WAVE Motion-Related Channel Model Development

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Authors:

Name	Company	Address	Phone	email
Mary Ann Ingram	Georgia Institute of Technology	School of ECE Atlanta, GA 30332-0250	404-894-0492	mai@ece.gatech.edu
Guillermo Acosta	Georgia Institute of Technology	School of ECE Atlanta, GA 30332-0250	404 297 7941	gacosta@gatech.edu

Abstract

A method to develop a commercial channel emulator model for a doubly selective vehicle-to-vehicle wireless channel is presented. The model was developed from measurements taken at 5.9 GHz in an expressway environment when the vehicles are traveling in the same direction. The probe waveform is a combination of a direct sequence spread spectrum (DSSS) waveform with an orthogonal frequency division multiplexing (OFDM) waveform with a chirp signal for pulse compression.

Outline

- Project Objective
- Measurement Description
- Channel Modeling
- Expressway Same Direction with Wall Model
- PER Testing
- Conclusions and Future Work

Project Objective

- Develop a channel model* for motion-related equipment certification test for 802.11p
- Base the model on measurements at 5.9GHz
- Demonstrate the test on a SPIRENT 5500 RF channel emulator

* Previous and current modeling methods can be found in [1] and [2], respectively

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Measurement Descriptions

- **Phase I – 2004**
  - Emphasis on sites with large delay spreads
  - 2.4 GHz with max range 300m (power limited)
  - 20 MHz bandwidth
- **Phase II – Spring 2006**
  - Emphasis on nominal LOS channels
  - 5.9 GHz with ranges up to 1 km
  - More scenarios, including roadside-to-vehicle
  - 10 MHz bandwidth

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Phase II Sites

138 Takes (184 GBytes), each one containing 16 0.6 second segments for the following locations:

- **Urban Canyon – dense, tall buildings**
  - Oncoming
    - 1 Km, 15m, 100m, 300m to 400m
  - Same-direction
    - 1 Km, 100m
- **Suburban Expressway – moderately dense, low-story buildings**
  - Oncoming
    - 400m, no center wall.
  - Same-direction
    - 400m; with and without center wall
  - RTV
    - 400m
- **Suburban Surface Street – moderately dense, low-story buildings**
  - Oncoming
    - 300m, 400m
  - Same-direction
    - 100m; 400m
  - RTV
    - 100m, 1 Km

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Expressway Same Direction Wall

- **The transmitter is in front approx. 400 m ahead**
- **Moderate traffic**
- **Notice the truck blocking the LOS**
- **Notice the overpass**

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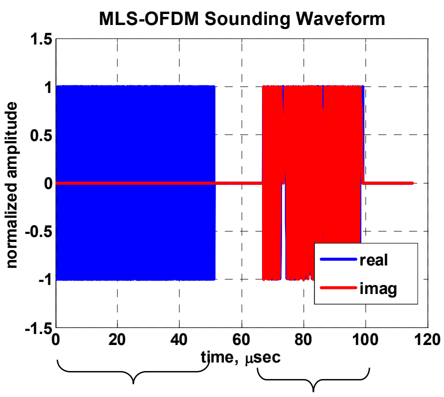
Expressway Oncoming

- Very low traffic
- No buildings
- Both vehicles on right lane

Sounding Waveform



100 ns 511-MLS 50 ns 512-OFDM

Maximum Path Length-MLS	15.33 km
Maximum Path Length-OFDM	7.68 km
T_c	50 ns
3 dB BW	20 MHz
T_{rp}	115.1 µs
Maximum Doppler Frequency	± 4.344 kHz

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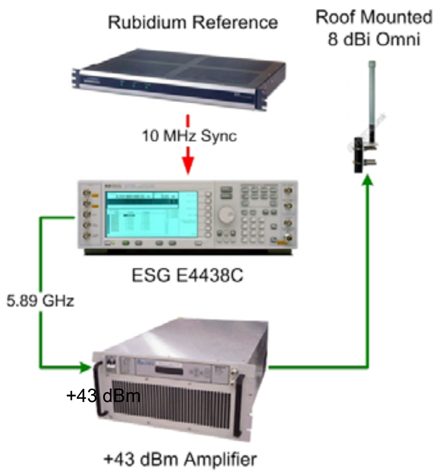
Phase II Transmitter



60 dB

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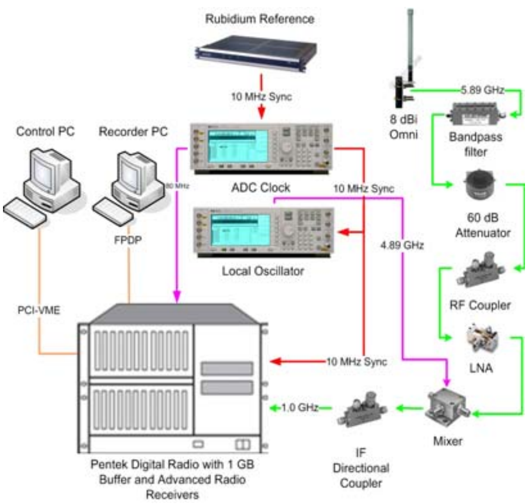
Phase II Receiver

Built a down-converting front end



RF BW	**40 MHz**
IF	**1 GHz**
ADC	**12 bit 80 MHz**
Data Rate	**20×10^6 complex samples/s**

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Signal Processing

- **We operate on the recorded complex baseband data as follows:**
  - Correlate the first ten repetitions of the combined waveform with the MLS sequence to find a suitable starting point
  - Separate MLS and OFDM parts
  - For the MLS part, we first use a Mueller-Mueller timing algorithm to obtain the 100 ns samples and then pass it through the correlator to create the IRs
  - For the OFDM part,
    - We remove the cyclic prefix and take the FFT
    - We then divide the received frequency response by the system's frequency response
    - We take the IFFT to obtain the IR

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  - Constraints
  - Tap delays and powers
  - Tap K factors
  - Doppler spectrum modeling
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Channel Modeling Constraints

- **Constraints of the commercial RF channel emulator**
  - Limited number of paths
  - Limited selection of Doppler spectrum shapes
- **Constraints of the measurement system**
  - 100ns delay resolution
- **Important that the model deliver 802.11p link performance similar to recorded channel**
  - Will emphasize inter-carrier interference effects from Doppler spread

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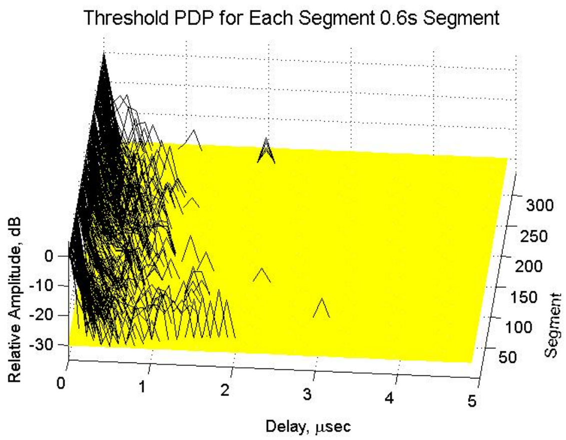
Tap Power and Delay Identification

- **Remove long-term trend (path loss)**
- **Obtain power delay profile (PDP) for each 0.6 sec segment by averaging the magnitudes squared of the impulse responses (IRs)**
- **Apply 30 dB threshold**
- **Average segment PDPs over the scenario to get a scenario power delay profile (PDP)**
- **Apply the 30 dB threshold again**
- **The non-zero bins of the scenario PDP will correspond to the "significant taps" of the model**

Segment PDPs for Expressway, Same-Direction



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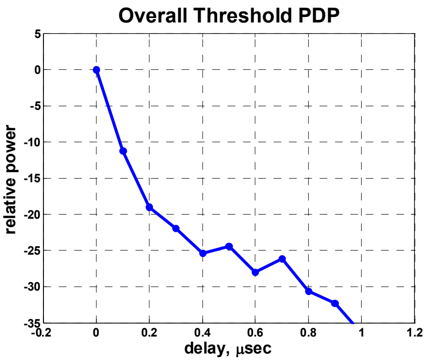
Scenario PDP for Expressway Same-Direction

- The delay resolution is 100 ns
- The significant bins for the model are the points > -30 dB
- Therefore, there are eight taps in this model



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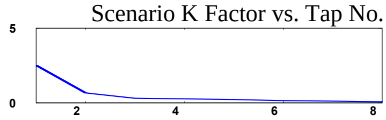
K Factor Identification

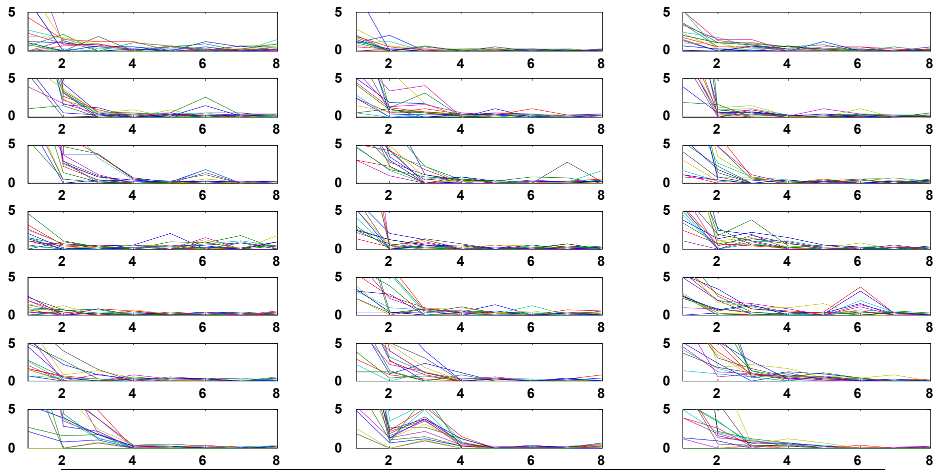
$$\text{K Factor} = \frac{\text{Power of Deterministic or Constant-Envelope Part}}{\text{Power of Random or Diffuse-Scattering Part}}$$

- Apply the Moment Method [3] to identify these powers for each tap in each segment
- Obtain an average deterministic power per tap for the scenario
- Obtain an average random power per tap for the scenario
- “Scenario K-Factors” are the ratio of these powers for each tap

Segment K Factors vs. Tap No. (21 Takes; 16 Segments per Take) Expressway, same-direction, wall

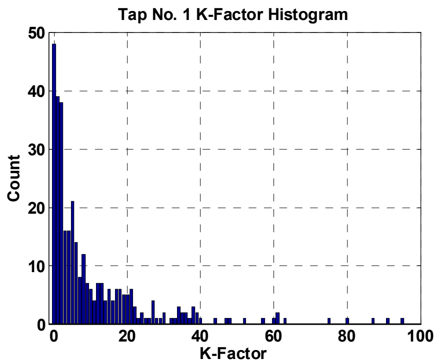
Scenario K Factor vs. Tap No.

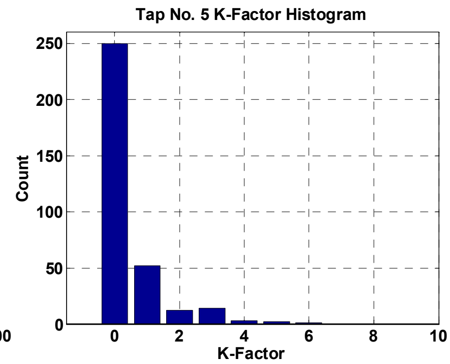




Segment K-Factor Histograms

- Wide variation: from zero to 95
- Limited variation, but still occasionally significant for later taps





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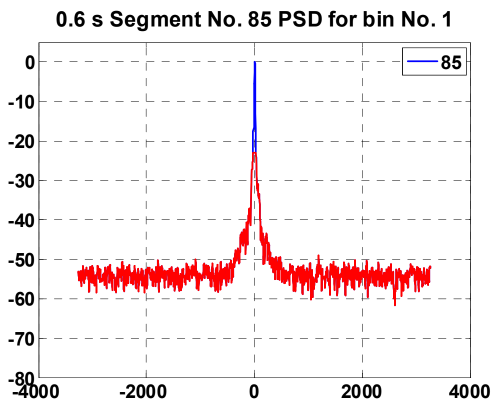
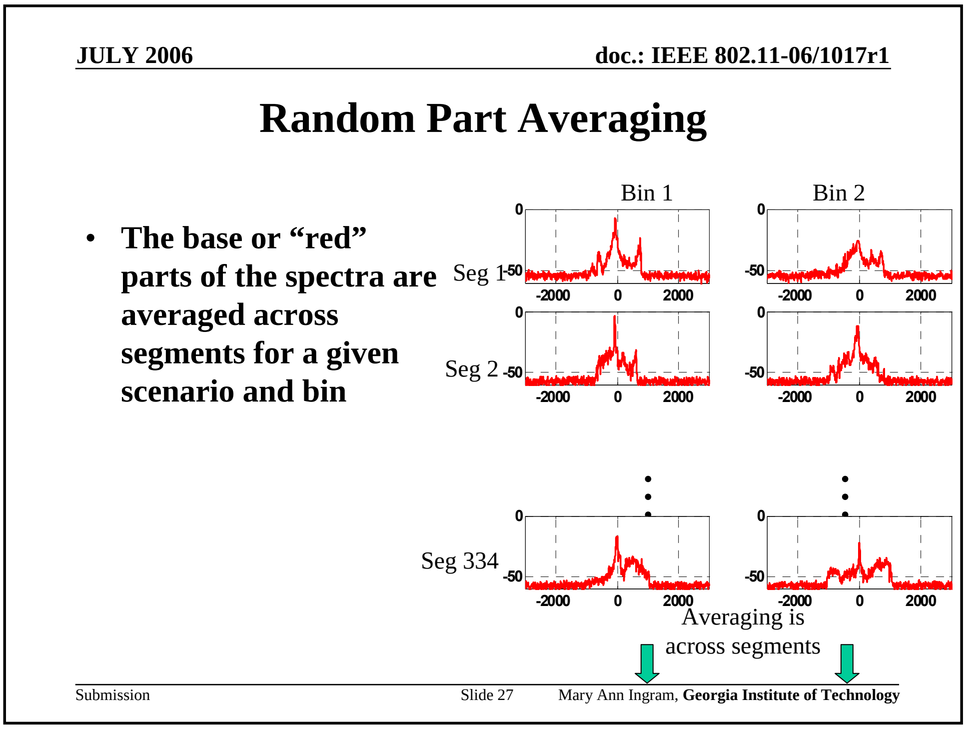
Spectrum Modeling Approach

- **Separate the deterministic part of the spectrum from the random part, for each tap and segment**
  - Two methods are considered:
    - Level method (used for the results shown)
    - Hole method
- **Average the random spectra over the segments**
- **Fit channel emulator shapes to the averaged random spectra**
  - Decide if one or two shapes per tap are necessary
- **Insert deterministic part**
- **Scale all frequencies to be consistent with specified vehicle speed**

Example of Level Approach

- **First bin, for well-separated vehicles traveling in the same direction on the expressway**

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Random Part Averaging
• The base or "red" parts of the spectra are averaged across segments for a given scenario and bin
Bin 1
Bin 2
Seg 1
Seg 2
Seg 334
0
-50
-2000
0
2000
Averaging is across segments
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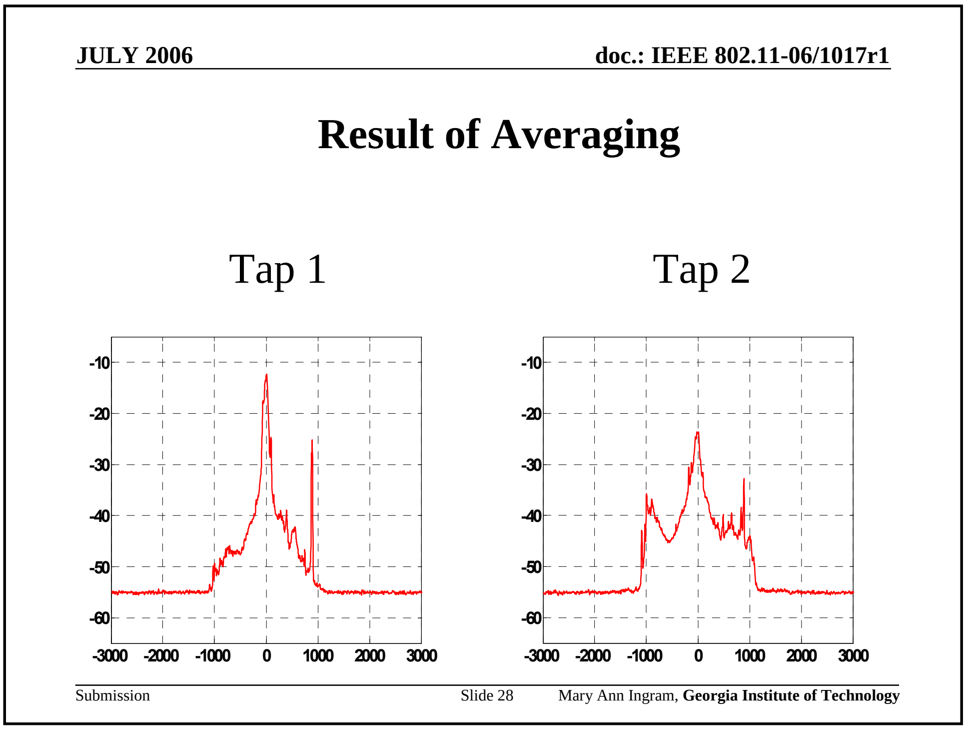
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Result of Averaging
Tap 1
Tap 2
-10
-20
-30
-40
-50
-60
-3000
-2000
-1000
0
1000
2000
3000
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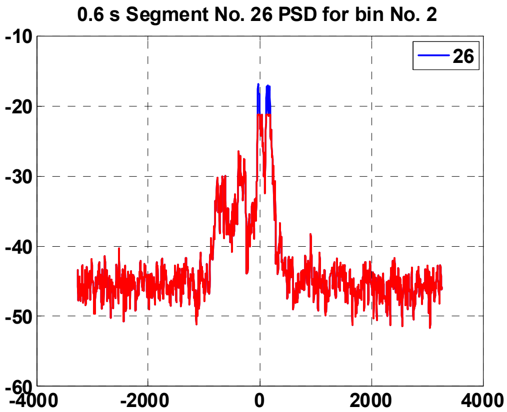
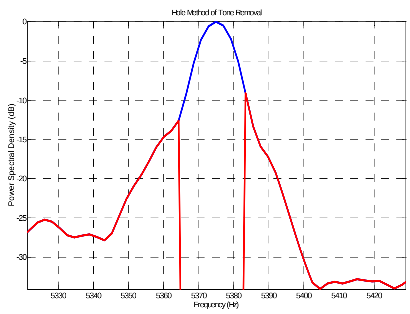
Problem with Level Approach

- **Sometimes it clips more than one line**



"Hole" Approach to Spectral Line Removal

- **Remove an area of the spectrum, centered at the peak, that corresponds to the power of the Rician (or constant envelope) component**



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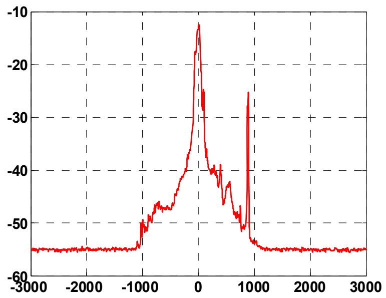
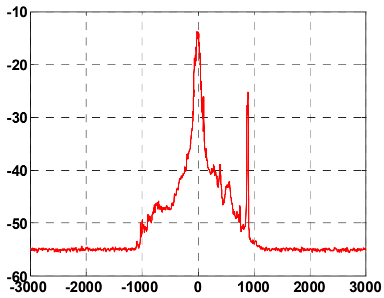
Comparing Averages for Level and Hole Methods

- **Tap 1, Expressway, same direction with wall**

Level Method



Hole Method



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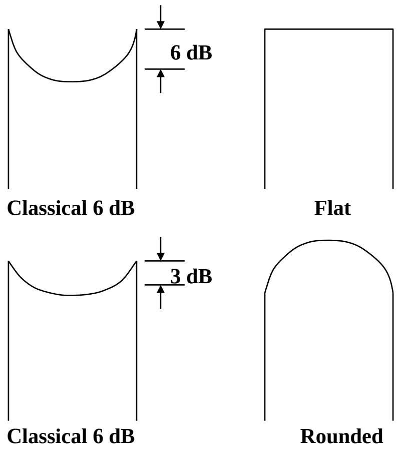
Channel Emulator Doppler Spectrum Shapes

- **Two or more paths with the same delay can be used to construct a "composite spectrum"**



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Shape-Fitting Cost Function

- **Even with two shapes, parts of the measured Doppler spectrum will not be well fit**
- **Intercarrier interference (ICI) is the primary channel impairment for mobile OFDM [4], so we use the Genetic Algorithm [9] to try to make**

Model ICI ≈ Measured channel ICI

- **Specifically, we minimize [2]**

$$\int \left| \varphi(f) - \varphi'(f) \right| f^2 df$$

Measured Doppler spectrum

Model Doppler spectrum

Higher Doppler frequencies are emphasized

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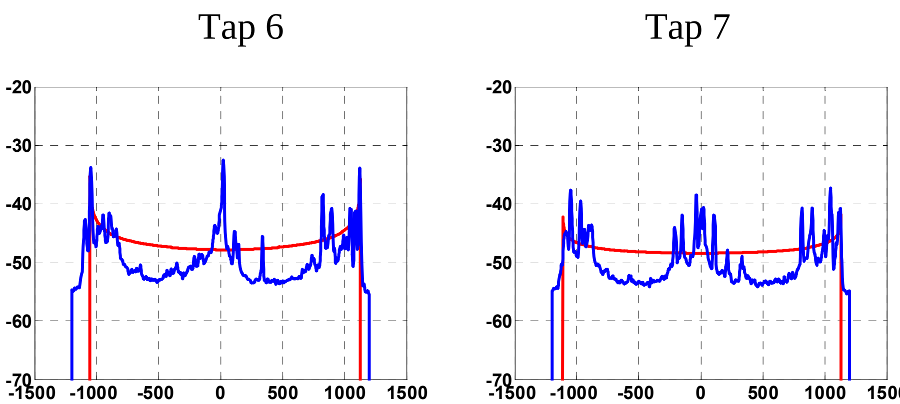
Example: One Shape per Tap Fitting



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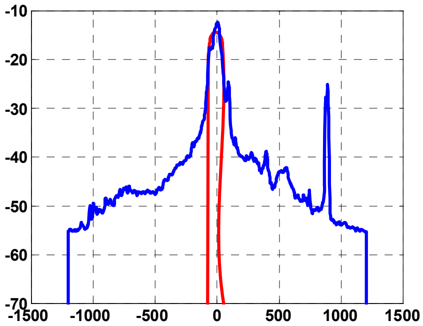
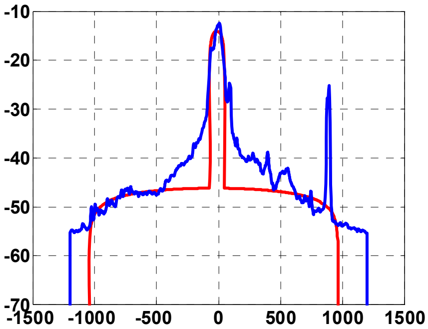
One vs. Two Shapes Example

- **Tap One with one shape**
- **Tap One with two shapes**

$ICI_{measured}$ (dB) – ICI_{model} (dB) = 11.52 dB



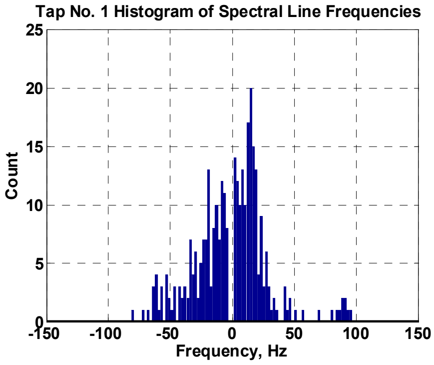
$ICI_{measured}$ (dB) – ICI_{model} (dB) = 6.23 dB



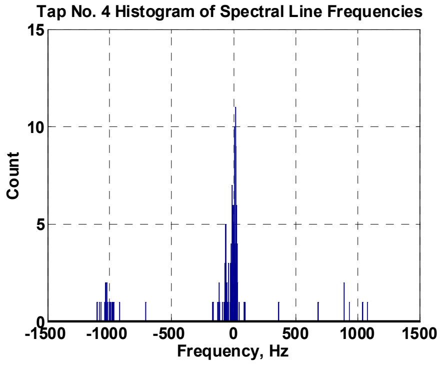
Constant Envelope Frequency Position

- **The LOS Doppler varies roughly from -100 Hz to +100 Hz**
- **Doppler frequencies as large as about 1200 Hz in magnitude**

Tap No. 1 Histogram of Spectral Line Frequencies



Tap No. 4 Histogram of Spectral Line Frequencies



Normalized Correlation Between Spectral Line Frequencies of Taps- Expressway, same-direction

0	0,25344	0,045529	0,12437	-0,010904	-0,01067	-0,15527	0,060848
0	0	0,19712	0,021794	-0,083639	-0,004934	-0,088806	0,14189
0	0	0	0,33887	0,052879	0,034775	-0,065462	-0,073024
0	0	0	0	0,27789	0,02787	-0,007087	0,029151
0	0	0	0	0	0,27233	0,12267	0,14823
0	0	0	0	0	0	0,36123	0,30059
0	0	0	0	0	0	0	0,42088
0	0	0	0	0	0	0	0

Very low correlation is exhibited between the frequencies of the adjacent tap's spectral lines

Spectral Line Location

- **Selection of tap spectral line for the model, Taps 1 and 2, was a somewhat arbitrary choice, but based on the histogram**
- **Low correlation meant that we could choose any frequencies for each tap that were within the range indicated by the histograms**

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Expressway Same Direction Model

Tap No.	Path No.	Tap Power (dB)	Relative Path Loss (dB)	Delay Value (ns)	Rician K (dB)	Freq. Shift (Hz)	Fading Doppler (Hz)	LOS Doppler (Hz)	Modulation	Fad. Spec. Shape
1	1	0.0	-1.4	0	23.8	-55	1407	-60	Rician	Round
1	2		-5.6	1	n/a	-20	84	n/a	Rayleigh	Round
2	3	-11.2	-14.2	100	5.7	-56	1345	+40	Rician	Classic 3 dB
2	4	0	-14.2	101	n/a	0	70	n/a	Rayleigh	Round
3	5	-19.0	-19.0	200	n/a	-87	1358	n/a	Rayleigh	Classic 6 dB
4	6	-21.9	-21.9	300	n/a	-139	1397	n/a	Rayleigh	Classic 3 dB
5	7	-25.3	-27.9	400	n/a	60	1522	n/a	Rayleigh	Classic 6 dB
5	8		-30.8	401	n/a	-561	997	n/a	Rayleigh	Classic 3 dB
6	9	-24.4	-24.4	500	n/a	50	1529	n/a	Rayleigh	Round
7	10	-28.0	-28.0	600	n/a	13	1572	n/a	Rayleigh	Round
8	11	-26.1	-31.5	700	n/a	-6	1562	n/a	Rayleigh	Classic 6 dB
8	12		-28.1	701	n/a	4	81	n/a	Rayleigh	Round

Expressway Same Direction Model Notes

1. **Taps 1, 2, 5 and 8 have composite spectra. Each tap comprises two paths. The first two taps each have Rician and Rayleigh paths. The overall K factor is 4.0 dB for Tap 1 and -1.8 dB for Tap 2. Tap 8 comprises two Rayleigh paths. All paths associated with a composite Doppler spectrum have excess delays differing by 1ns. This is to ensure that the channel emulator creates them as separate paths. Because of its limited bandwidth, the unit under test will perceive two paths that differ in delay by only 1 ns as having essentially the same delay.**
2. **“n/a” means “not applicable.”**
3. **This channel is normalized so that the first tap power is 0 dB.**
4. **The parameters are named according to the Spirent SR5500 TestKit control software.**
5. **The SR5500 parameters LOS AOA and LOS Doppler are interdependent.**
6. **The SR5500 parameters Fading Doppler and Fading Doppler Vel. are interdependent.**

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  - Sources of hardware and software
  - Test setup description
  - PER results
- **Conclusions and Future Work**

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Sources of Hardware and Software

- **Channel emulator purchased on the contract**
- **OBU and RSU prototypes supplied by Transcore**
- **Network interface programs provided by Filip Weytjens of Transcore**
- **C++ TX and RX PER measurement programs written at Georgia Tech using the ping application with the IPv6 protocol**

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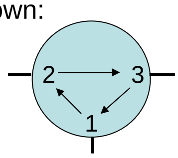
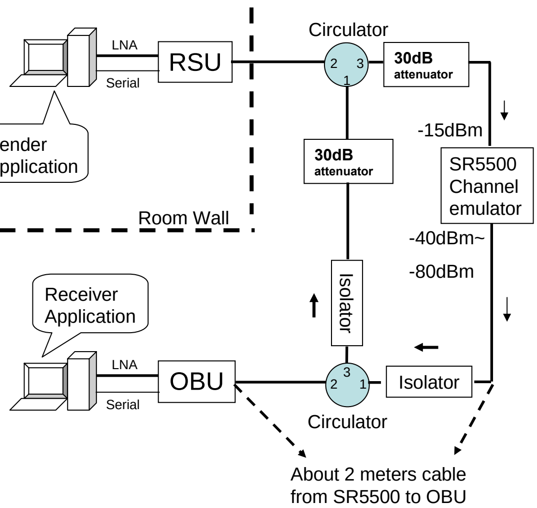
PER Setup Diagram

- RSU = TX and OBU = RX, but these can be reversed
- Circulator D3C4080 allows signal flows only as shown:



- Isolator D314084 allows signals to flow only one way



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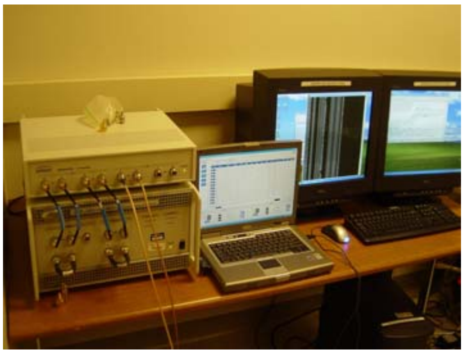
TX/RX Isolation in the Test Setup

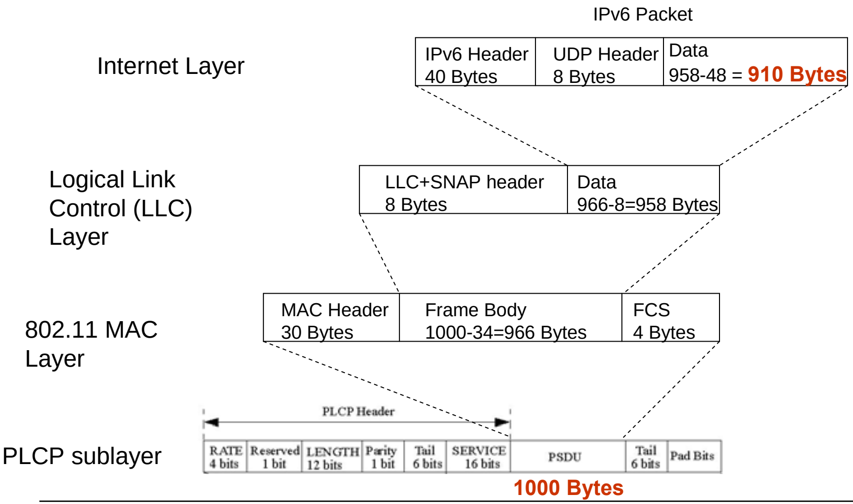
- Each unit placed in a closed cardboard box, lined with absorber and wrapped in aluminum foil
- Placed in different rooms with door closed during tests



SR5500 Channel Emulator

Transmitter and Receiver units

Setting the IPv6 Payload Length for a 1000-Byte PSDU



PER Test Parameters

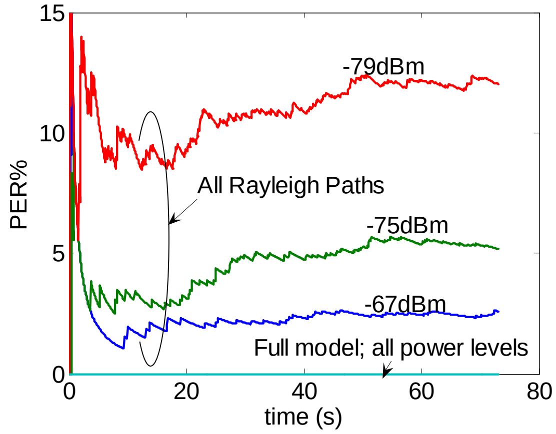
- **Network interface**
  - TX power: highest setting (~ 15 dBm)
  - Data rate: 6 Mbps
  - Channel: 5.87 GHz
- **Sending Application**
  - Packet size: 910 or 210 Bytes (IPv6 payload)
  - Packet interval: 15 ms
  - Maximum number of packets: 10K to 100K

Cumulative PER Results for the1000-Byte PSDU

- **15 ms packet transmission rate is only 66.7 packets/sec; 5 seconds is only 333 packets**
- **Higher transmission rate caused buffer problems**
- **Full model gives essentially**

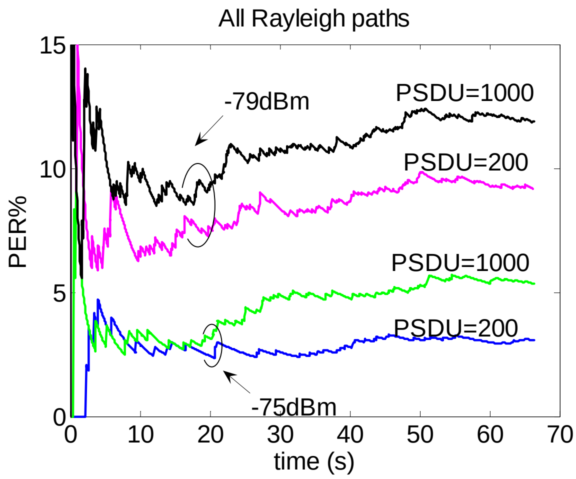
  PER = 0% for

  -79 dBm and higher
- **Non-LOS case still less than 10% at -75 dBm**



Non-LOS Case for Two PSDU Lengths

- **200-Byte PSDU passes at -79 dBm**



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Conclusions

- **An 8-tap, non-separable model was produced for the expressway, same-direction, with wall scenario**
- **DSSS was preferred for PDP estimation, while OFDM (using DSSS for time-synchronization) was preferred for Doppler estimation**
- **Limited model degrees of freedom led to a model-fitting cost function based on ICI difference**
- **Some taps clearly require at least two paths to avoid excessive ICI difference**
- **PER measured with the prototypes and the full channel emulator model for 1000 Byte PSDU at -79 dBm was essentially 0%**
- **Removal of the LOS increased the PER, but at -75 dBm, it was still below 10%**
- **5 seconds is not enough for a statistically significant PER measurement if the packet transmission period is only 15 ms**

Future Plans

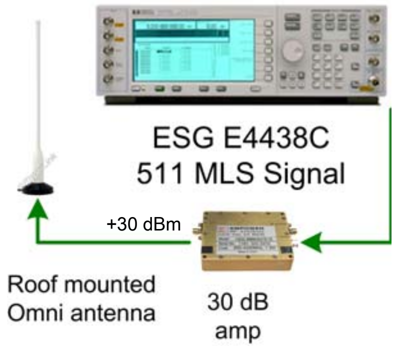
- **Process four or five more scenarios and summarize the results in a journal article**
- **Develop dynamic models, preferably dynamic (e.g. Markov chain) FER models, suitable for network analysis (NSF proposal submitted)**
- **Investigate improved methods for K factor, PDP and Doppler estimation from the OFDM probe waveform**
- **Measure and process 2X2 MIMO at 2.4GHz**

References

1. G. Acosta-Marum and M.A. Ingram, "A BER-based partitioned model for a 2.4 GHz vehicle-to-vehicle expressway channel," in International Journal on Wireless Personal Communication, July 2006.
2. G. Acosta-Marum and M.A. Ingram, "Doubly selective vehicle-to-vehicle channel measurements and modeling at 5.9 GHz," to appear in Proc. Wireless Personal Multimedia Communications Conference (WPMC 2006).
3. L. J. Greenstein, D. G. Michelson, and V. Erceg, "Moment-method estimation of the Ricean *K*-factor," in *IEEE Communications Letters*, vol. 3, No. 6, pp. 175-176, June 1999.
4. X. Cai and G.B. Giannakis, "Bounding performance and suppressing intercarrier interference in wireless mobile OFDM," IEEE Trans. Comm. Vol. 51, No. 12, December 2003.
5. http://ideas.repec.org/c/cod/matlab/ga.html

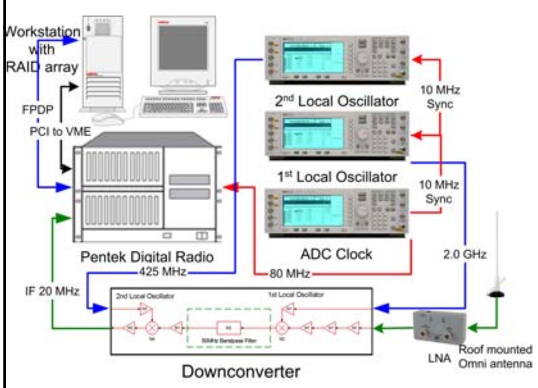
Extra Slides

Phase I Transmitter

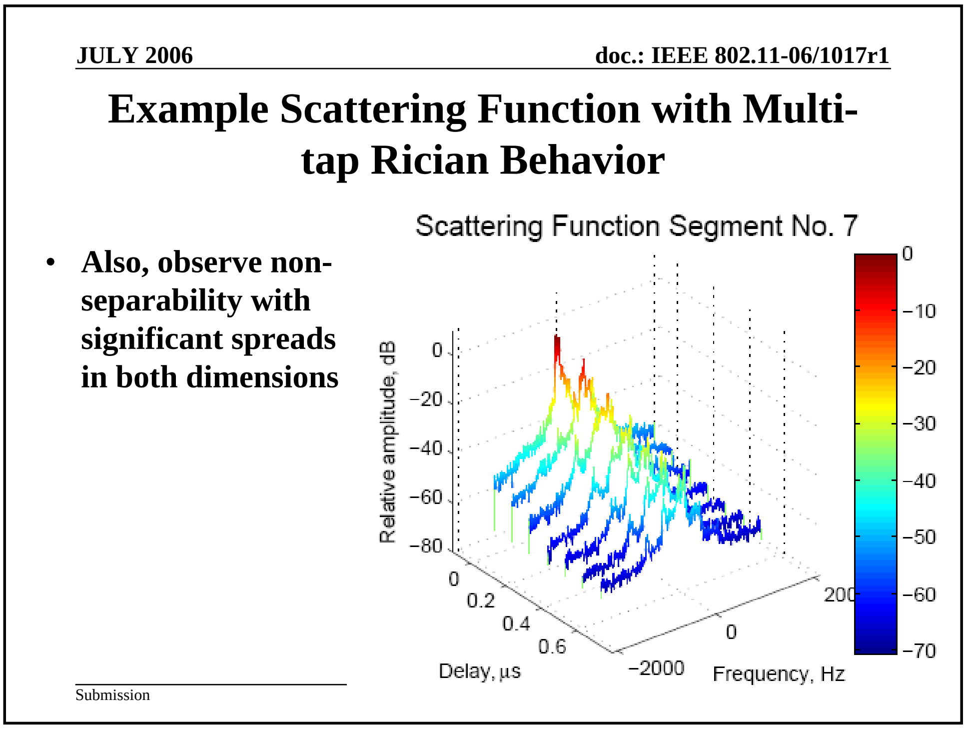


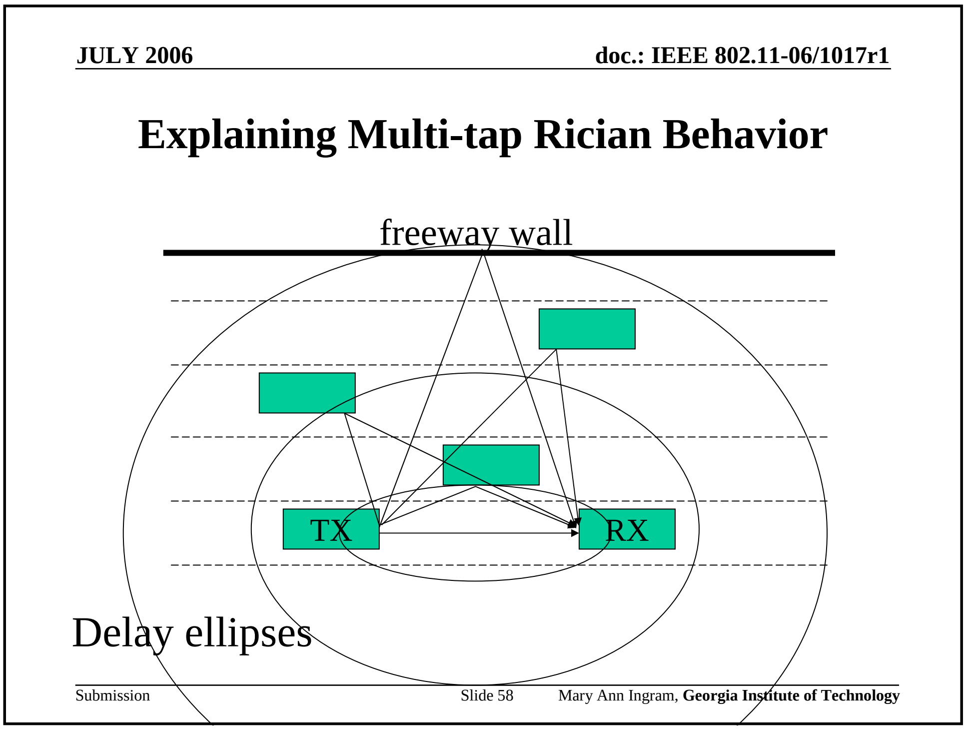
Length MLS	511
T_c	50 ns
3 dB BW	20 MHz
T_{rp}	25.5 µs
Maximum Path Length	7.65 km
Maximum Doppler Frequency	19.5 kHz

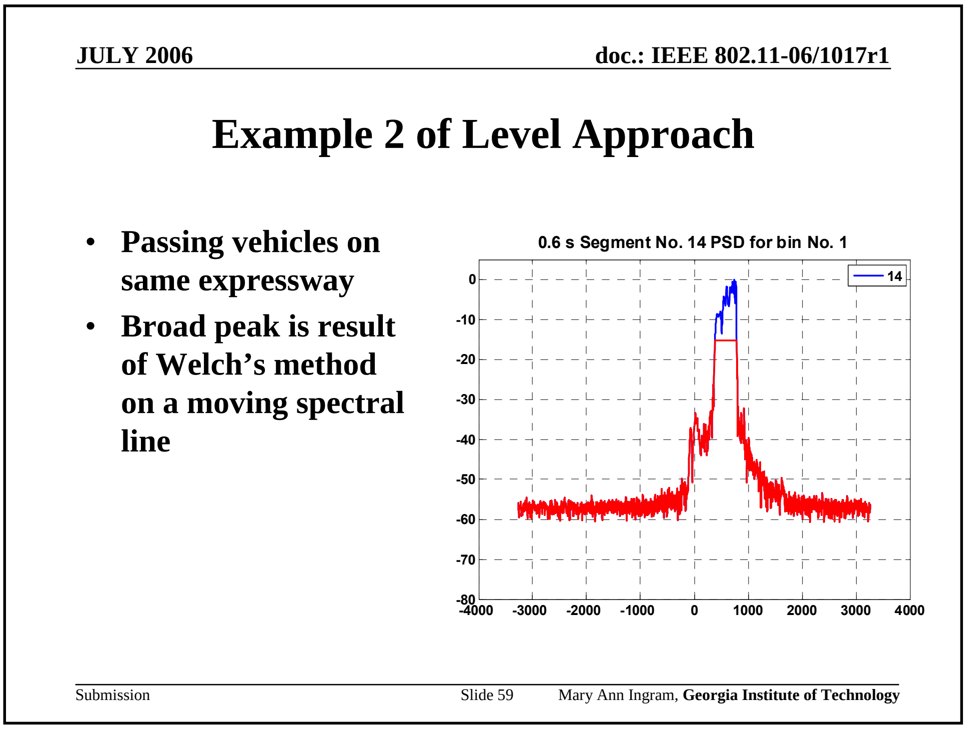
Phase I Receiver



1st IF	445 MHz
2nd IF	20 MHz
IF Filter BW	46 MHz
ADC	12 bit 80 MHz
Data Rate	20×10^6 complex samples/s
Recording Speed	80 Mbytes/s


JULY 2006
doc.: IEEE 802.11-06/1017r1
Example Scattering Function with Multi-tap Rician Behavior
• Also, observe non-separability with significant spreads in both dimensions
Scattering Function Segment No. 7
Relative amplitude, dB
0
−20
−40
−60
−80
0
0.2
0.4
0.6
Delay, µs
−2000
0
200
Frequency, Hz
0
−10
−20
−30
−40
−50
−60
−70
Submission


JULY 2006
doc.: IEEE 802.11-06/1017r1
Explaining Multi-tap Rician Behavior
freeway wall
TX
RX
Delay ellipses
Submission
Slide 58
Mary Ann Ingram, Georgia Institute of Technology


JULY 2006
doc.: IEEE 802.11-06/1017r1
Example 2 of Level Approach
• Passing vehicles on same expressway
• Broad peak is result of Welch's method on a moving spectral line
0.6 s Segment No. 14 PSD for bin No. 1
14
0
-10
-20
-30
-40
-50
-60
-70
-80
-4000
-3000
-2000
-1000
0
1000
2000
3000
4000
Submission
Slide 59
Mary Ann Ingram, Georgia Institute of Technology