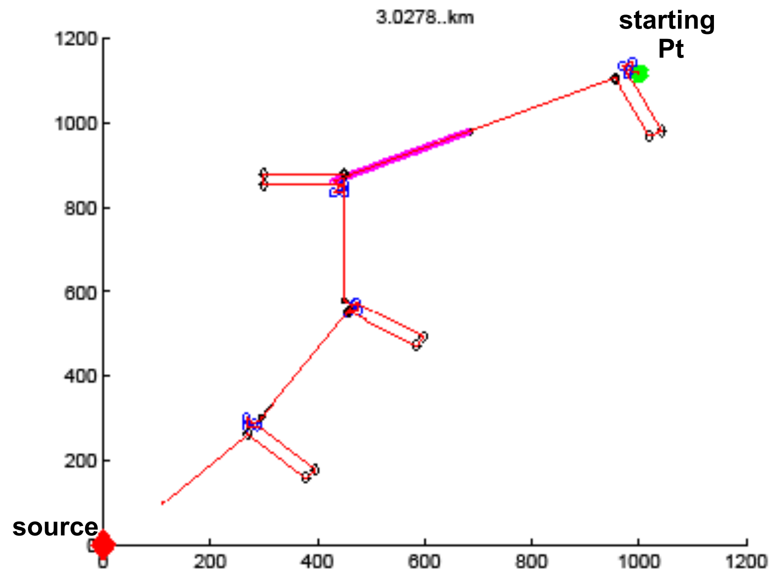
θ=10º
r=400m

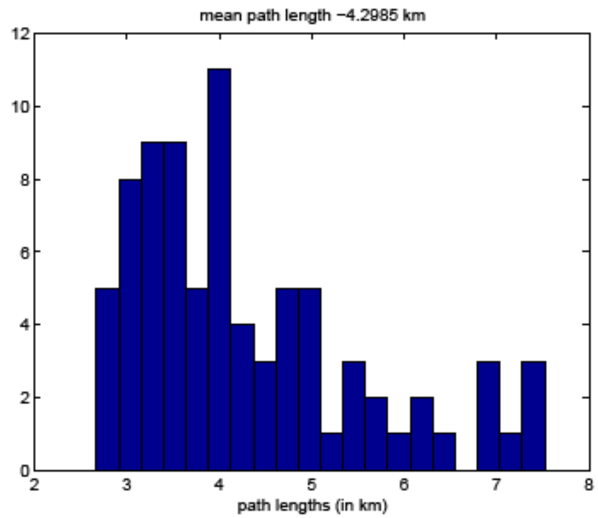
1. Slow & deep fading & d_{peak} ↓ as r/R ↓

2. Fading depends on *approach angle* θ

RSS-Adapted Optimotaxis







Mean Path length ≈ 3 times the shortest distance (1.5Km)

8 times shorter than optimotaxis

Multi-agent systems: take-aways

- Wireless-enabled multi-agent systems are a powerful concept
  - Simple sensing and/or actuation
  - Sophisticated functionalities
- Bio-inspiration is a compelling but fuzzy tool set
  - Idea generator, but must still do theory, system design, evaluation
- Interesting recent results
  - Space-time localization
  - Beacon following
  - Stigmergic medium access
- We are only at the beginning…

Conclusions

- We have come a long way in wireless
- But easily 20 more years of research excitement
  - Faster, Farther, Smarter
  - Inherently cross-disciplinary: hardware, comm/info theory, signal processing, networking
  - Demos becoming easier to do (at lower freqs): SDR, roombas, drones
- Our focus at UCSB
  - Millimeter wave
  - Distributed MIMO
  - Bio-inspired design: minimalism and scale
  - Concept demonstrations