Developments in Characterization of Mobile Radio Propagation

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Antennas & Propagation Society

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Messages to Drive Home with

- **Nature of Complexity involved**
  - Almost Impossible for Analytical or Computer based Solutions
  - Thus, Most are Empirical Models based Field Measurements
  - Hard to Generalize and Scale based on Few Measurements
  - Thus, New Measurements needed Whenever Variables Change
  - Statistically Meaning Data takes Extensive Efforts and Costly

- **Some Understanding of Mobile Radio Models**
  - What they are: Mostly Fading and Multi-path Effects
  - Mostly Statistical in Nature
  - Basic Underlying Theory is not so Hard

- **Some Appreciation of Development Progress over the Years**
  - Key Contributions and Drivers
  - Necessity of Models and Relations to Technology Evolution
Outline

- **Radio Propagation Fundamentals**
  - Spectrum • General Considerations
- **Mobile Radio Propagation for Cellular/PCS**
  - Objectives • Dependencies • Usage
  - Multi-Discipline Perspectives
- **Channel Modeling Framework**
  - Underlying Math Models & Reality •
  - Association with Technology Progress
- **Channel Models**
  - Key Contributions • Fundamentals of Path Loss • Models for Cellular Engineering • Models for MODEM Engineers Models • Attempt for Coherent & Comprehensive Consolidation of Models
- **An Example of Recent Propagation Study**
- **What’s Ahead in Mobile Radio Propagation**
### Frequency Spectrum

<table>
<thead>
<tr>
<th>Freq. Band</th>
<th>Designation</th>
<th>Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-30 kHz</td>
<td>VLF</td>
<td>Navigation, sonar</td>
</tr>
<tr>
<td>30-300 kHz</td>
<td>LF</td>
<td>Navigational Beacons</td>
</tr>
<tr>
<td>300-3000 kHz</td>
<td>MF</td>
<td>AM, Maritime Radio, Direction Finding</td>
</tr>
<tr>
<td>3-30 MHz</td>
<td>HF</td>
<td>Shortwave, amateur radio, Telephone, Telegraph</td>
</tr>
<tr>
<td>30-300 MHz</td>
<td>VHF</td>
<td>TV, FM, Mobile Radio, Radar, Air Traffic</td>
</tr>
<tr>
<td>300-3000 MHz</td>
<td>UHF</td>
<td>TV, Microwave Links, Radar, Satellite</td>
</tr>
<tr>
<td>3-30 GHz</td>
<td>SHF</td>
<td>Microwave Links, Satellites, Radar</td>
</tr>
<tr>
<td>30-300 GHz</td>
<td>EHF</td>
<td>Radar</td>
</tr>
<tr>
<td>300-10^7 GHz</td>
<td>IR/Optics</td>
<td>Fiber Optical Links</td>
</tr>
</tbody>
</table>

**Designation:**
- **V:** Very, **L:** Low, **H:** High, **U:** Ultra, **S:** Super, **E:** Extremely, **F:** Frequency

### Cellular

<table>
<thead>
<tr>
<th>Reverse (MS→BS)</th>
<th>Forward (BS→MS)</th>
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<tbody>
<tr>
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<table>
<thead>
<tr>
<th>824</th>
<th>825</th>
<th>835</th>
<th>845</th>
<th>846.5</th>
<th>849</th>
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<tbody>
<tr>
<td>A''</td>
<td>A</td>
<td>B</td>
<td>A'</td>
<td>B'</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10 MHz</td>
<td>10 MHz</td>
<td>1.5</td>
<td>2.5</td>
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</table>

45 MHz

### PCS

<table>
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<th>Reverse (MS→BS)</th>
<th>Forward (BS→MS)</th>
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<tbody>
<tr>
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<table>
<thead>
<tr>
<th>1850</th>
<th>1865</th>
<th>1870</th>
<th>1885</th>
<th>1890</th>
<th>1895</th>
<th>1905</th>
<th>1910</th>
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<tbody>
<tr>
<td>A</td>
<td>D</td>
<td>B</td>
<td>E</td>
<td>F</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 MHz</td>
<td>5</td>
<td>15 MHz</td>
<td>5</td>
<td>5</td>
<td>15 MHz</td>
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</table>

80 MHz
Fundamentals of Propagation Classification

- **Antenna Locations**
  - Terrestrial, Satellite, Airborne,

- **Propagation Media**
  - Lower Atmosphere, Surface, Ionosphere, Meteor, Underwater

- **Propagation Path Obstructions**
  - NLOS, LOS, Free Space (Fresnel Zone Clearance)

- **Signal Attenuation Mechanisms**
  - Spreading, Reflective, Diffractive, Absorptive (moist, rain)

- **Signal Propagation Mechanisms**
  - Reflection, Diffraction, Scattering, Refraction

- **Polarization**
  - Vertical, Cross, Horizontal, Circular

- **Terrestrial Channel Features**
  - Terrain, Man-Made Obstacles, Waters, Foilage

* Those most important for Cellular/PCS indicated in Bold
Particulars of Propagation for Cellular/PCS

• **Modeling Objectives**
  - Obtain location & time dependent characteristics for *optimum spectrum utilization*
    - Signal Path Loss • Signal Impairment • Interference Statistics

• **Modeling Dependencies**
  - Physical Environment
    - Natural and Man-Made Features
  - Signal Type
    - Frequency • Signal BW • Polarization
  - Technology
    - Analog or Digital • Modulation/Coding • Multiple Access Methods • Advancement of Signal Processing Techniques

• **Usage of Models**
  - Cell Planning: Coverage (Outage), Capacity (Interference)
  - Control Algorithm Design: Access, Power Control, Handoff
  - Receiver/Transceiver Design: Modem, Coding, Interleaving, Equalizer, Rake Receiver, ...
## Multi-Discipline Perspectives

<table>
<thead>
<tr>
<th>Problems of Interest</th>
<th>EM Radio Propagation</th>
<th>Cellular Network</th>
<th>Communications</th>
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<tbody>
<tr>
<td></td>
<td>Physics of Propagation</td>
<td>Link Budget</td>
<td>Signal Processing</td>
</tr>
<tr>
<td></td>
<td>frequency • polarization</td>
<td>path loss • fade margin</td>
<td>fade rate • Doppler shift</td>
</tr>
<tr>
<td></td>
<td>antenna type/height • physical &amp; electrical properties of medium</td>
<td>diversity gain</td>
<td>coherence BW &amp; time •</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td># of multi-paths •</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>diversity correlation</td>
</tr>
<tr>
<td></td>
<td>Attenuation • Diffraction</td>
<td>cell size • # of cells</td>
<td>Mod/Demod • Interleaving</td>
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<tr>
<td></td>
<td>Reflection • Refraction</td>
<td>BS locations • freq reuse</td>
<td>FEC • Channel Equalizer</td>
</tr>
<tr>
<td></td>
<td>Scattering • Penetration</td>
<td>antenna type/heights</td>
<td>Rake Receiver • Codes</td>
</tr>
<tr>
<td>Goodness of Solution</td>
<td>Analytic./Computer Sol’ns</td>
<td>Customer Satisfaction</td>
<td>Performance Compliance</td>
</tr>
<tr>
<td></td>
<td>simplicity, applicability &amp; closeness to field measured data</td>
<td>call attempt success rate •</td>
<td>Minimum E$_b$/N$_o$ • BER</td>
</tr>
<tr>
<td></td>
<td></td>
<td>call drop rate •</td>
<td>FER • Diversity Gain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>handoff success rate •</td>
<td>Acquisition Time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>handoff rate</td>
<td></td>
</tr>
<tr>
<td>Ultimate Goals</td>
<td>• Formulation of Analytical Models</td>
<td>• Minimum Investment</td>
<td>• Max. Bits/Sec/Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Customer Satisfaction</td>
<td>Shannon’s Limit</td>
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Taxonomy of Mobile Radio Propagation

• Propagation Conditions and Network Deployment
  - Frequency: Cellular, PCS, MMDS, LMDS, Wireless LAN ...
  - Environment: Cluttered City, Urban, Suburban, Rural, Indoors, ...
  - Cell Size: Macro-, Micro-, Pico-cell, (Hierarchical)
  - Antenna: Height, Directivity, Polarization, Tilt, Spacing
  - Coverage: Outdoors, In-Building, Subway, ...
  - Mobility: High Speed, City Driving, Pedestrian, Fixed

• Models of Main Interest (Statistics in Nature)
  - Network Planning
    • Path Loss and Slow (Long-Term) Fading
    • Diversity Correlation between Sector Antennas, Sectors, and Neighboring Base Stations
  - Communication System Design
    • Fast (Short-Term) Fading, Coherence Time, Doppler Frequency
    • Multipath Delay Profile: RMS Delay, Coherence BW, Correlation
    • Angular Spread: RMS Beamwidth, Correlation
Main Factors to Propagation Characterization

FCC Spectrum
- Cellular Band (8 to 900 MHz)
- PCS Band (1.8 to 1.9 GHz)

Cellular Engineering
- Cell Planning: Size, Freq. Reuse, Coverage Probability

Radio Network Tech.
- Macro-, Mini-, Pico-cell, Networking in Hierarch.
- Dynamic Freq. Assign., Smart Antenna

Cellular Standards
- AMPS, TDMA, CDMA
- 1G, 2G, 3G, 4G...

Communication Tech.
- Analog vs. Digital
- Narrow to Wide BW
Mathematical Framework of Models

**Black Box Approach**

System: \( h(t) \leftrightarrow H(\omega) \)

- **Linear Time-Invariant System**
  - Input: \( h(t) \)
  - Output: \( H(\omega) \)
  - Changes in Time

- **Linear Time-Variant System**
  - Input: \( h(t) \)
  - Output: \( H(\omega) \)
  - Changes Randomly

- **Statistical Linear Time-Variant System**
  - Input: \( h(t) \)
  - Output: \( H(\omega) \)
  - Changes Randomly

**Simple Undergraduate Level**

**Maybe Graduate Level**

**Definitely Graduate Level**

SO, What's the Dig Deal?
So, What is the Big Deal?

It comes in myriad of shapes and sizes!

Methods based on Physical Theory for Generalization don’t exist yet, probably never will.

Why Not A General Theory?

Simulate

Requires tons of input data and runs forever.

Make Field Measurements

Expensive

Return for investment not good business.

- Subject Not that Well Understood
- Slow Advancement in Scientific Knowledge

Doing Better in Europe, however.
Tech. Evolution & Detailed Structures needed

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Technology</th>
<th>Details</th>
</tr>
</thead>
</table>
| 1970-1983  | AMPS                  | Path Loss: Mean, Variance (Shadow Fading)  
Doppler Effects: FM Noise (Rayleigh fading)  
Diversity: Spatial Correlation |
Doppler Effects: Rayleigh Fading, Interleaving, Demodulation |
| 1990-1993  | IS-95                 | Delay Spread Characteristics (~ 1 µsec)  
- Higher Delay Resolution Needed  
- # of resolution paths • fading stats and correl. btwn them • how fast they come & go  
Correlation btwn Sectors/Cells for Soft HO |
| 1998-2000  | cdma200               | Delay Spread Characteristics (> 1/4 µsec)  
- Even higher resolution needed, # of resol. paths more critical, Stats of each path may not be Rayleigh anymore |
Propagation Scenario for AMPS & TDMA

Forward Link Signal Reception

Forward Link Interference Scenario for AMPS and TDMA (N=7)

An Example of Importance in Prop. Character. Interference level strongly dependent on propagation exponent \( \alpha: \sim 1/r^\alpha \)

→ Major Impact on Frequency Reuse Efficiency

Six Major Interferers of about equal strength
Everybody interferes with everybody else

Another Example:
Depends on Multipath Condition
Due to breakage in orthogonality between same cell users’ codes
But, Distance Dependent PL not as Important as in AMPS & TDMA
**Cellular Engineering: Coverage Reliability**

**Shadow Fading Log-Normal Model**

\[ Y(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\bar{x})^2}{2\sigma^2}} \]

\( x: \) PL, \( \bar{x}: \) mean PL, \( \sigma: \) SF Sigma

**Typical Objective for Area Coverage = 90 %**

**Contour Reliability**

Example for Max PL Allowed = 150 dB (from Link Budget)

**Path Loss**

- 150 dB
- 150-\( \sigma \) dB
- 150-2\( \sigma \) dB

\( R_a \)  50 %
\( R_b \)  84 %
\( R_c \)  93 %

**BS**

**Area Reliability**

Fade Margin: \( F_{mg} \)

\[ P_{cov}(A) = 90 \% \Rightarrow F_{mg} = 1.6 \sigma \]

**Shadow Fading Log-Normal Model**

\[ P_{cov}(r) = \int_{x_{max}}^{\infty} Y(x - \bar{x}(r)) \, dx \]

\( x_{max}: \) Max. PL allowed

**PL, dB**

- 150 dB
- 150-\( \sigma \) dB
- 150-2\( \sigma \) dB
What do Cellular Engineers care about?

- **Path Loss vs. Distance Model** (~ $1/r^{\alpha}$)
  - Cell Coverage Radius: Noise Limited Area [$\alpha \uparrow \Rightarrow R_c \downarrow$]
  - Cell Radius: Interference Limited Area [$\alpha \uparrow \Rightarrow N_{\text{reuse}} \uparrow$]

- **Shadow Fading Model** (Log-Normal with $\sigma$)
  - Cell Radius: Link Budget Margin [$\sigma \uparrow \Rightarrow R_c \downarrow$]
  - Correlation over Distance (Exponential) [?] (In HO simulation)

- **Fast Fading Model** (Rayleigh Fading)
  - Min. Required S/N (Eb/No) or S/I (Eb/Io) [$\downarrow \Rightarrow R_c, \text{Cap.} \uparrow$]
    - Usually already accounted for in numbers given by Comm Eng.
  - Doppler Spreading [typ; mid speed (30 km/hr): Eb/No $\uparrow$]
    - Usually already accounted for in numbers given by Comm Eng.
  - Correlation over Distance (Bessel Function; $\lambda/2$ Decorrelation)
    - Useful for estimating the interval (vs. speed) for averaging out fast fading in the field measured data for local mean PL analyses

- **Delay Spread Multi-path Details** (Coherence BW & Time)
  - TDMA Equalizer or CDMA Rake Receiver Performance
    - Not usually used, but can provide good area specific information which may be accounted for in cell planning.
Evolution of Channel Models

• **1st Generation Analog**
  - Time-Variant Memoryless: time
    • Path Loss, Fast Fading: Doppler Freq., Slow Fading

• **2nd Generation TDMA and CDMA**
  - ... Time-Dispersive: (time & delay)
    • + Coherence Bandwidth, Coherence Time

• **2G+ and 3G TDMA and CDMA**
  - ... Horizontal Angular Spread: (time, delay & angle)
    • Beam Profile: effective beam width, correlation

• **3G+, 4G and beyond (???)**
  - ... Vertical Angular Spread
  - ... Polarization
  - ... Fixed Cellular with High Frequency and Wide BW
    • Terminal Antenna Directivity and Pointing Direction
Key Papers in Mobile Radio Channel

Fundamental Theories


P.A. Bello, “Characterization of Randomly Time-Variant Linear Channels,” IEEE T. Comm

Path Loss: Measurement Based


Path Loss: Physical Theory Based

F. Ikegami, “Propagation Factors Controlling Mean Field Strength in Urban Streets,” IEEE T. A/P


Wideband Delay: Early Measurements


Fast Fading: Theory and Measurements

M. Nakagami, “The m-Distribution: A General Formula of Intensity of Rapid Fading,”


Rayleigh & Rice Distributions, GWSSUS Channel

1944 1963

< 1960 1968

1968 1980

1984 1988

Rayleigh Dist., Bessel Correl
Nakagami, Jake’s Model

Walfisch-Ikegami Model
(Cost231 Micro-cell Model)

Hata/Okumura Model
(Cost231 Macro-cell Model)
Mathematical Model for 1G Analog

Variable:
- Temporal

System Model

\[ \text{Re}\{e^{j\omega_c t}\} \]

\[ h(t) \]

\[ \text{Re}\{h(t)e^{j\omega_c t}\} \]

Model:
\[ h(t) = c(t) = l(d) \cdot r(t) \cdot s(t) \]

path loss
\( l(d) \)

fast in \( t \)
\( r(t) \)

slow in \( t \)
\( s(t) \)

First Order Dist.
Rayleigh
Log-Normal

Second Order Corr.
Bessel
Exponential

Doppler Effects

\[ H(f) \]

\[ F\{\cdot\} \quad F^{-1}\{\cdot\} \]
Mathematical Model for 2G Digital System

Variables:
- Temporal
- Delay Profile

\[ h(\tau; t) = c(\tau; t) = \sum a_i(t) \delta(\tau - \tau_i) \]
\[ h(t) = \frac{\tau}{\tau} \int C(t; \tau) d\tau \]

System Model

\[ \delta(t)e^{j\omega_c t} \]
\[ h(\tau; t) \]
\[ h(\tau; t)e^{j\omega_c (t - \tau)} \]

Impulse Response

\[ \tau \leftrightarrow f \]

Transfer Function

\[ H(f; t) \]

Doppler Function

\[ D(\tau; v) \]

Doppler Spreading

\[ \tau \leftrightarrow f \]

\[ \tau \leftrightarrow f \]

Coherence BW

AutoCorr: \( \phi_h(\tau; \Delta t) \)
\[ E[h(\tau; t)h(\tau; t + \Delta t)] \]

Scattering Function

\[ S(f; v) \]

\[ t \leftrightarrow v \]

\[ t \leftrightarrow v \]
**2D Time Varying Channel Illustration**

**Illustration**

Series of Delay Profile Snapshots

$p(\tau, t_1)$, $p(\tau, t_2)$, $p(\tau, t_3)$, ..., $p(\tau, t_n)$

Fourier Transform over $t$

$P(\tau, \lambda) = \mathcal{F}_t[p(\tau, t)] = \int_{-\infty}^{\infty} p(\tau, t) e^{-j2\pi\lambda t} dt$

$\lambda$: Doppler Spectrum
Mathematical Model for 2G+

Variables:
- Temporal
- Delay Profile
- Spatial

System Model

\[ \delta(t)e^{j\omega_ct} \]

\[ h(\tau;\theta;t) \]

\[ h(t-\tau) \cdot g(\theta-\eta) \cdot e^{j\omega_c(t-\tau)} \]

Industry Accepted Model which includes angular domain Yet to Come

- \[ h(t) \ldots \ldots \ldots 1D \text{ Channel Model} \]
- \[ h(\tau;t) \ldots \ldots \ldots 2D \text{ Channel Model} \]
- \[ h(\tau;\theta;t) \ldots \ldots \ldots 3D \text{ Channel Model} \]
What's Ahead for Mobile Radio Propagation?

- **Smart Antenna**
  - Angular Resolution and Inter-ray Correlation

- **Fixed Cellular**
  - Revisit of Mobile Channel Models for Terminal
    - Fixed, High Elevation, Directional

- **Wider Bandwidth for 3G and Beyond (5, 10, 15 MHz)**
  - Finer delay resolution needed
  - Present inter-ray correlation models need to be revisited

- **Other Channels not addressed in this talk**
  - Indoors, and Micro- and Pico-Cells

- **Higher Frequency**
Case Study, 1: Fixed Wireless Channel

- Paper: IEEE J. on SA/Com, March 99 (AT&T-Labs)
- Measurement Equipment
  - Frequency = 1.9 GHz; Signal BW = 8 MHz
  - Time Resolution = .125 µsec
  - Measurement setup
    - Where: Suburban areas in NJ and Illinois
    - BS Tx antenna: 65° Beam Width
    - MS Rx antenna: Height = 3 to 10 m, BW = 32° BW and Omni
    - Path length: .5 to 2 km
- Findings
  - Directional case: spike-plus-exponential profile
    - Longer delay paths arrive at angles and come through side lobes - higher attenuation for longer delay paths makes sense
    - Power ratio between spike to exponential paths ~ K = 8 dB
    - RMS time delay of exponential paths ~ \( \tau_0 = .2 \mu\text{sec} + \)
    - K and \( \tau_0 \) essentially not correlated
    - Relatively insensitive to antenna heights and path length
  - Omni case: no such structure found
Case Study, 2: Theory

\[ g(\tau; t) = \sum_i [A_i + a_i(t)] \delta(\tau - \tau_i) = \sum_i A_i \delta(\tau - \tau_i) + \sum_i a_i(t) \delta(\tau - \tau_i) = g_F(\tau) + g_M(\tau; t) \]

\( A_i \) is a fixed amplitude and \( a_i(t) \) is zero mean complex Gaussian

**Mean Amplitude**

\[ E[g(\tau; t)] = E[g_F(\tau)] + E[g_M(\tau; t)] = E[\sum_i A_i \delta(\tau - \tau_i)] \rightarrow \sum_i A_i \]

**Mean Power**

\[ E[g^2(\tau; t)] = E[g_F^2(\tau)] + E[g_M^2(\tau; t)] = E[\sum_i A_i^2] + E[\sum_i a_i^2] = \sum_i A_i^2 + \sum_i \sigma_i^2 \]

**Delay Profile**

\[ P_i = \frac{|A_i|^2 + \sigma_i^2}{\sum_i |A_i|^2 + \sum_i \sigma_i^2} \]

**RMS Delay Spread**

\[ \tau_{rms}^2 = \sum_i \tau_i^2 P_i - \left( \sum_i \tau_i P_i \right)^2 \]
Case Study, 3: Findings and Completeness

**General Model**

\[ g(\tau; t) = \sum_i A_i \delta(\tau - \tau_i) + \sum a_i(t) \delta(\tau - \tau_i) \]

**Directional Antenna Case**

**Empirical Model based on Measurements: Spike-plus-exponential**

\[ g(\tau; t) = A_0 \delta(\tau - \tau_0) + \sum a_i(t) \delta(\tau - \tau_i) = A_0 \delta(\tau - \tau_0) + b \sum_{i=0}^{\Delta t_n} e^{-i\Delta \tau} \delta(\tau - i\Delta \tau) \]

- Strong direct arrival path + many lower strength late arrival paths.
- Strength of late arrival paths decreases exponentially.

**Completeness in Characterization**

- Distance dependency? - No, based on .5 to 2 km range measurements
- Resolution dependency? - Would not show up if BW < 5 MHz or so
  - Finer structure which warrants a different model may exists.
- Environment dependency? Not reported
- Antenna Beam Width Dependency? Not reported.
- Frequency dependency? - Not reported.
- Fading distribution of individual paths? - Not reported.
- Fading distribution of combined signal? - Not reported.
- Correlation between multiple paths? - Not reported