Experimental 4G Research in Motorola Labs

Tim Thomas and **Tom Krauss**
Principal Staff Engineers
Communications Research Laboratories
Motorola Labs
Schaumburg, IL

Outline

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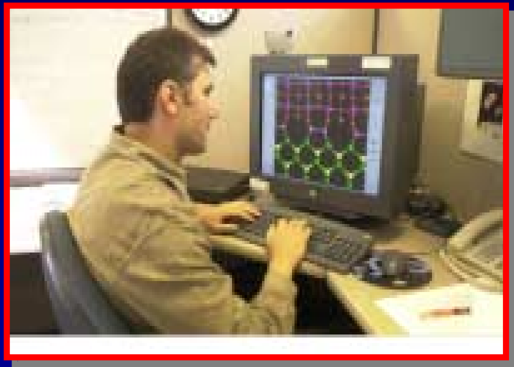
Motorola Labs 4G Vision and Research Program Overview

What is Motorola Labs?

MOTOROLA LABS

- > 800 researchers worldwide
- Mid- to long-range research charter
- Broad range of research areas to support current businesses and potential new businesses
- Relationships with over 200 universities, national labs and customer labs



Motorola Labs Broadband Wireless Research

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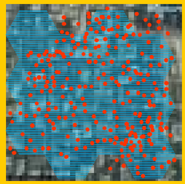
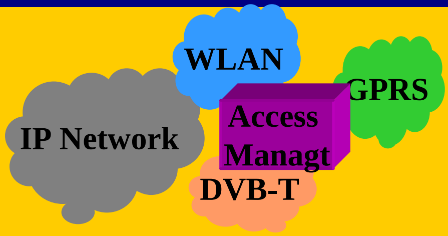
Strategic Framework

Business value analysis



B3G Systems and Architecture

Cellular, WLAN & broadcasting systems for mobile public access including Hot-Spots; architecture, protocols and technology



3.5G

New, 3G-compatible, air interface, with improved coverage, capacity, and range

4G

4th Generation cellular system, including a new air interface operating in a new spectrum allocation

WLAN

- **Architecture for corporate, private and public WLANs**
- **Technology for power and QoS**
- **Next Generation WLAN**

4G Research Program Overview

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Experimental

- Field Data Collection
  - –Compare tx and rcv algorithms
  - –Path loss/delay spread
  - –Spatial characteristics
  - –Measured channels for simulation
  - –Scatterers identification
  - –Broadband IP traffic
- 4G prototype transceiver systems
  - –RF & baseband
  - –Realistic applications
  - –Feedback for system design

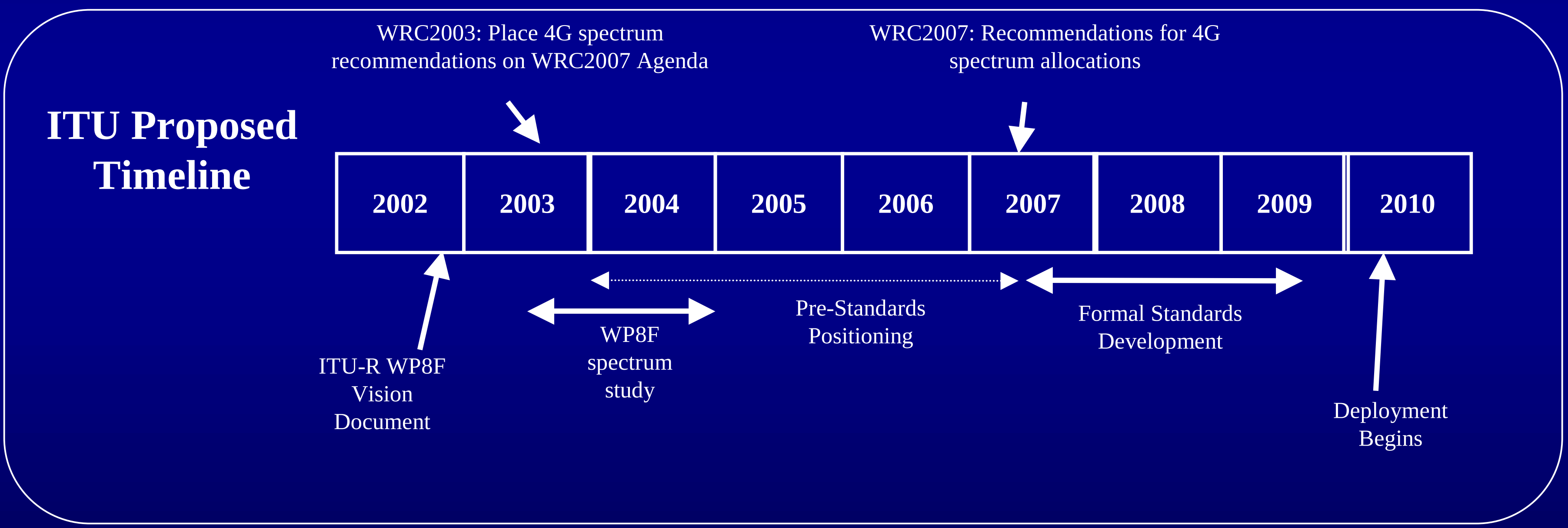
Studies & Simulations

- System-level
- Medium access control
- Link adaptation
- Transmit and receive antenna arrays
- Frequency domain modulation methods
- Channel estimation
- Error correction coding
- Hybrid ARQ

4G System Design

4G Context

- **4G is the next major generation of mobile cellular systems**
  - **Vastly higher bit rates (>100 Mbps)**
  - **Lower cost for comparable functions**
  - **A new higher efficiency air interface or interfaces**
  - **Extended wireless Internet, multimedia, new applications**



OFDM/Adaptive Antenna Overview

OFDM Overview

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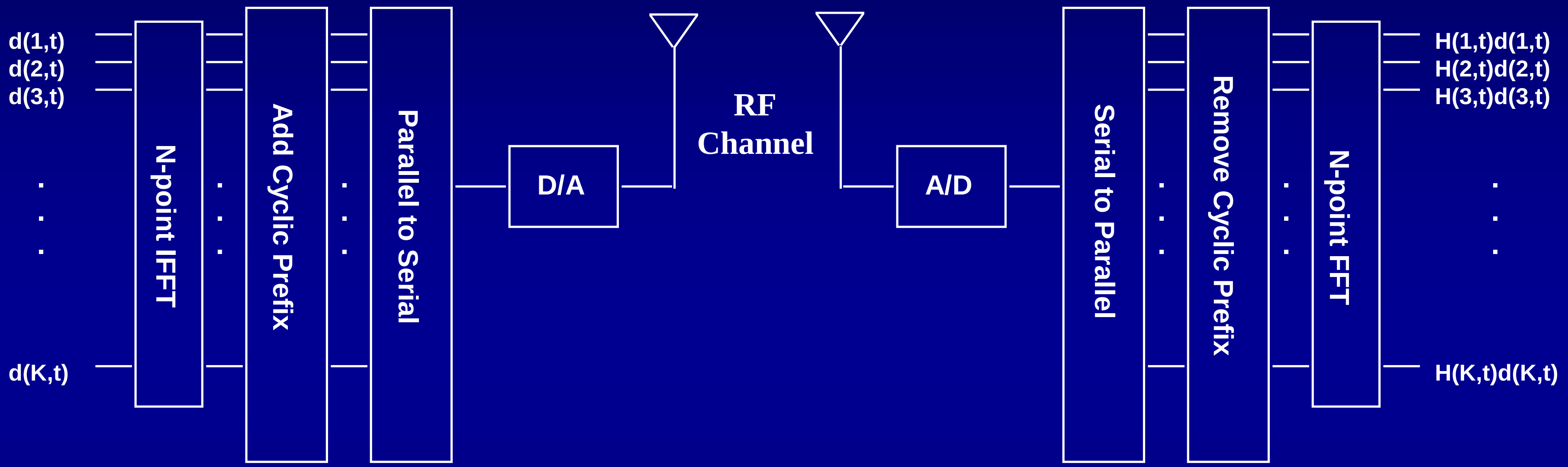
Transmitter: One Branch of Receiver:



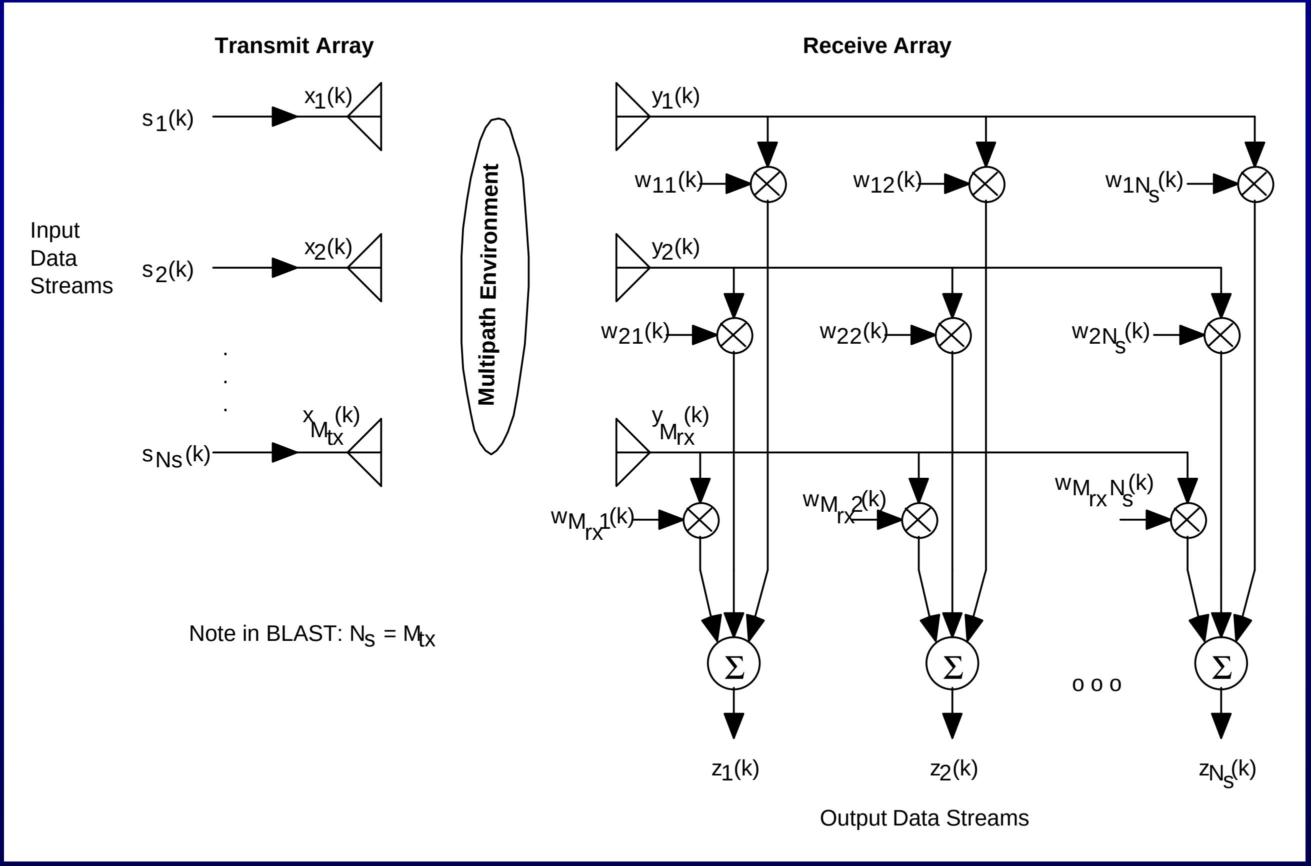
- **Cyclic prefix absorbs delay spread**
  - **No Inter-Symbol Interference (ISI) if CP≥max delay spread on the channel.**
  - **Delay spread causes gain and phase rotations on the subcarriers.**
  - **Each sub-carrier is properly modeled as being flat Rayleigh faded.**
- **Drawback of cyclic prefixes:**
  - **Increased redundancy**
  - **However, simplified receiver processing justifies the overhead**

Frequency-Domain Array Processing

- Antenna Arrays add the space dimension to baseband signal processing methods.
  - Ultimate Goal: Increase Capacity via interference suppression, spatial diversity, beamforming → SDMA, MIMO, etc.
- AA Techniques originally developed for flat-faded channels can be directly applied on each frequency bin
  - ST-coding, MIMO, SDMA, MMSE, ZF, Successive Cancellation, ML, etc.
  - Significant complexity savings compared with time-domain methods
- Tracking the channel in all 3 dimensions (space-time-freq.) is key:
  - Frequency-Domain methods allow more precise control over how the AA algorithms track the propagation environment
- Exploiting diversity in all dimensions is also key:
  - Frequency-Domain methods facilitate the separate optimization of the receiver characteristics in each dimension
    - In OFDM: Bit-interleaved coded modulation across subcarriers combined with Alamouti outperforms the well-known space-time coding methods
    - In MIMO-OFDM: Interleaving coded bits across antennas and subcarriers picks up both transmit and frequency diversity

MIMO Overview

- Technique for increasing the transmitted data rate with multiple transmit antennas and adaptive array receiver processing
- Each transmit antenna transmits an independent data stream irrespective of what is transmitted on the other transmit elements.
- Combine the receive elements to separate out the transmitted data streams.



Alamouti Space-Time Code

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- Rate-1 orthogonal space-time block code for two transmit antennas.
  - Spatial diversity with no channel knowledge required at TX.

- Originally presented for quasi-static flat channels. (IEEE JSAC, Oct. 1998)
  - Channel constant over an encoding pair.

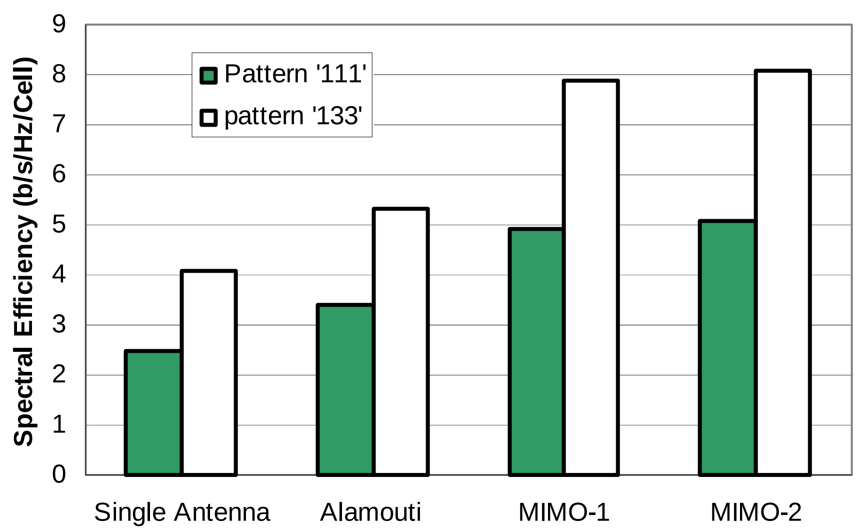
- Two frequency-domain symbols { $d(k,2t)$, $d(k,2t+1)$ } are multiplexed onto two antennas over two symbol intervals.
  - First symbol interval:
    - Antenna 1 transmits $d(k,2t)$
    - Antenna 2 transmits $d(k,2t+1)$
  - Second symbol interval:
    - Antenna 1 transmits $-d^*(k,2t+1)$
    - Antenna 2 transmits $d^*(k,2t)$

	Symbol Interval 1	Symbol Interval 2	
Tx Antenna 1:	$d(k,2t)$	$-d^*(k,2t+1)$	…
Tx Antenna 2:	$d(k,2t+1)$	$d^*(k,2t)$	…

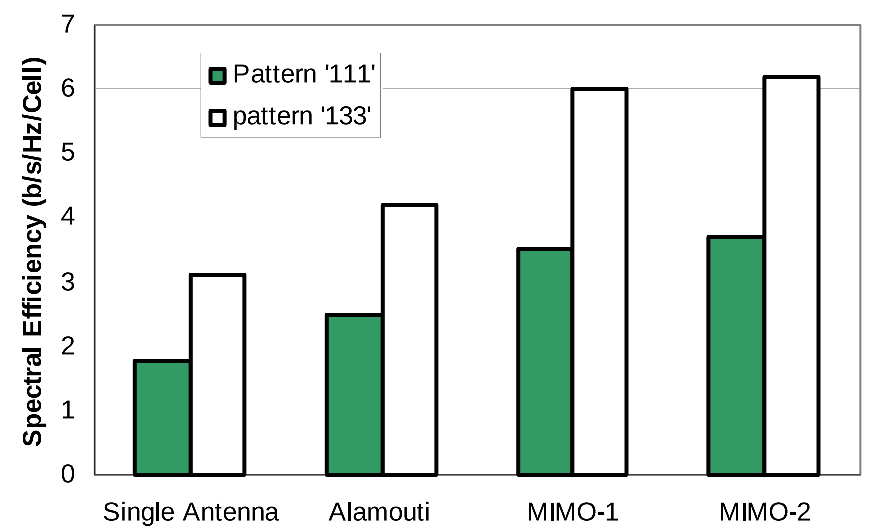
- When channel is constant, Max Likelihood decoder is a simple linear combiner across the receive antennas and the two symbol intervals.
  - Aggregate channel responses of the two symbols are orthogonal to each other.

System Level Results (Allerton 2001 paper)

- At the Shannon limit:



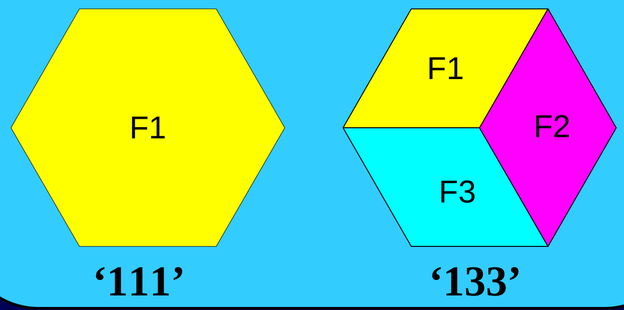
- 4 dB from the Shannon limit



ASSUMPTIONS:

1. 2 Tx and 2 Rx antennas
2. Fully loaded cells (120 cells in network)
3. MIMO-1 is BLAST, MIMO-2 is closed loop
4. System is interference limited
5. Mobiles randomly placed in cells

Frequency reuse plans:



Field Data Collection Overview and Selected Results

4G Experimental System Description

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- 4G Experimental System
  - 3.675 GHz band (experimental license)
  - 20 MHz channel bandwidth
  - 12 antennas, 6 sectors
  - 2 TX antennas at base
    - ~41 cm antenna spacing (5 λ)
  - 2 RCV antennas at mobile
    - ~75 cm antenna spacing (9.3 λ)
  - 25.6 MHz baseband sample rate
  - 1024 FFT & 751 subcarriers
- Field Data Collection
  - Synchronized to GPS
  - 4 KW ave EIRP
  - High SNR, >20 dB typically
  - Speed from 0 to 60 mph
  - ~7000 channel snapshots of 25 ms

Field Data Collection Experiments

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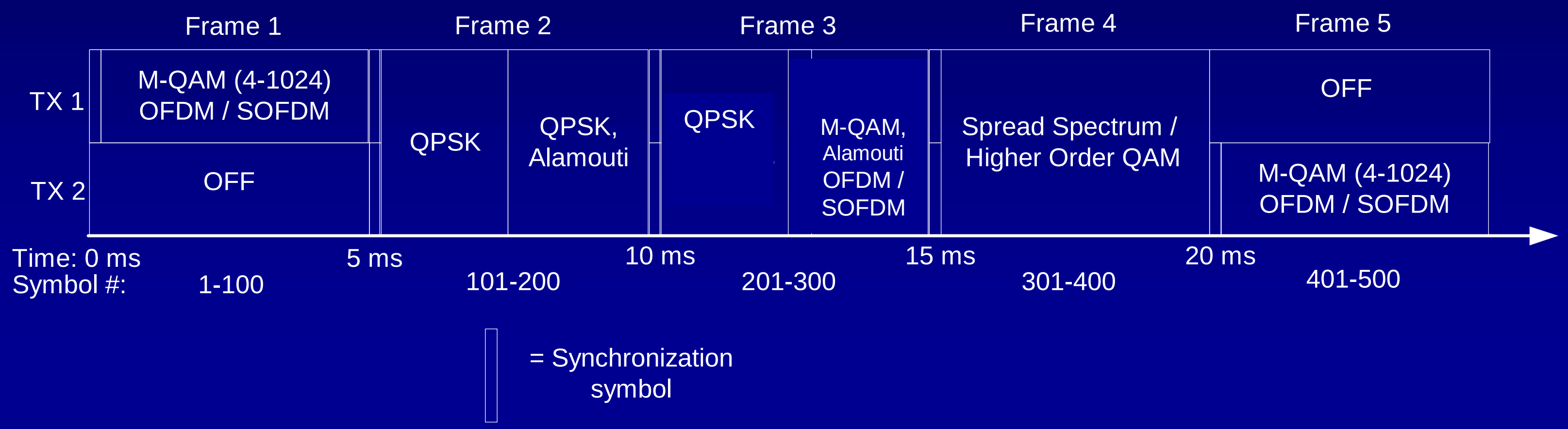
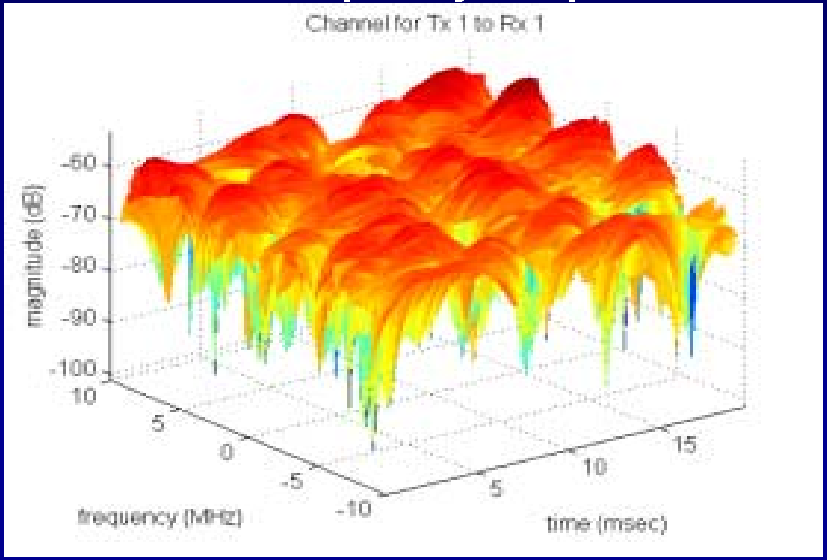
- Transmit signal: programmable periodic waveform, 2 antennas



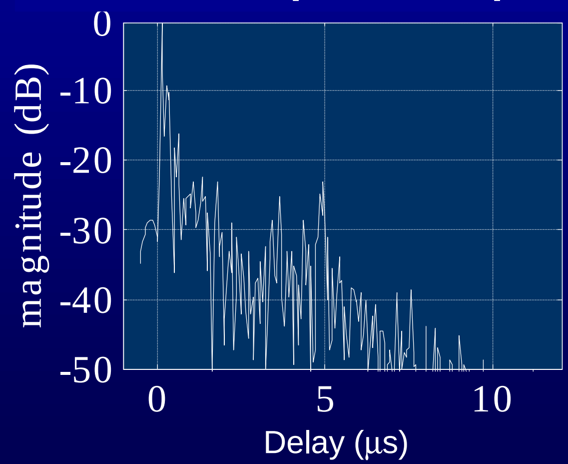
- Collect baseband data once each 2 – 2.5 seconds
- Experiment with different transmit/receive algorithms
  - Diversity and MIMO experiments: 1-1, 1-2, 2-1, 2-2
  - Different modulation and coding: OFDM, Spread-OFDM
- Also measure the 2x2 20 MHz channel impulse response
- Database accessible through custom MATLAB Application Program Interface (API) and Graphical User Interface (GUI)

Example Outdoor Channels

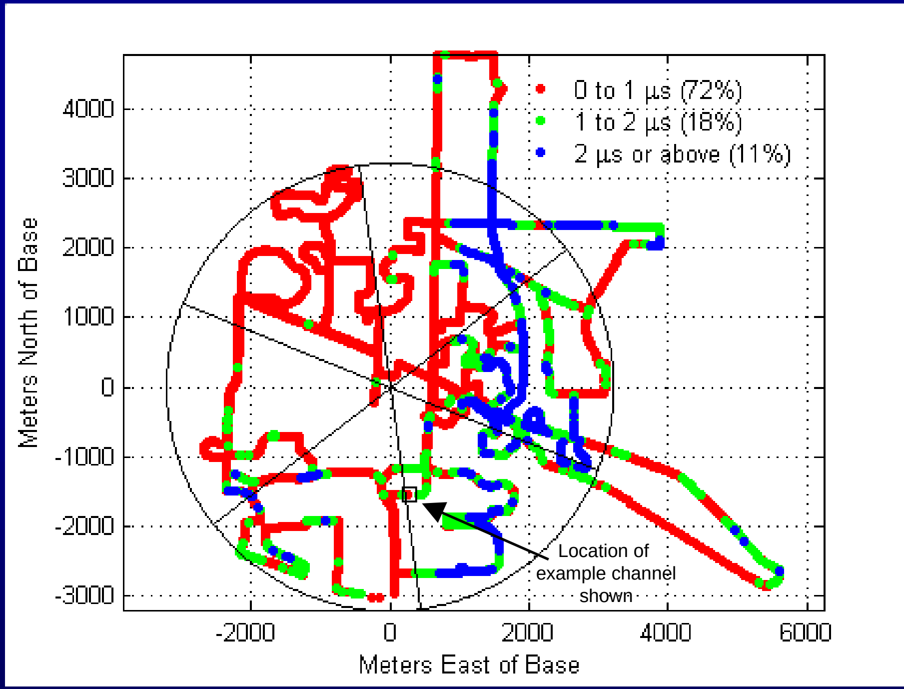
Time/Frequency Response



Channel Impulse Response

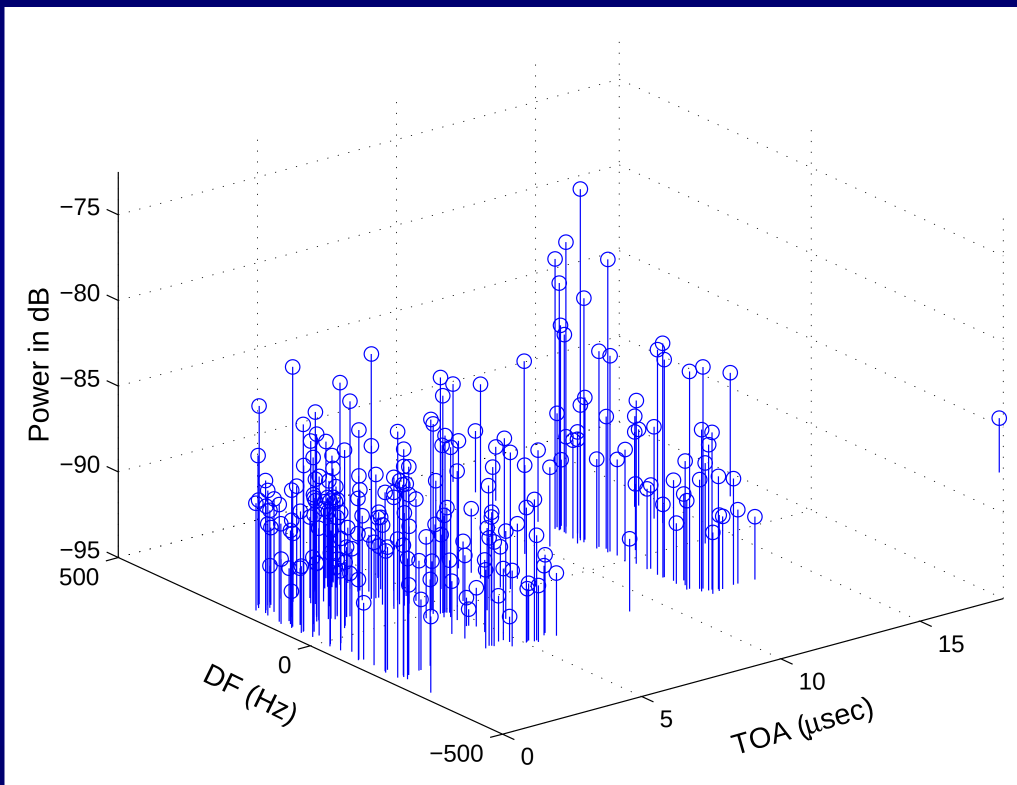


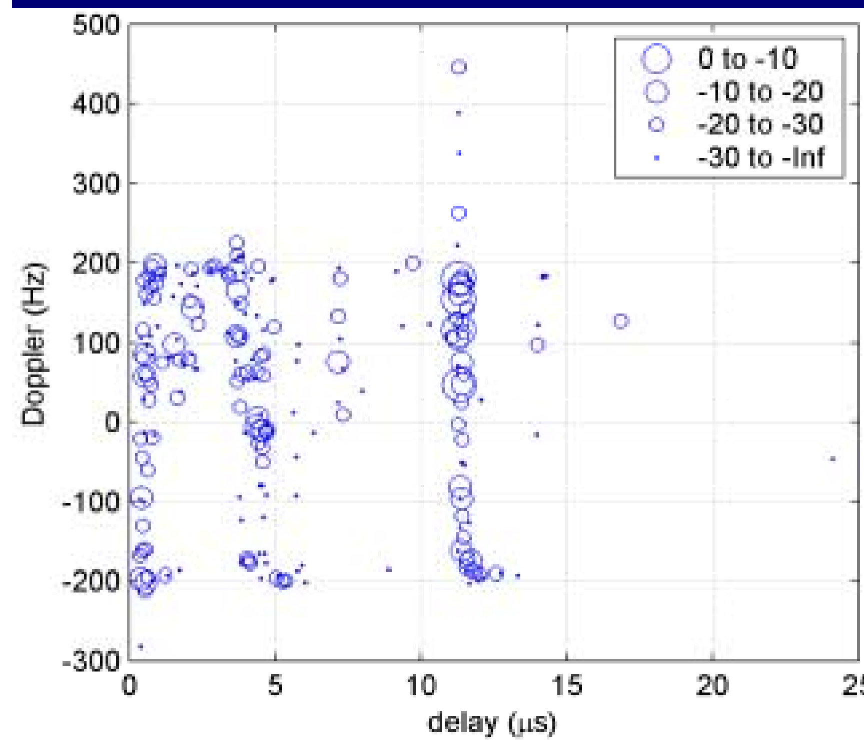
Delay Spread on drive routes in outdoor coverage area



Example Channel #1

Channel characterized by discrete TOA / DF pairs, found by CHAMPS algorithm (presented at VTC Fall 03)





Example of non-LOS industrial area where delay profile is dominated by a distant reflector (the test van was moving at 35 MPH (192 Hz)). The power ranges in the legend of the right plot are in dB where the maximum power is normalized to 0 dB.

Example Channel #2

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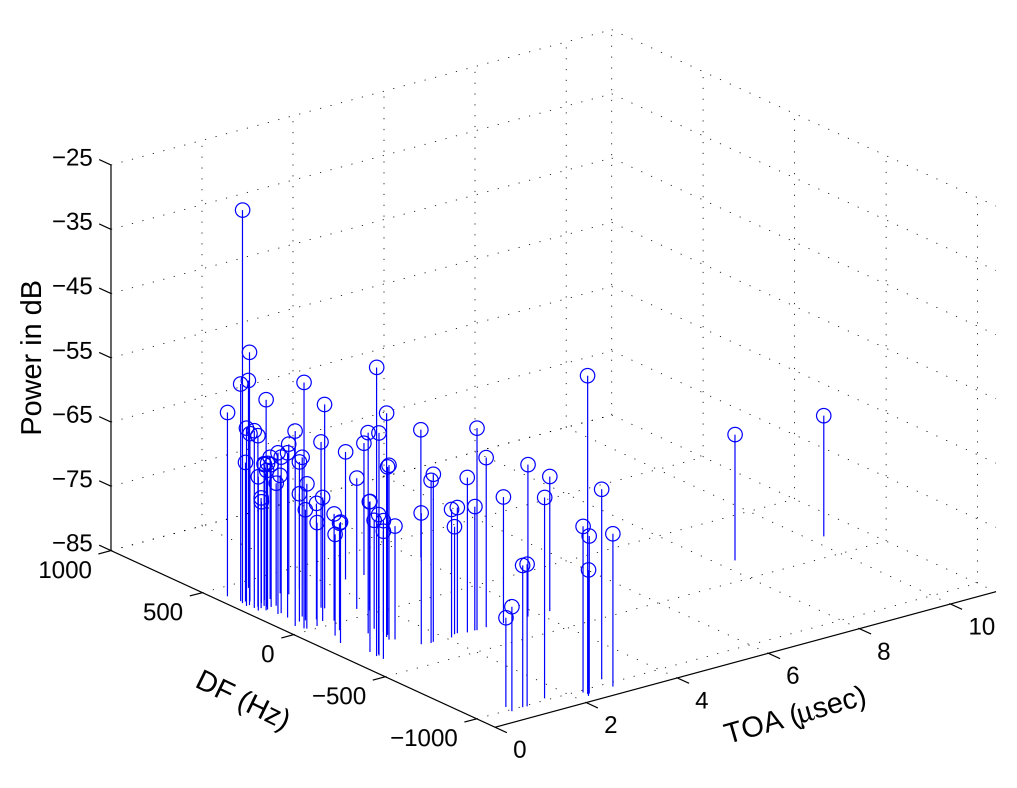

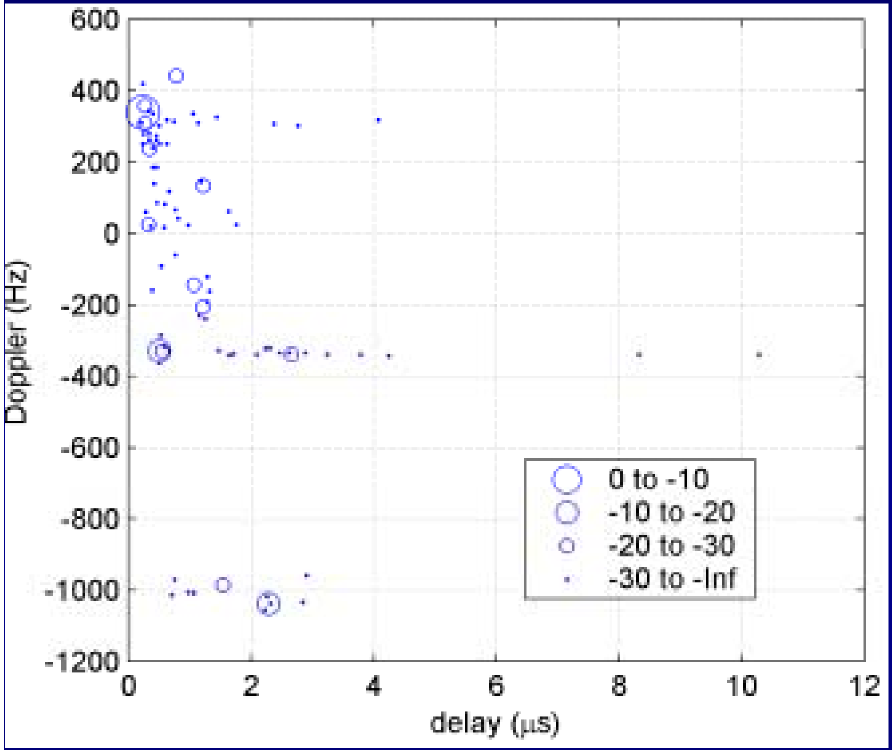

LOS interstate example where the test van is moving at 61 MPH (335 Hz) with 3× expected Doppler caused by vehicles traveling in opposite direction. The power ranges in the legend or the right plot are in dB where the maximum power is normalized to 0 dB.

PDF and CDF of Number of Rays

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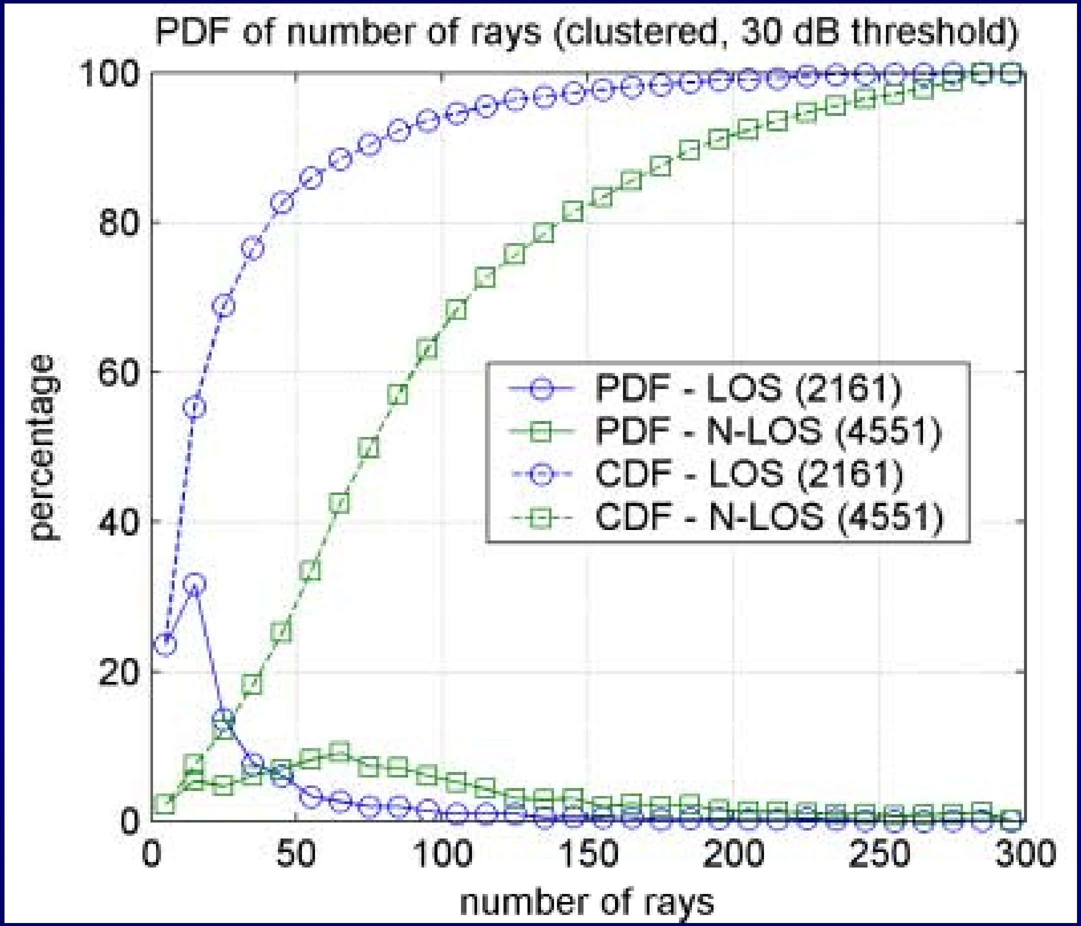

Probability Distribution Function (PDF) for number of rays (after clustering) with power within 30 dB of peak, for Line-Of-Sight (LOS) and Non-LOS (N-LOS) snapshots.

RMS and Differential Delay Characterization

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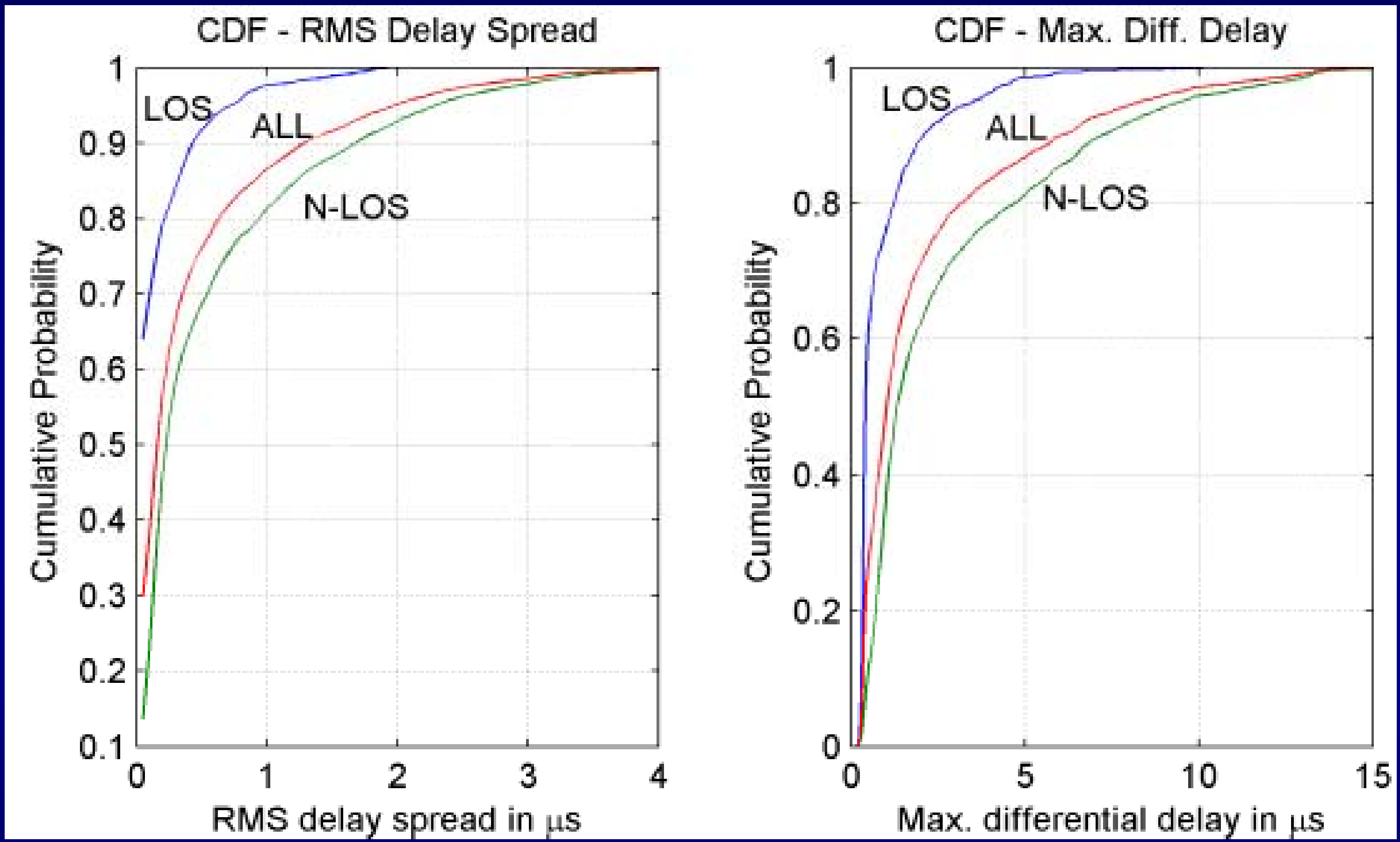

CDFs of RMS and maximum differential delay spread for a <u>15 dB threshold</u>.

Doppler Spread Characterization

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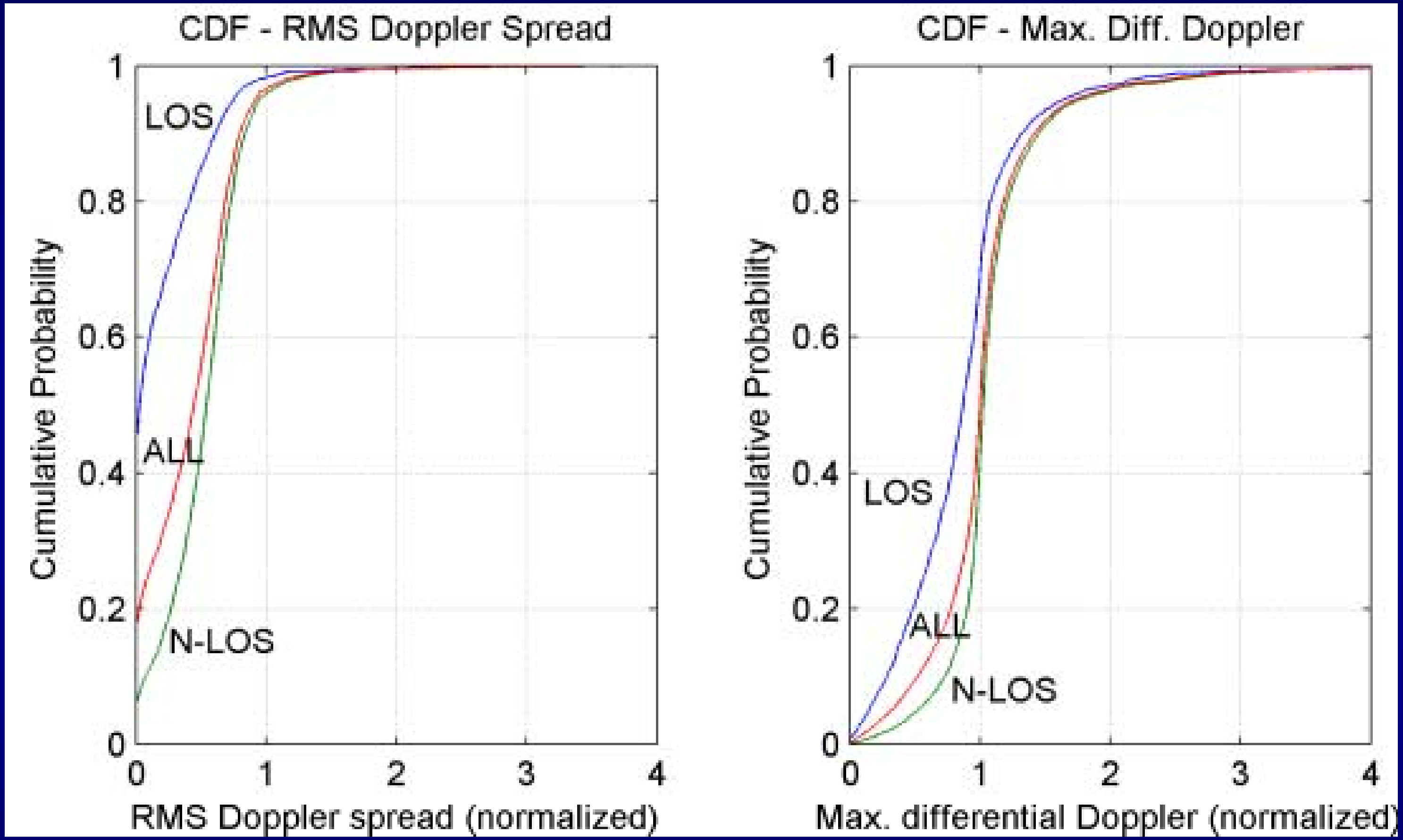
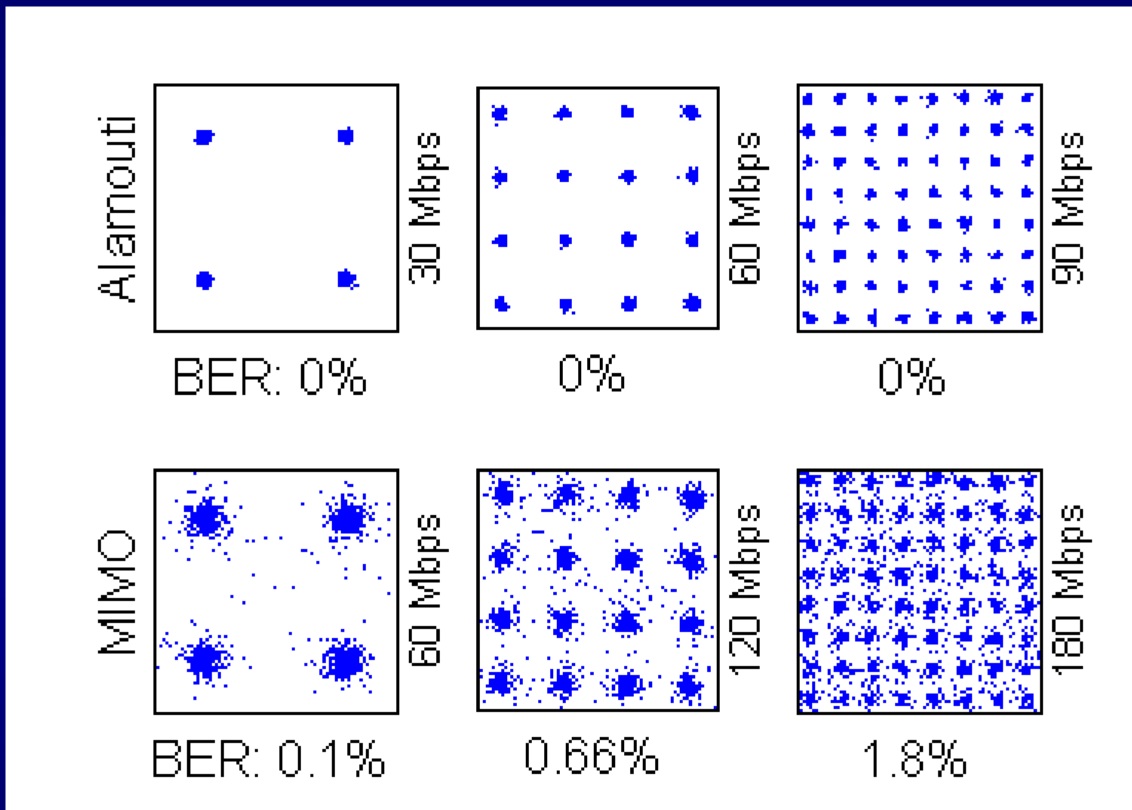


CDFs of RMS and maximum differential normalized Doppler spread for a 15 dB threshold (only when speed was greater than 1 mph).

Alamouti vs MIMO

- QAM Constellations & Uncoded BER (Off-line)



- "Alamouti" scheme has both transmit and receive diversity (2x2)

- 2x2 MIMO processing:
  - linear MMSE equalization
  - offers 2x the data rate

- non-linear receiver processing and coding can help achieve the higher capacity benefits of MIMO transmission
- For MIMO to perform well, need good spatial conditioning

Spatial Conditioning: 2x2 MIMO Performance

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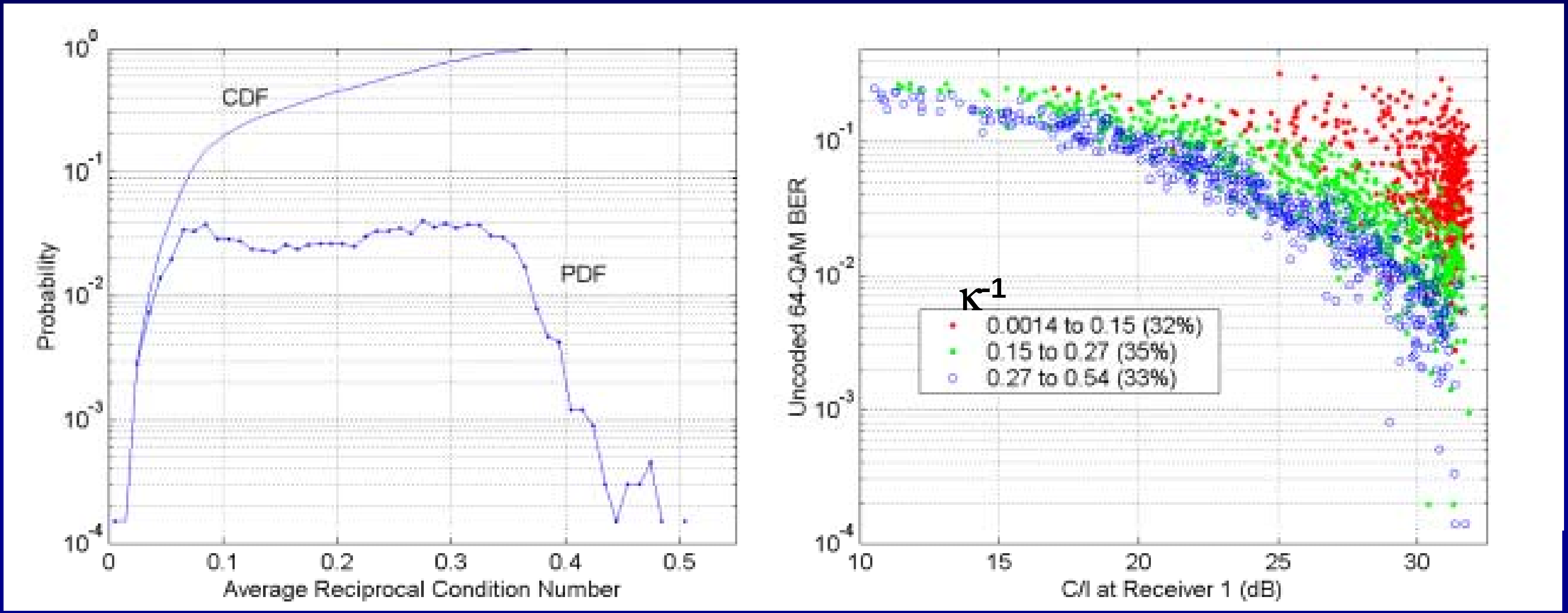

- The average reciprocal condition number (0< κ^{-1} <1) gives a rough sense of how well 2x2 MIMO will work
  - κ^{-1} =1: The spatial Tx signatures are orthogonal and equal magnitude
  - κ^{-1} =0: Singular 2x2 channel matrix, can't separate the two Tx streams
- Although κ^{-1} never reaches unity, the 64-QAM performance indicates that there is enough spatial separation much of the time to support MIMO operation
- Field observation: κ^{-1} >.3 indicates good spatial conditioning, κ^{-1} <.2 indicates poor spatial conditioning
- channel exhibits good spatial conditioning (i.e., the channel is suitable for MIMO operation): ~30% of the time in suburban, 55-80% of the time in urban

OFDM MIMO vs. Alamouti Tx Diversity

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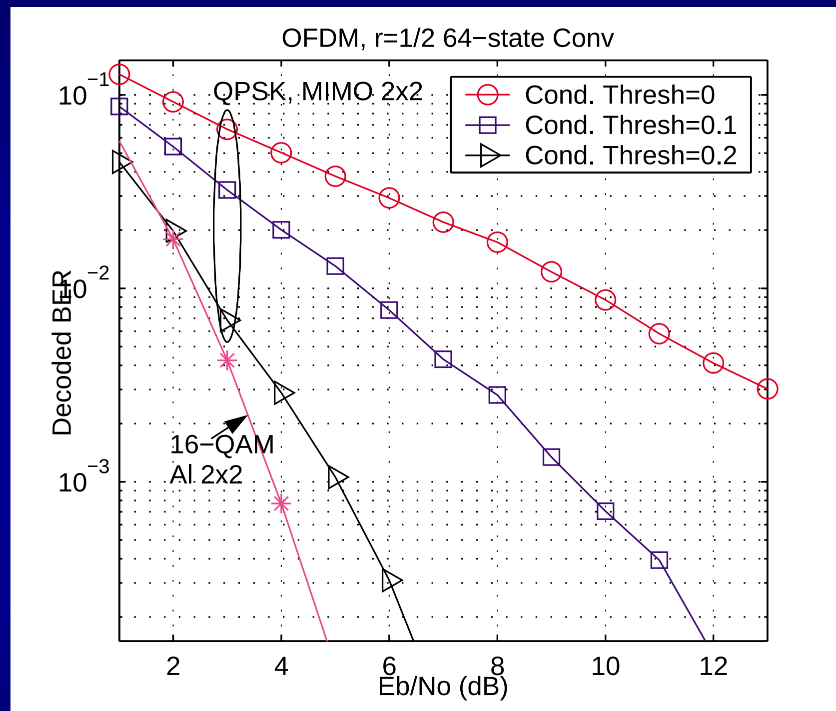
- QPSK MIMO vs. 16 QAM Single Stream (equivalent data rates)



- MIMO is sensitive to the channel condition number
- OFDM performance with Alamouti Tx+Rx diversity is better than 2x2 open-loop MIMO
  - However, MIMO results are based on linear MMSE receiver - non-linear receivers and closed-loop techniques may improve MIMO performance

Identifying Sources of Delay Spread in the Physical Environment

How can we explain the dynamics of the power delay profile?

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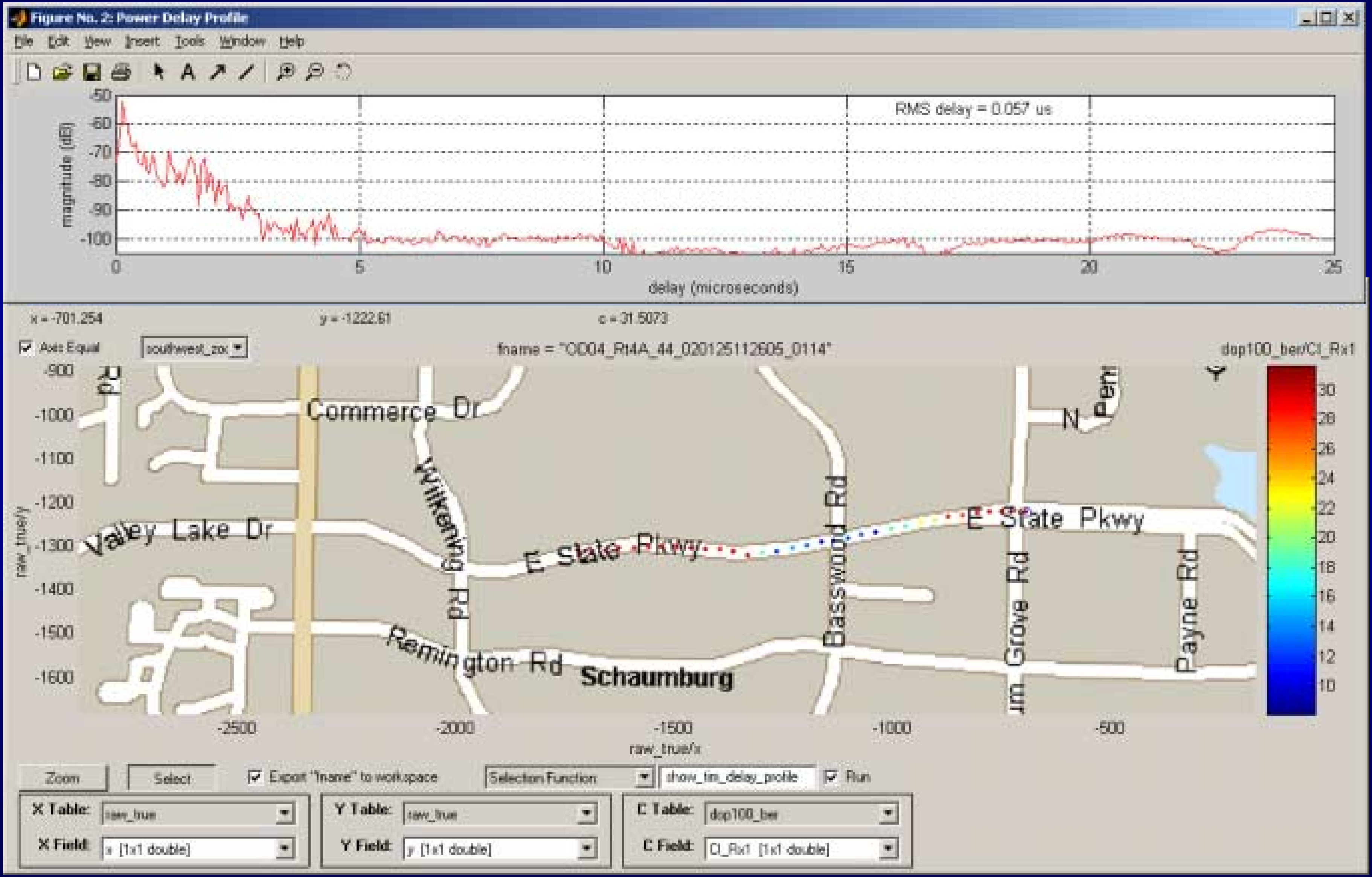

How can we explain the dynamics of the power delay profile?

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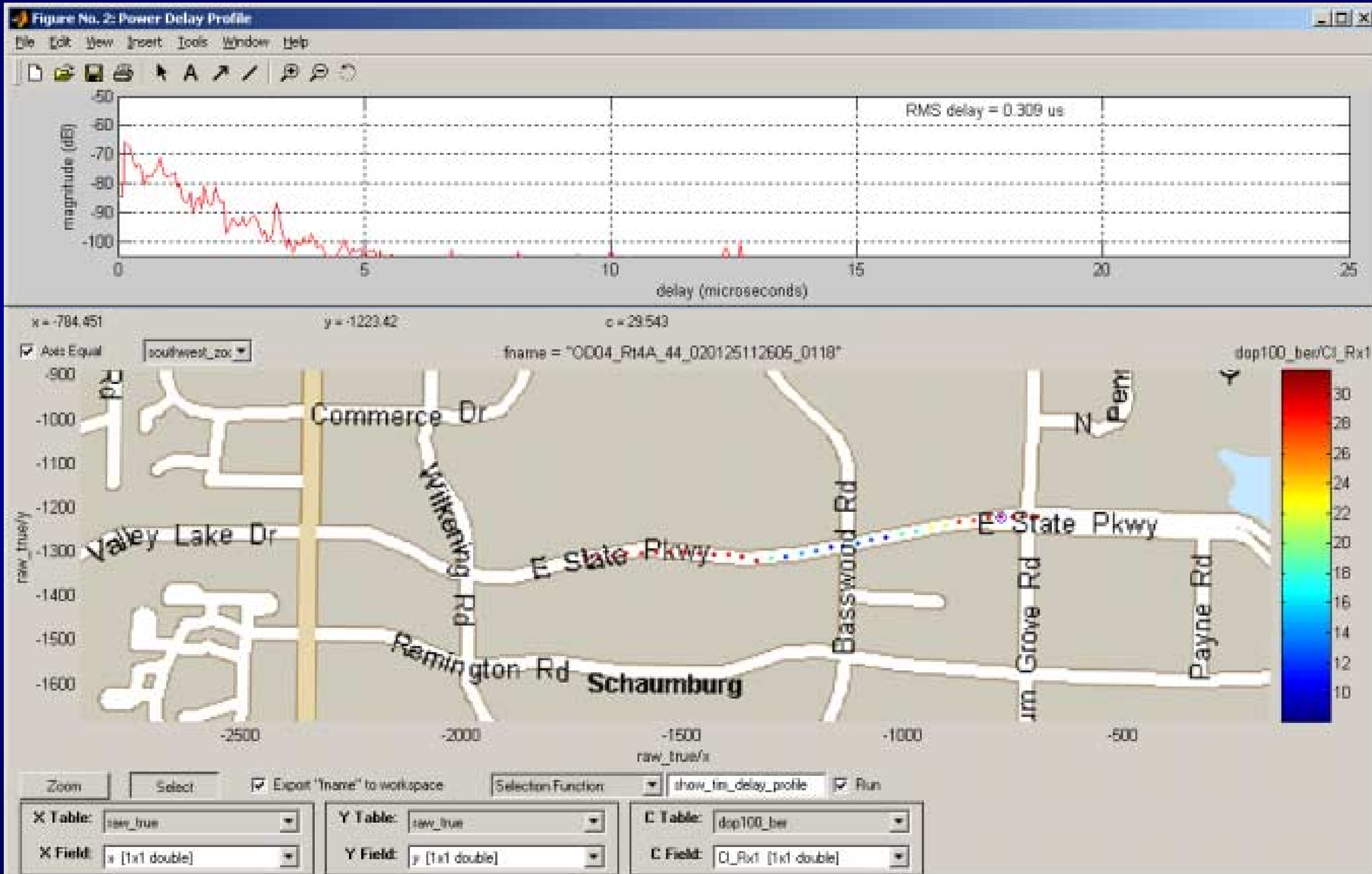

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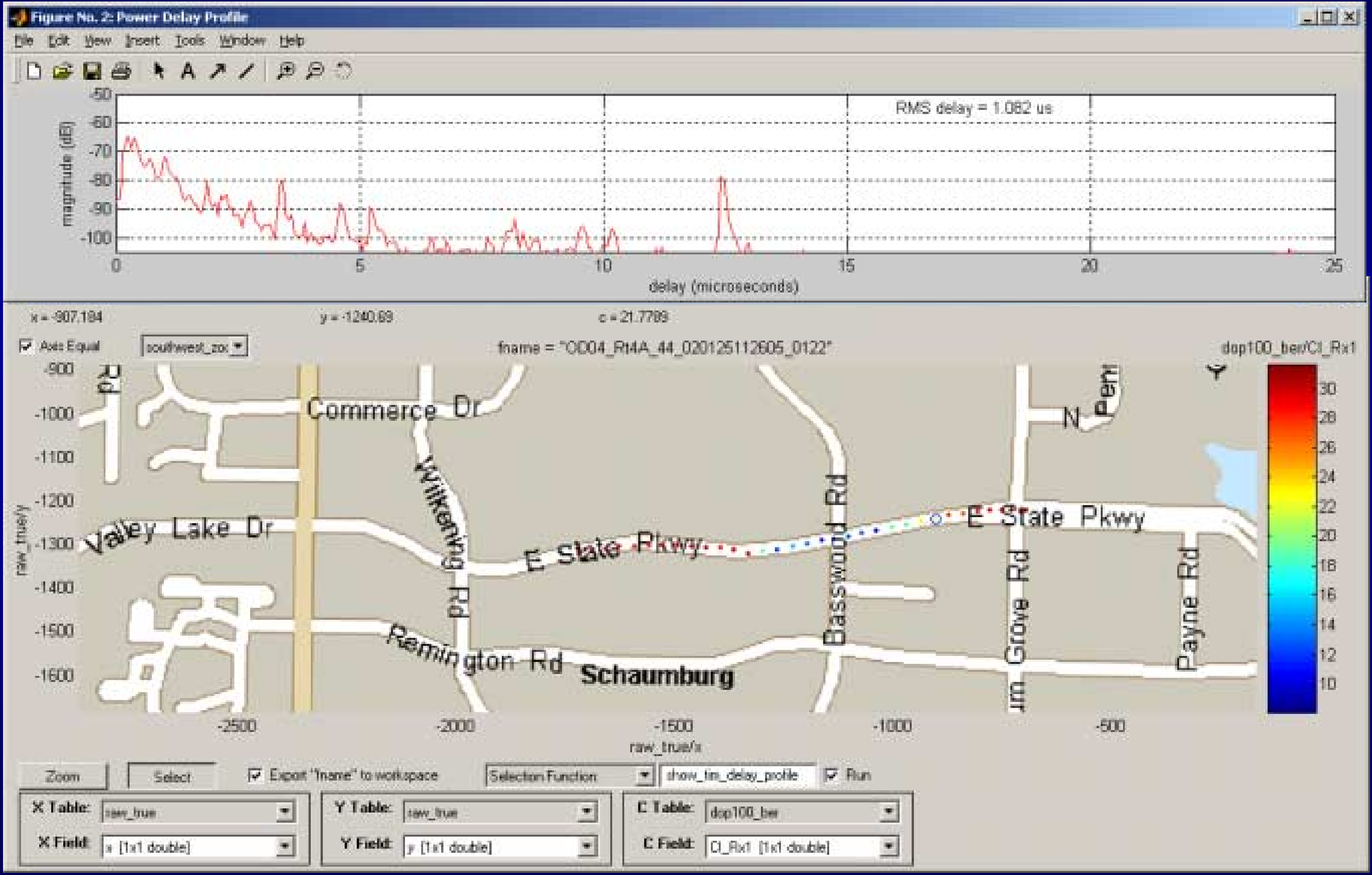

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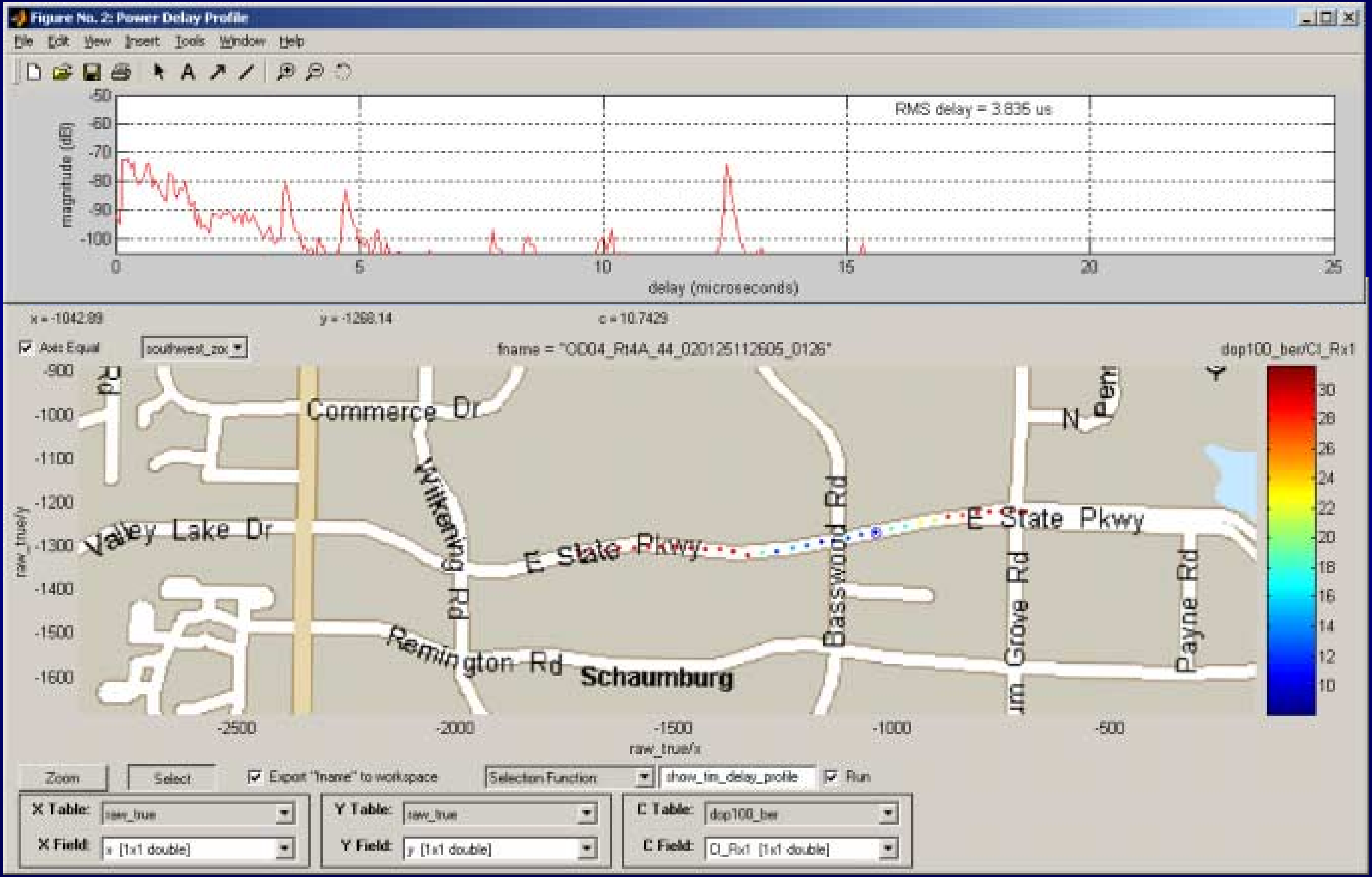

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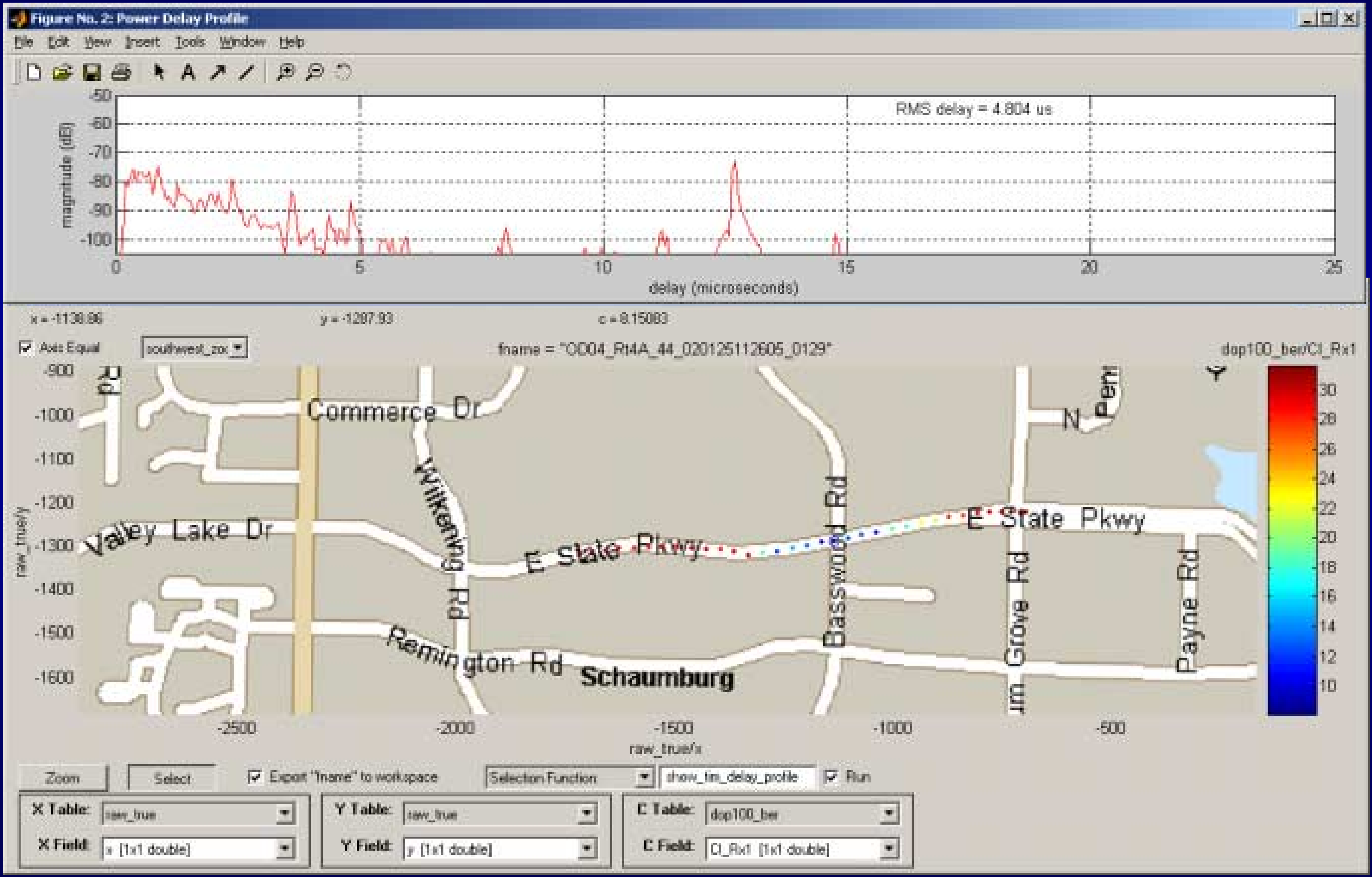

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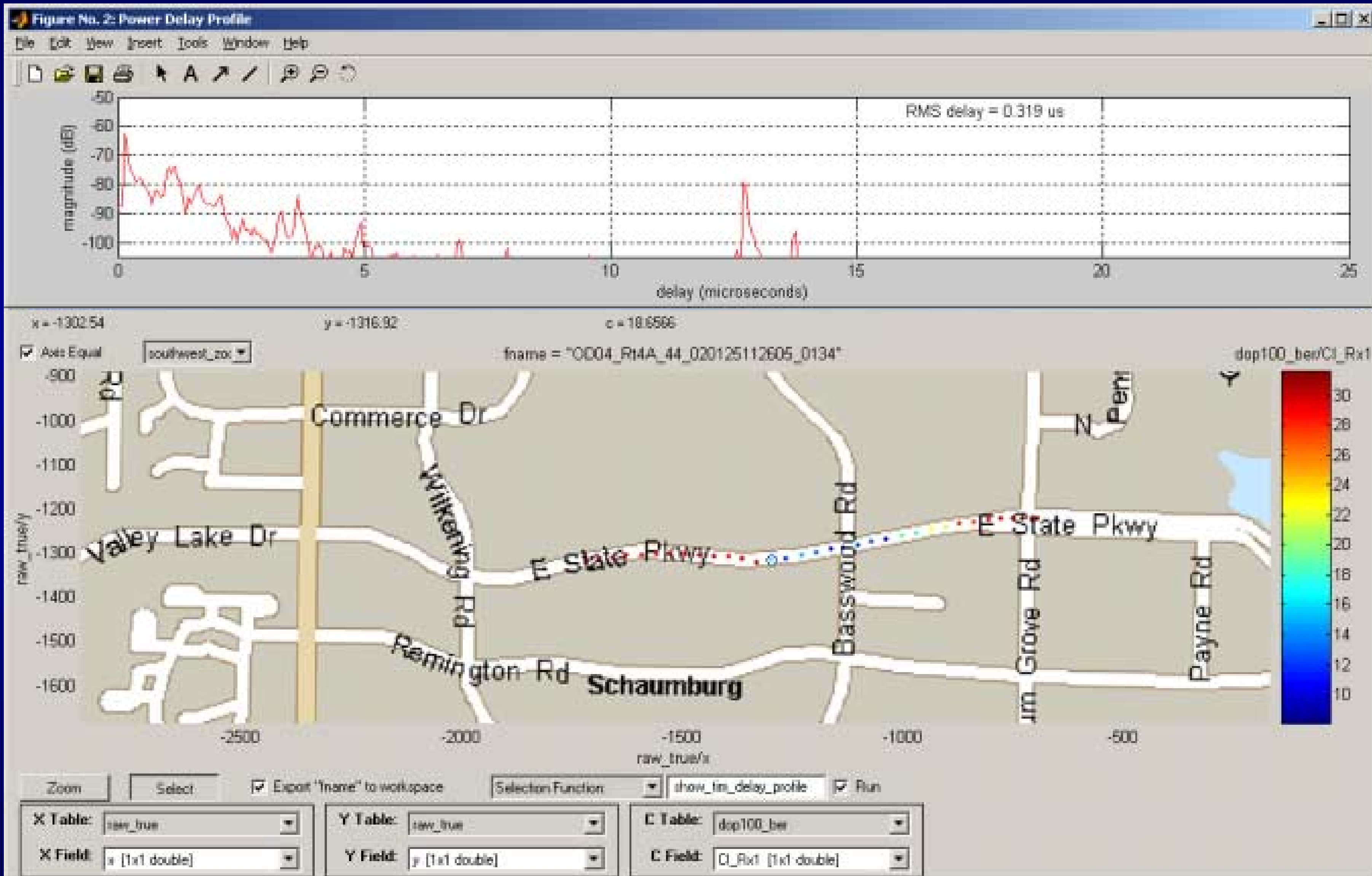

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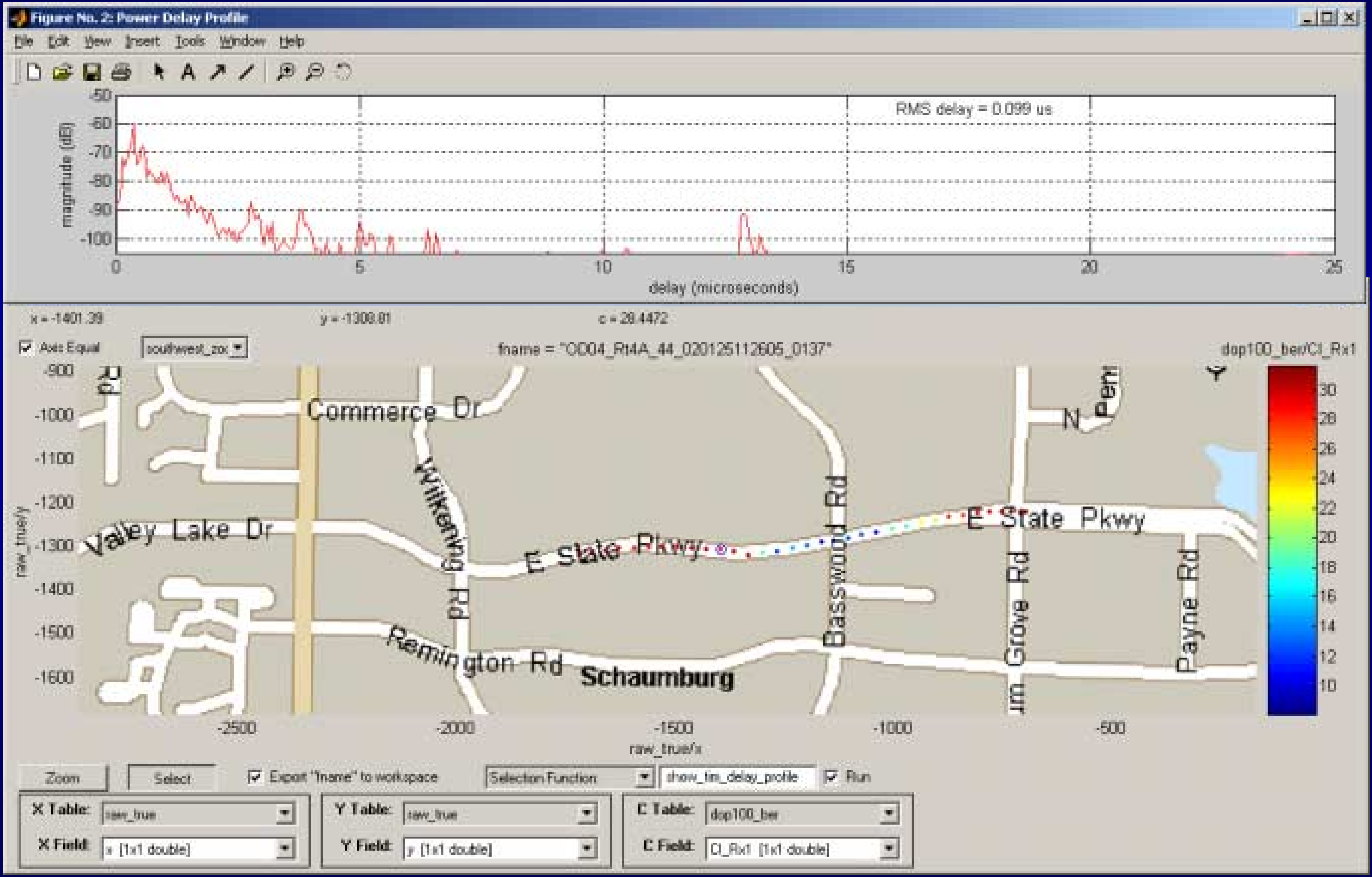

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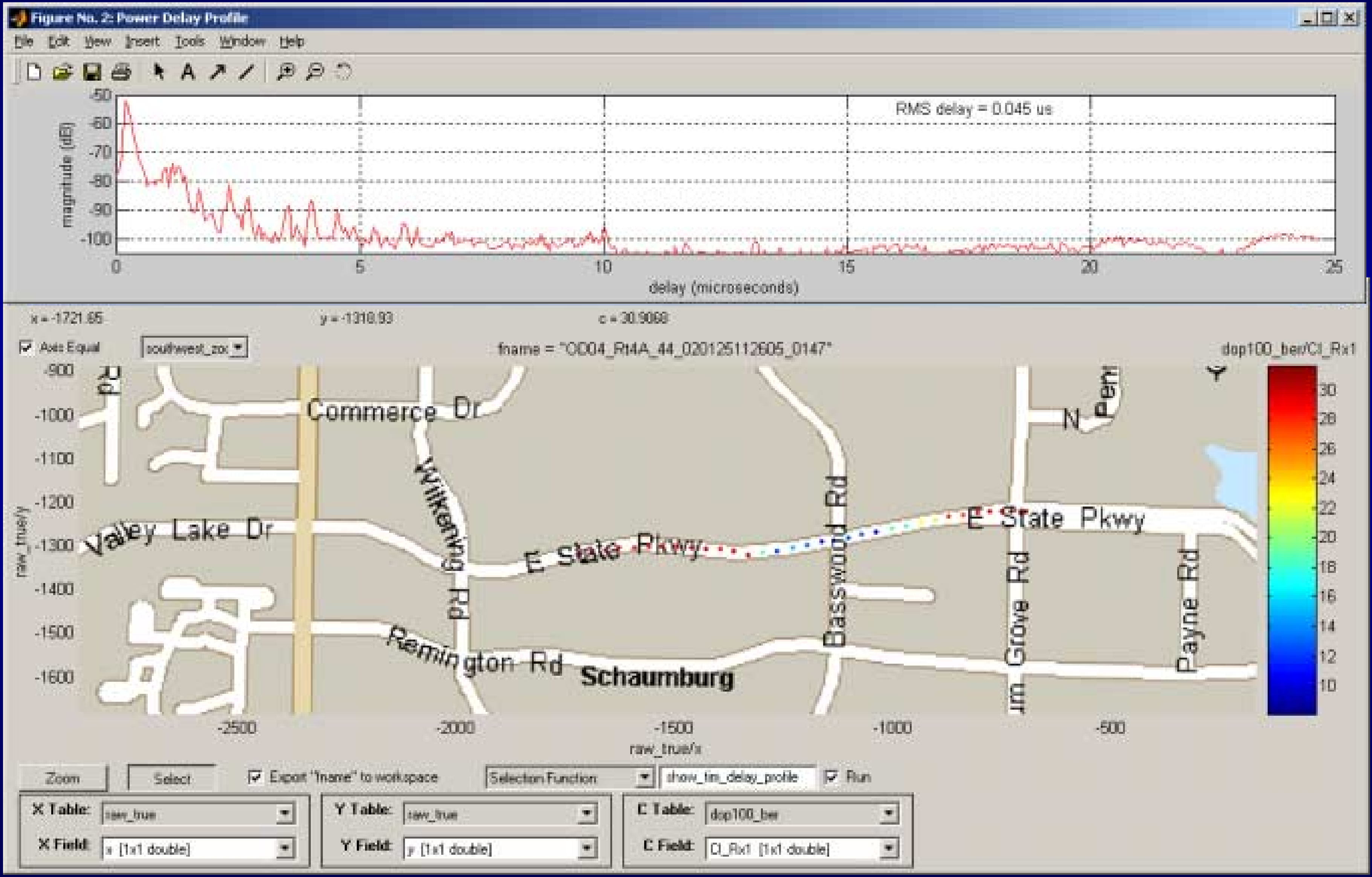
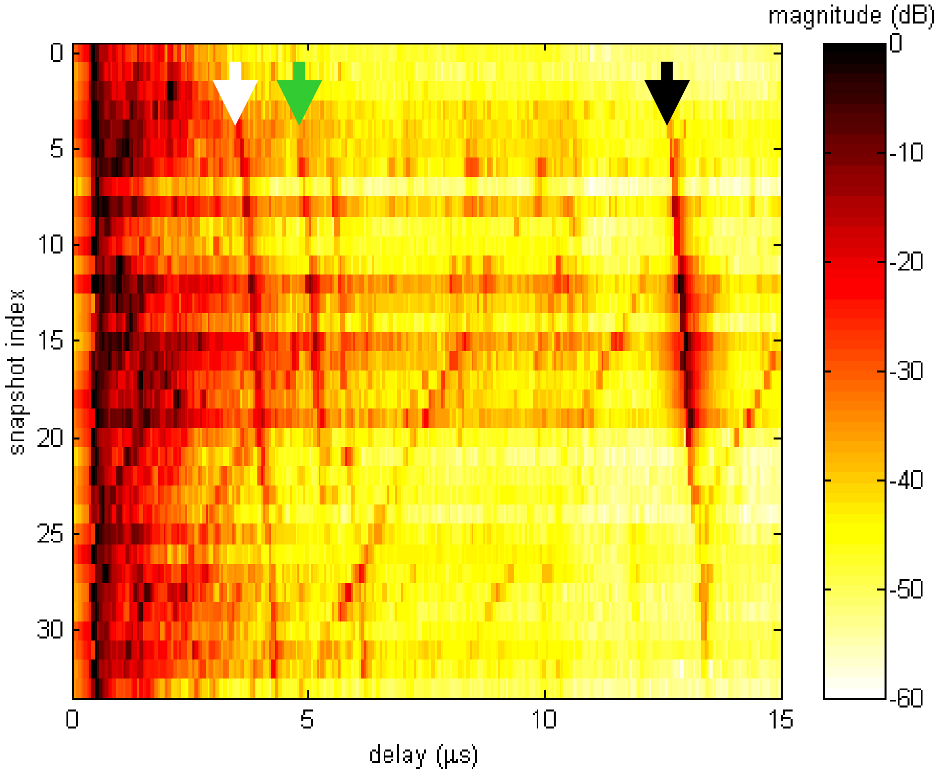
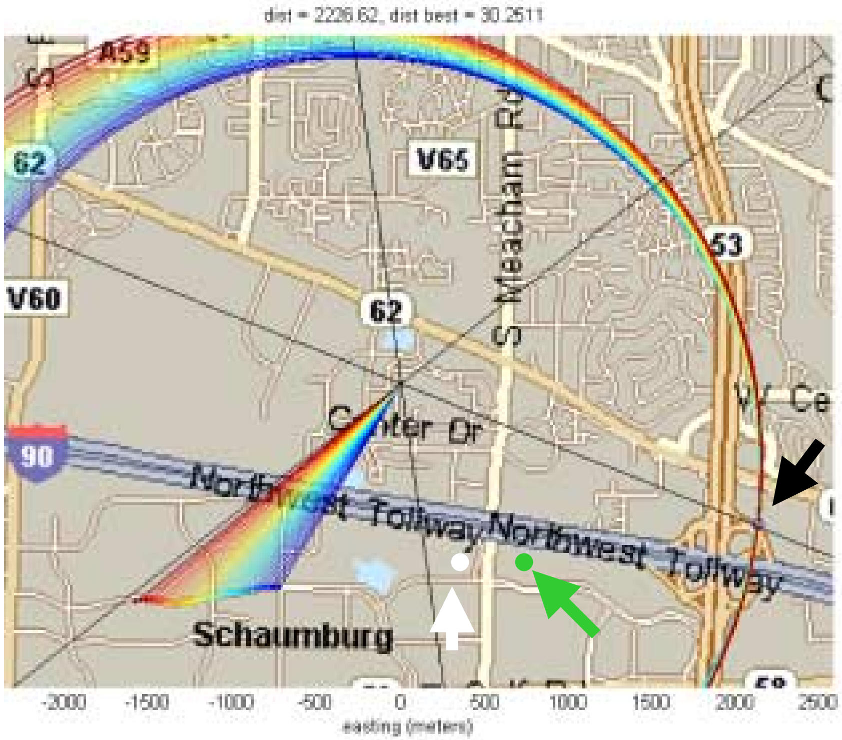


Identification of the Scatterers

- Plotting the power delay profile over time illustrates the temporal behavior of multipath components
- If multipath is due to a single bounce, then the scatterer is located on an ellipse with the transmitter and receiver being the foci and the eccentricity is the propagation delay





Field Data makes "Physical Sense"

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Portable Antenna Characterization

Recent Work – Portable Antennas

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- Field experiments with portable devices
- Calibrated very carefully
- Anechoic chamber – spherical pattern, both polarizations
- Different orientations – head/hip/hand
- Different devices / antennas
- Different environments: Urban & Suburban
  - Indoor office
  - Indoor retail
  - Sidewalk
  - Truck
- Measurements of received power and 2x2 spatial channel

Indoor / Sidewalk Pedestrian Measurements





Portable Antenna Field Data Results

- **Received Power**




RECEIVED POWER (DB) – ALL ENVIRONMENTS				
		Head	Hip	Hand
DUT1	Ant 1	-0.6	-1.4	-2.0
	Ant 2	1.8	-1.3	-4.7
	Ant 3	-0.3	-2.0	0.7
DUT2	Ant 1	3.0		1.2
	Ant 2	4.2		-0.1
	Ant 3	0.4		-0.3
DUT3	Ant 1	-0.5	-1.9	-0.3
	Ant 2	-0.9	-2.2	-0.5
LAP-TOP	Ant 1			3.2
	Ant 2			3.2

- Across all 12 environments, large power differences
- Consistent with anechoic chamber measurements

Portables: 2x2 Spatial Conditioning

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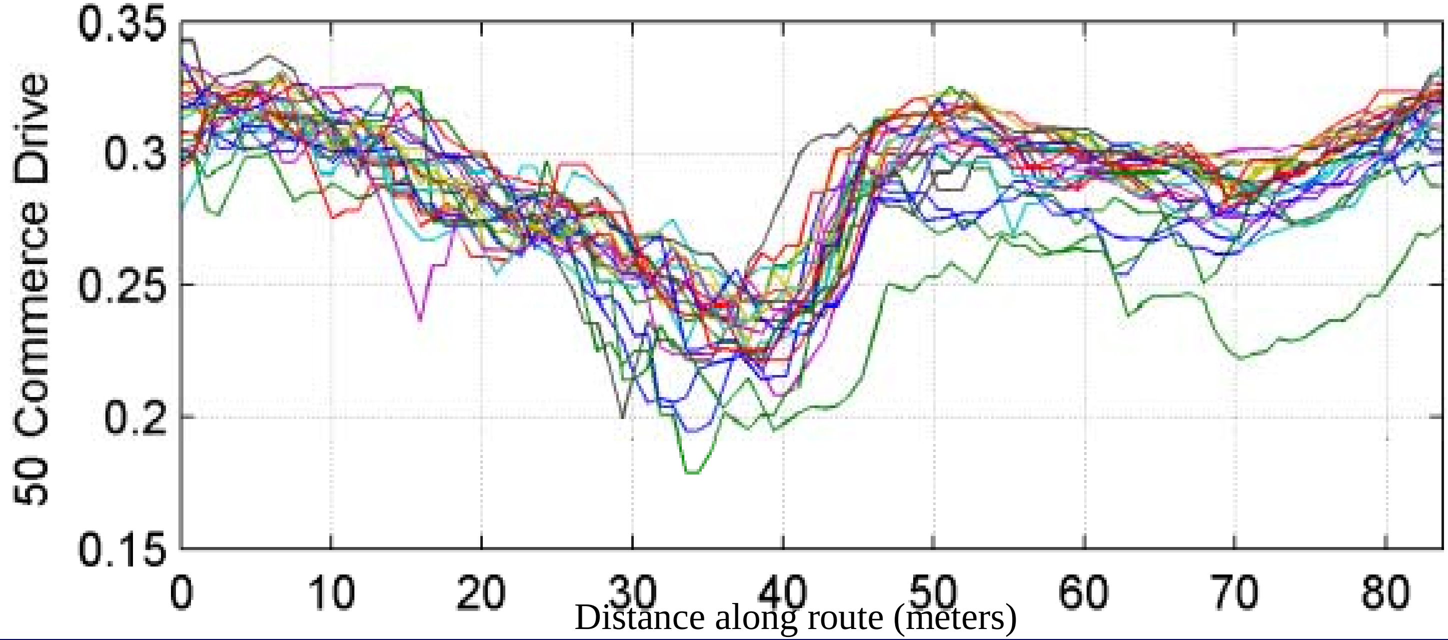
- RCN = Reciprocal Condition Number
  = ratio of smallest to largest singular value of 2x2 channel
- Averaged over short time interval and entire bandwidth
- Observed to be more a function of *ENVIRONMENT* than *ANTENNAS*

Mean RCN in Indoor Office area, different antenna pairs



- *Exception*: large receive power imbalance corresponds to lower RCN

Indoor Channel - Time Variation

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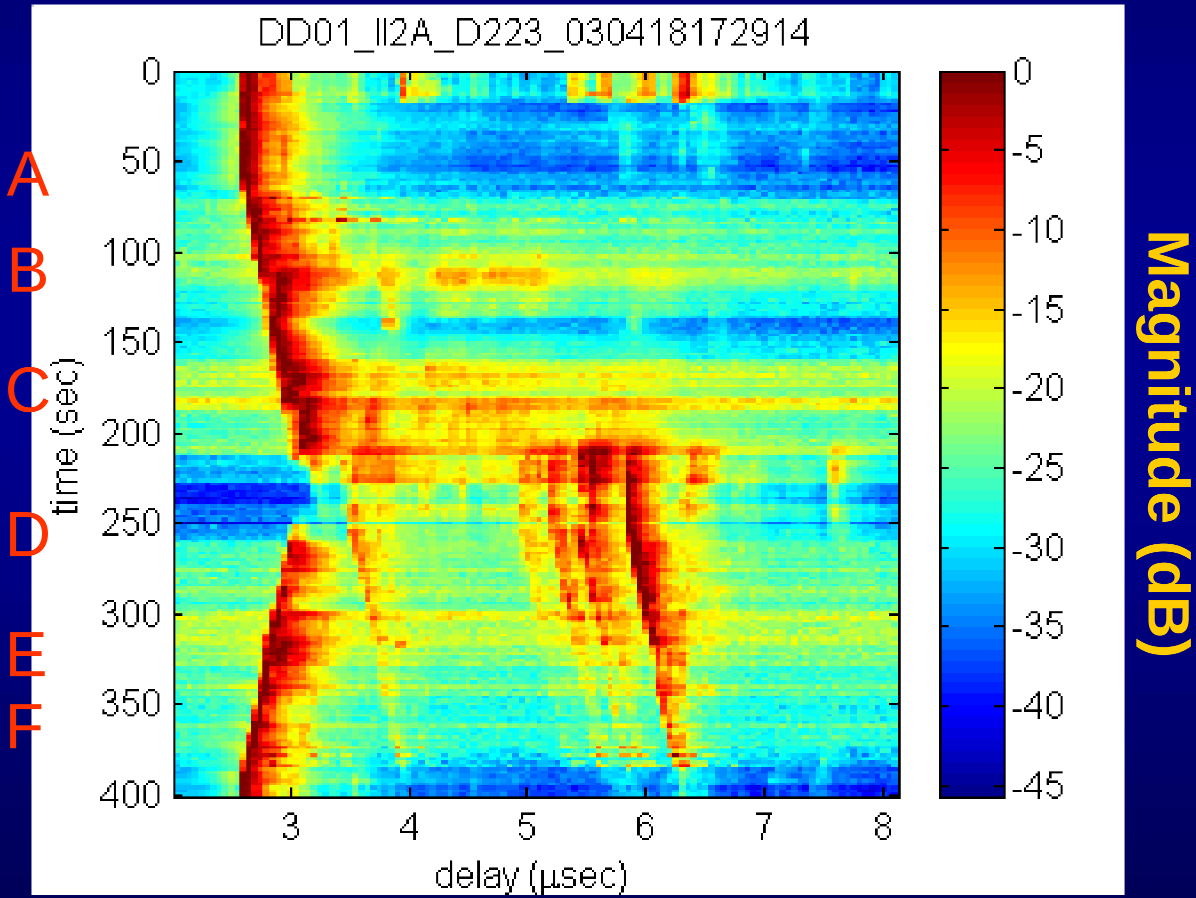
Power-Delay Profile Image



Indoor Doppler Spectra

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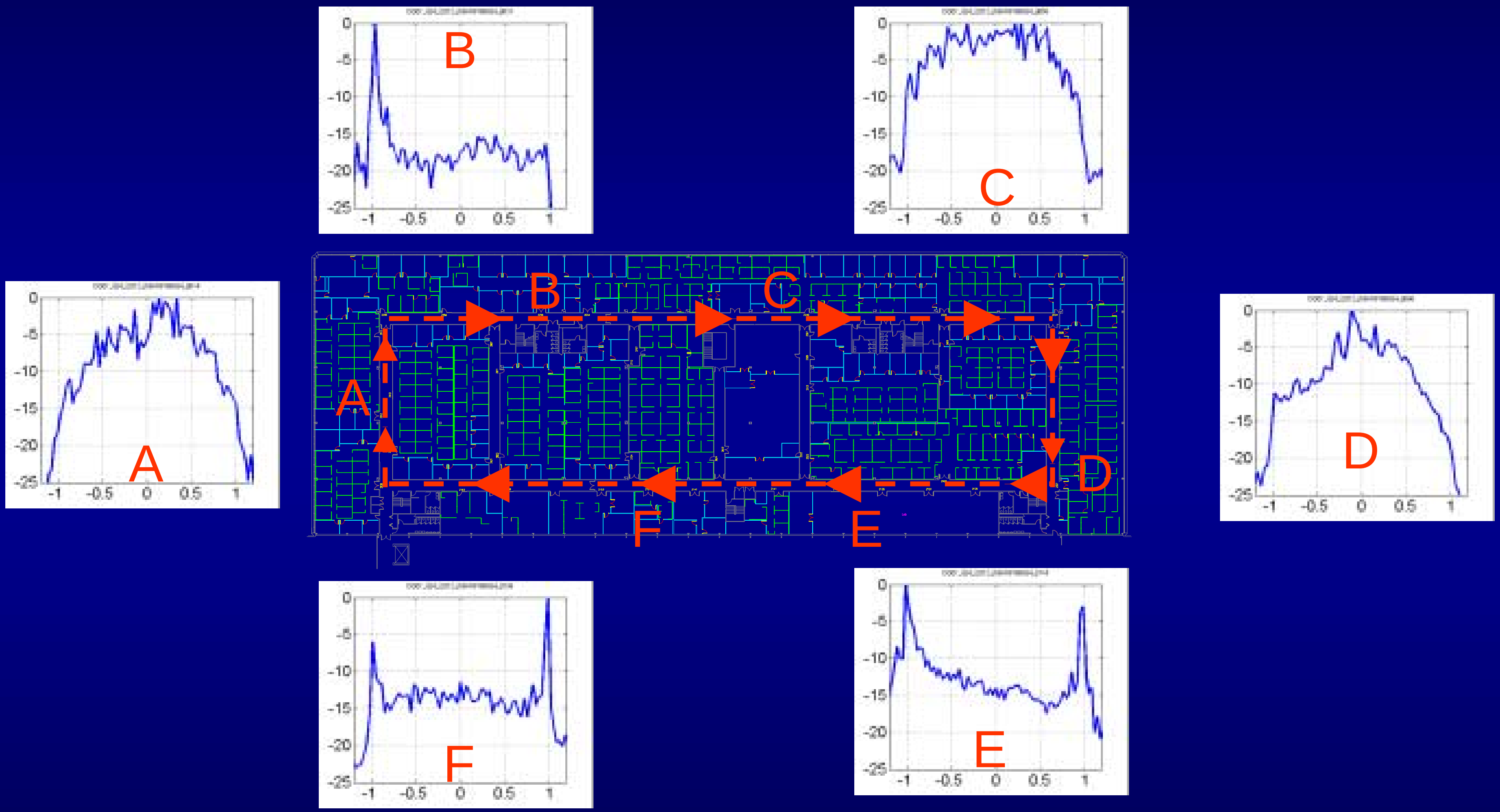

Prototype Transceiver System

Turbo Coded OFDM Transceiver System

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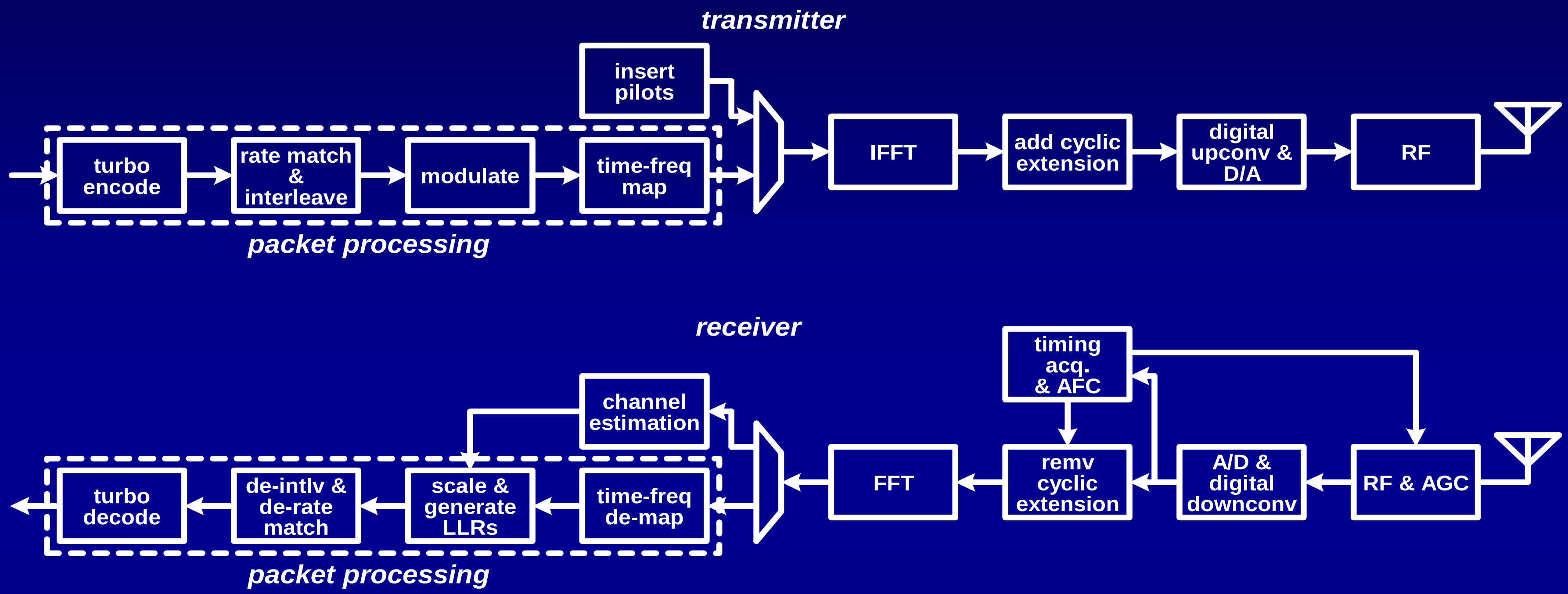

- Time division duplex
- 20 MHz RF bandwidth at 3.675 GHz
- 1x1
- OFDM
  - 751 active subcarriers (1024-point (I)FFT)
  - 25 kHz spacing
  - 10 ms cyclic extension

- Turbo coded
  - 3G code generator
  - Specialized "high-throughput" turbo interleavers
- Nine modulation and coding rates
- Automatic gain control
- Coarse and fine timing synchronization
- Automatic frequency control
- Coherent channel estimation

System Performance Testing

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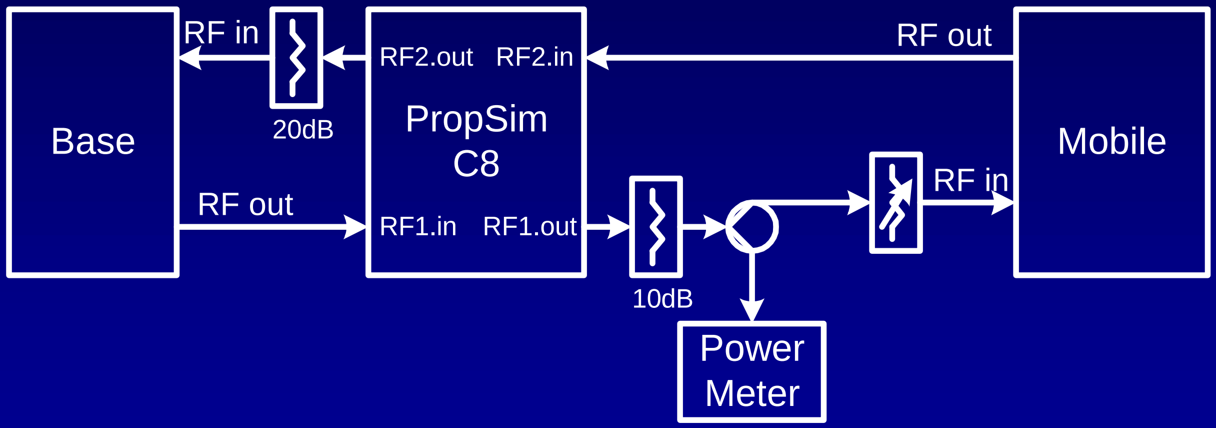

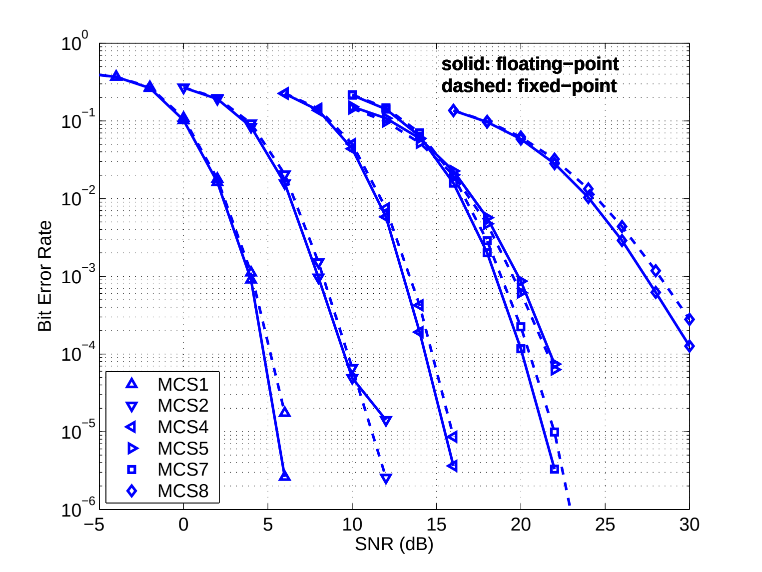

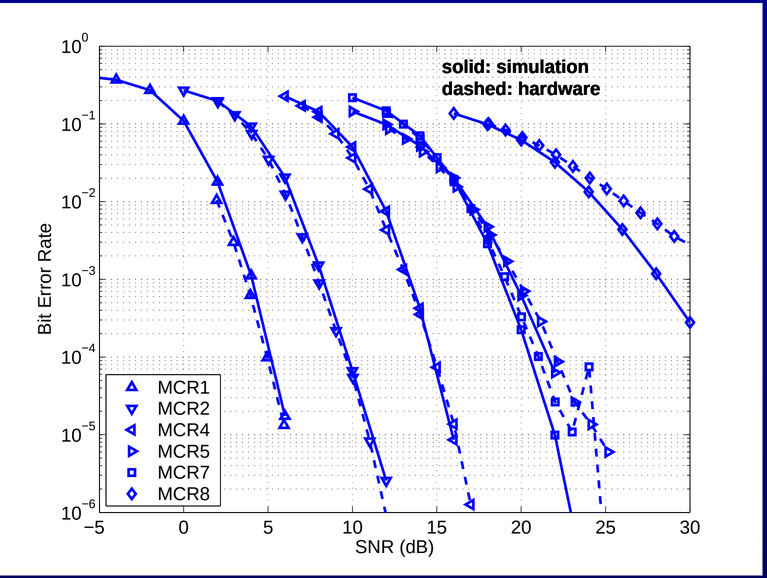

Wireless Ethernet Bridge Demonstration

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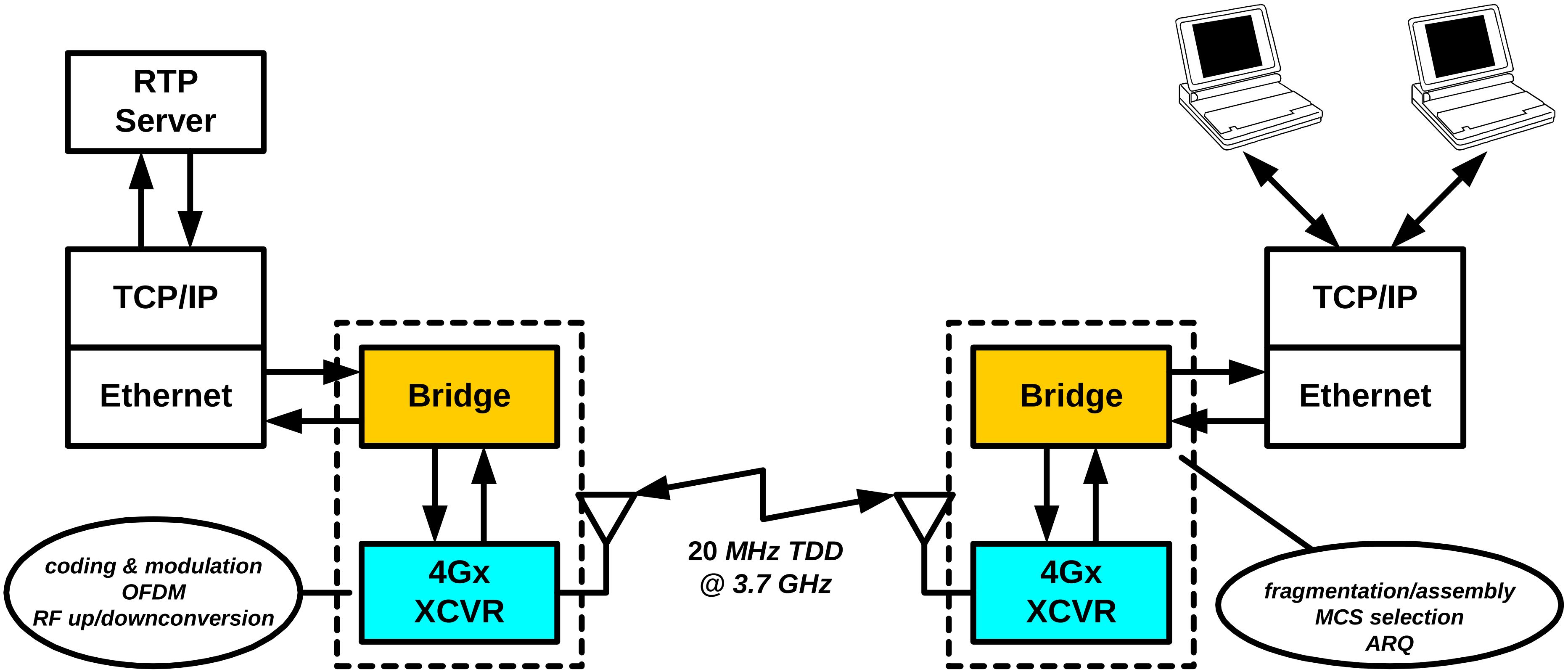

THE END To learn more:

MOTOROLA LABS

- **IEEE VTC-2002 Fall, Vancouver Canada, September 24-29, 2002**
  - V. Nangia, K. Baum, “Experimental Broadband OFDM System: Field Results for OFDM and OFDM with Frequency Domain Spreading”
  - J. Kepler, T. Krauss, S. Mukthavaram, “Delay Spread Measurements on a Wideband MIMO Channel at 3.7 GHz”
  - A. Talukdar, M. Cudak, “Radio Resource Control Protocol Configuration for Optimum Web Browsing”
  - X. Zhuang, F. W. Vook, “Code-Assisted MIMO Joint Detection and Decoding in Turbo-Coded OFDM”
  - T. Thomas, F. Vook, “A Method of improving the performance of successive cancellation in mobile spread MIMO-OFDM”
- **IEEE VTC-2003 Spring, Jeju Korea, April 21-24, 2003**
  - T. Krauss, T. Thomas, F. Vook, "Direction of Arrival and Capacity Characteristics of an Experimental Broadband Mobile MIMO-OFDM System”
- **IEEE ICC-2003, Anchorage Alaska, May 11-15, 2003**
  - T. Thomas, K. Baum, F. Vook, “Modulation and Coding Rate Selection to Improve Successive Cancellation Reception in OFDM and Spread OFDM MIMO Systems”
  - B. K. Classon, P. J. Sartori, V. Nangia, X. Zhuang, K. L. Baum, “Multi-Dimensional Adaptation and Multi-User Scheduling Techniques for Wireless OFDM Systems”
- **IEEE VTC-2003 Fall, Orlando Florida, October 4-9, 2003**
  - T. A. Thomas, T. P. Krauss, F. W. Vook, “CHAMPS: A Near-ML Joint Doppler Frequency/TOA Search for Channel Characterization”
  - T. P. Krauss, I. Lisica, X. Zhuang, “An Experimental Evaluation of the Subscriber Antenna Pattern Effect in a MIMO-OFDM System”

Thank You! Questions / Discussions are most welcome.