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Developments in Characterization of Mobile Radio Propagation

May 19, 1999
IEEE Santa Clara Valley
Antennas & Propagation Society

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Messages to Drive Home with

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- **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

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

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

Cellular

	824–825	825–835	835–845	845–846.5	846.5–849
Reverse (MS→BS)	A"	A	B	A'	B'
Forward (BS→MS)	1	10 MHz	10 MHz	1.5	2.5
	869–870	870–880	880–890	890–891.5	891.5–894

45 MHz

PCS

	1850–1865	1865–1870	1870–1885	1885–1890	1890–1895	1895–1910
Reverse (MS→BS)	A	D	B	E	F	C
Forward (BS→MS)	15 MHz	5	15 MHz	5	5	15 MHz
	1930–1945	1945–1950	1950–1965	1965–1970	1970–1975	1975–1990

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

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- **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, ...

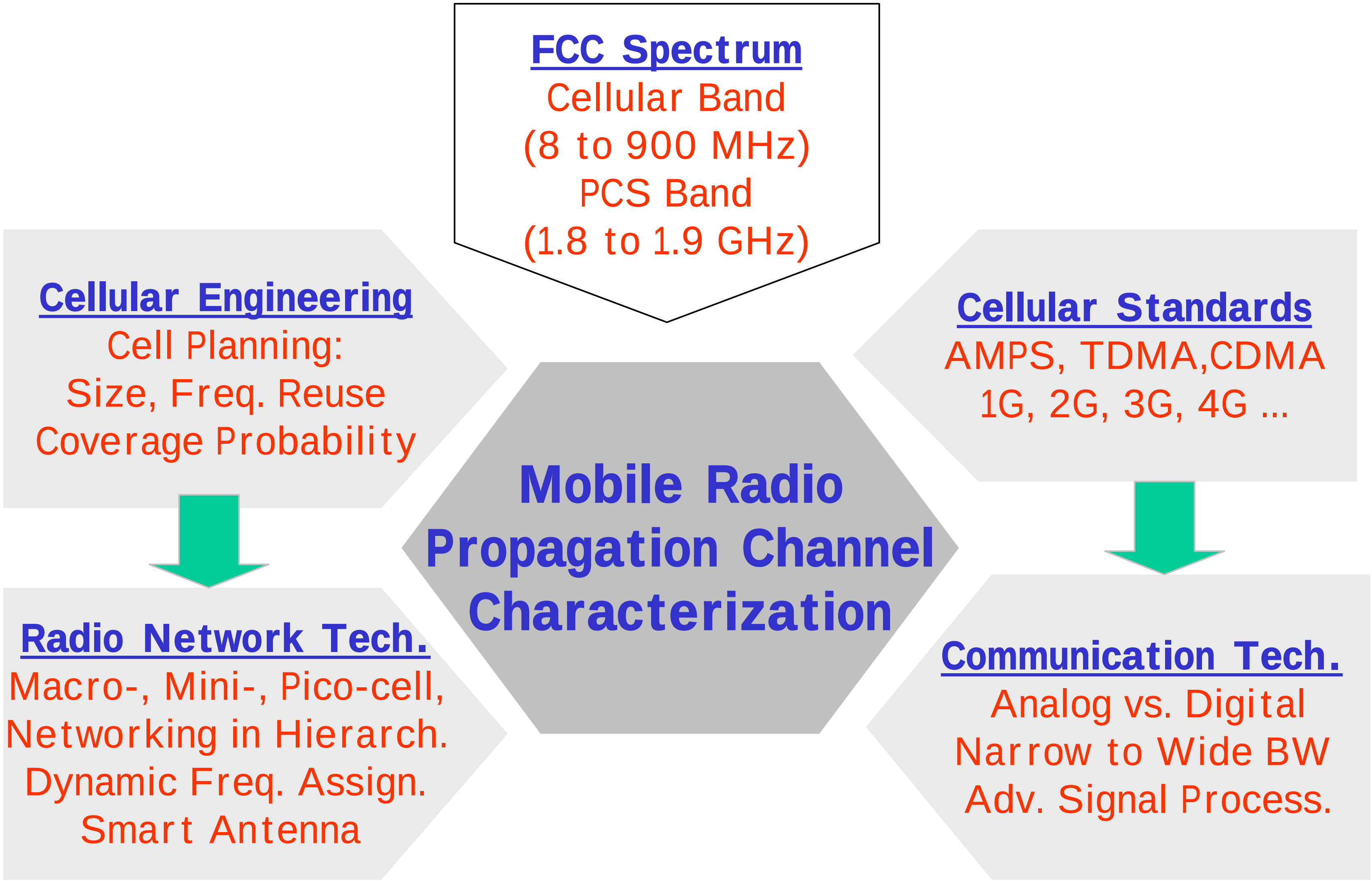
Multi-Discipline Perspectives

	EM Radio Propagation	Cellular Network	Communications
Problems of Interest	Physics of Propagation frequency • polarization • antenna type/height • physical & electrical properties of medium	Link Budget path loss • fade margin • diversity gain	Signal Processing fade rate • Doppler shift coherence BW & time • # of multi-paths • diversity correlation
Solutions Sought	Models b/ Phys. Theories Attenuation • Diffraction Reflection • Refraction Scattering • Penetration	Radio Network Design cell size • # of cells BS locations • freq reuse antenna type/heights	Comm. System Design Mod/Demod • Interleaving FEC • Channel Equalizer Rake Receiver • Codes
Goodness of Solution	Analytic./Computer Sol'ns simplicity, applicability & closeness to field measured data	Customer Satisfaction call attempt success rate • call drop rate • handoff success rate • handoff rate	Performance Compliance Minimum E_b/N_o • BER FER • Diversity Gain Acquisition Time
Ultimate Goals	• Formulation of Analytical Models	• Minimum Investment • Customer Satisfaction	• Max. Bits/Sec/Hz Shannon's Limit

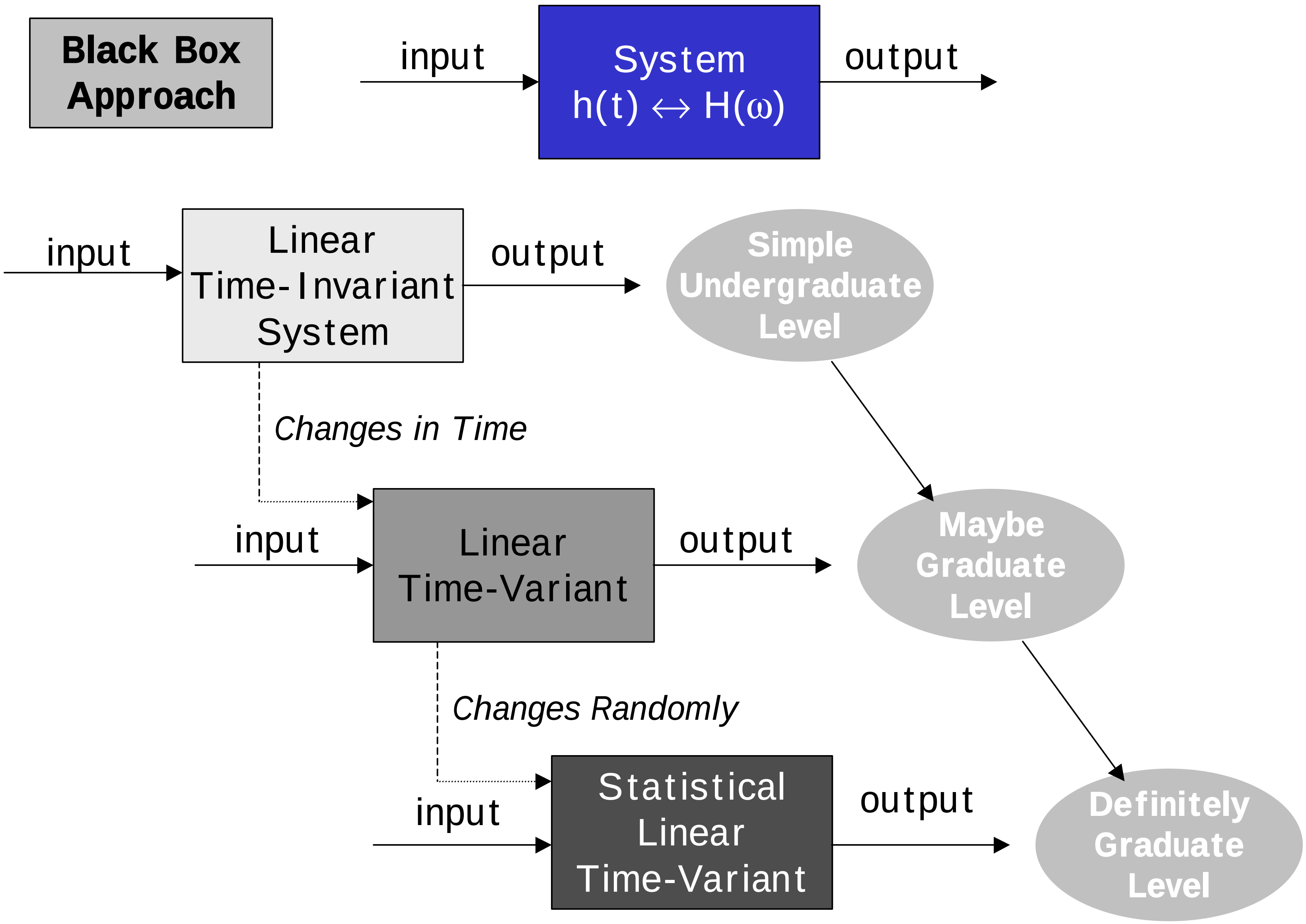
Taxonomy of Mobile Radio Propagation

- **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
    - Mutipath Delay Profile: RMS Delay, Coherence BW, Correlation
    - Angular Spread: RMS Beamwidth, Correlation

Main Factors to Propagation Characterization

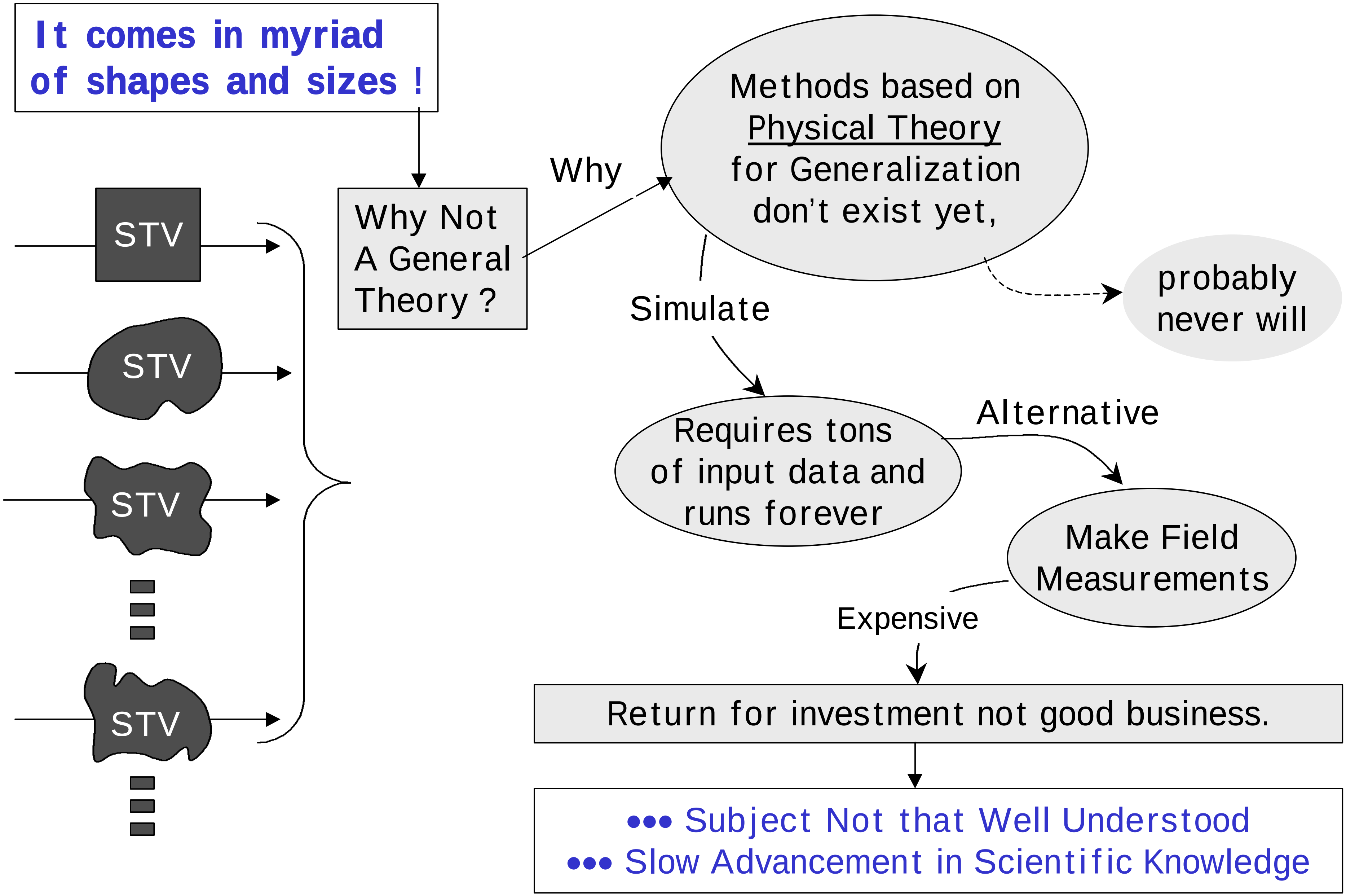


Mathematical Framework of Models



SO, What's the Dig Deal?

So, What is the Big Deal?



Doing Better in Europe, however.

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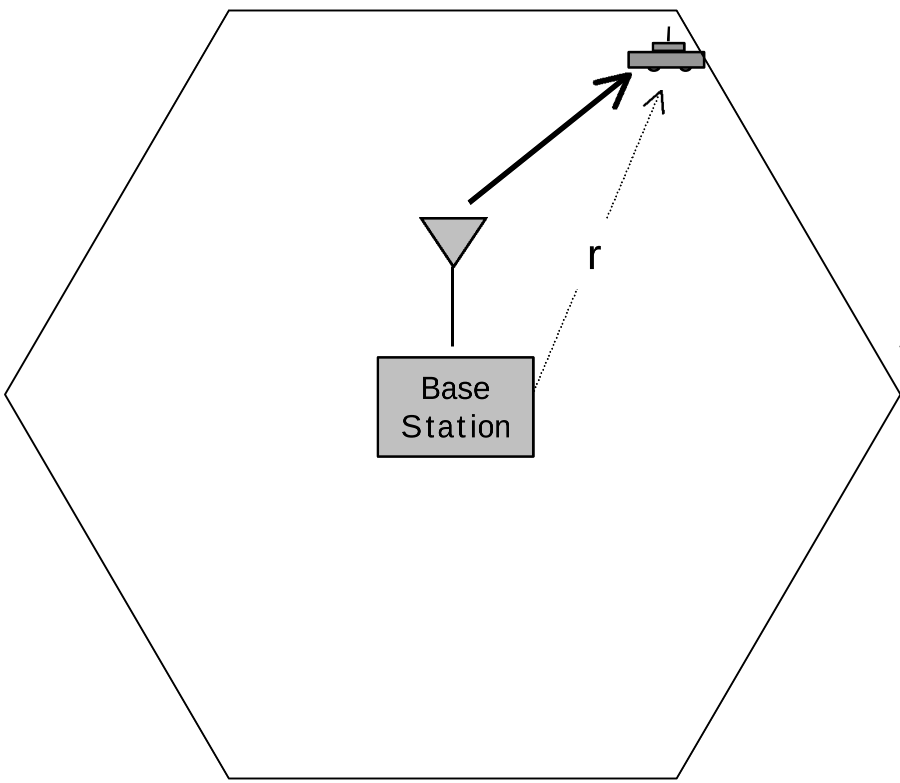
Tech. Evolution & Detailed Structures needed

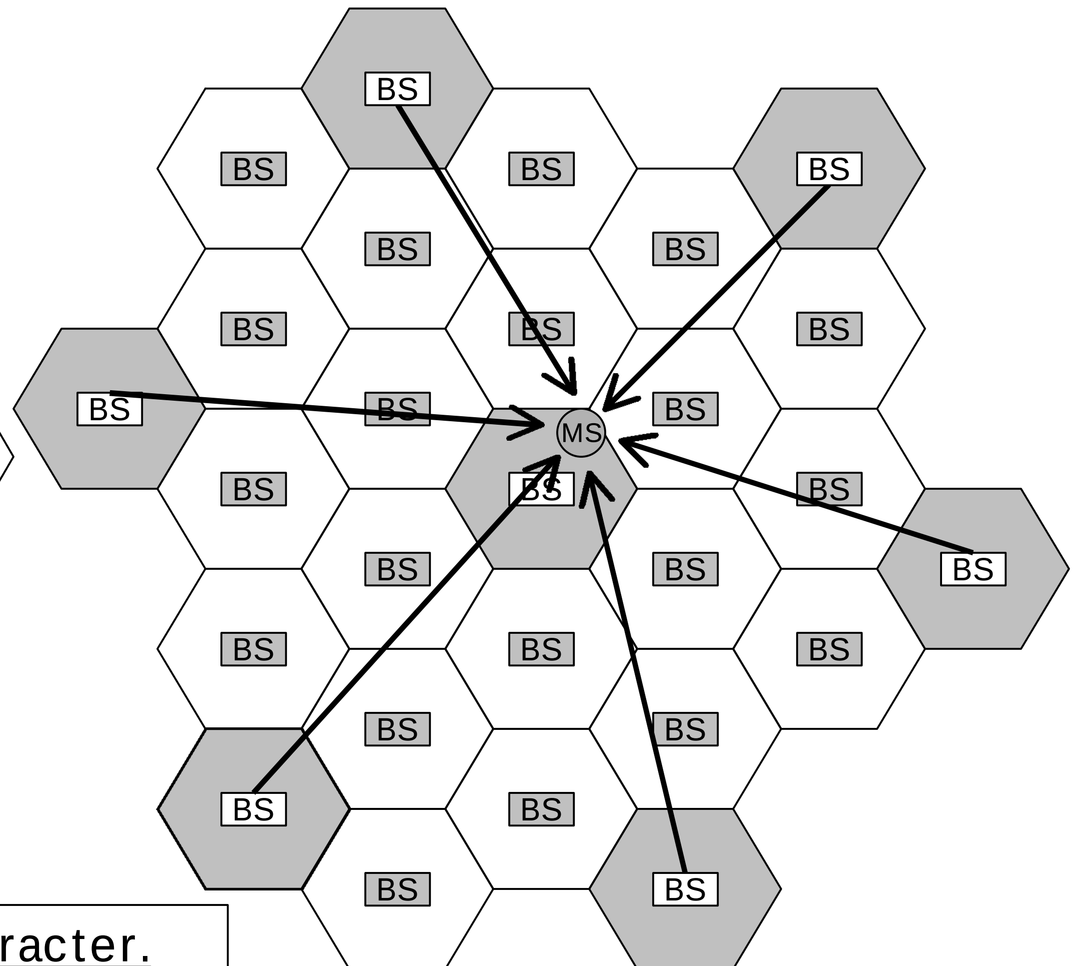
Period	System	Band	Detailed Structures needed
1970 - 1983	**AMPS** Analog FM 30 KHz	**Narrow Band Analog**	**Path Loss:** Mean, Variance (Shadow Fading) **Doppler Effects:** FM Noise (Rayleigh fading) **Diversity:** Spatial Correlation
1989 - 1992	**IS-136** Digital TDMA 30 KHz	**Narrow Band Digital**	**Delay Spread:** Equalization up to ~ 42 μsec delay needed. **Doppler Effects:** Rayleigh Fading, Interleaving, Demodulation
1990 - 1993	**IS-95** Digital CDMA 1.25 MHz	**Wide Band Digital**	**Delay Spread Characteristics (~ 1 μsec)** • Higher Delay Resolution Needed • # of resolution paths • fading stats and correl. bwtn them • how fast they come & go **Correlation btwn Sectors/Cells for Soft HO**
1998 - 2000	**cdma200** Digital CDMA > 5 MHz	**Broad Band Digital**	**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



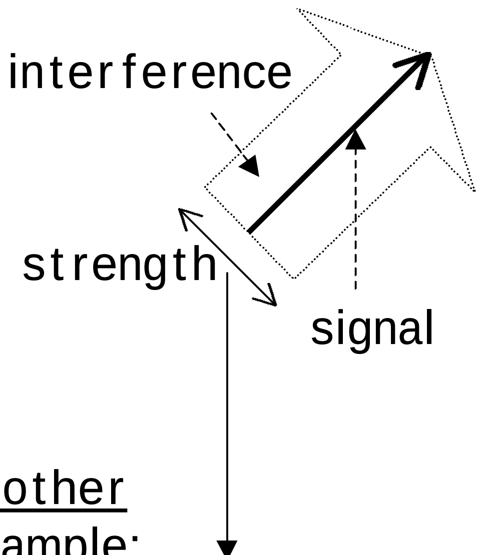
Forward Link Interference Scenario for AMPS and TDMA (N=7)



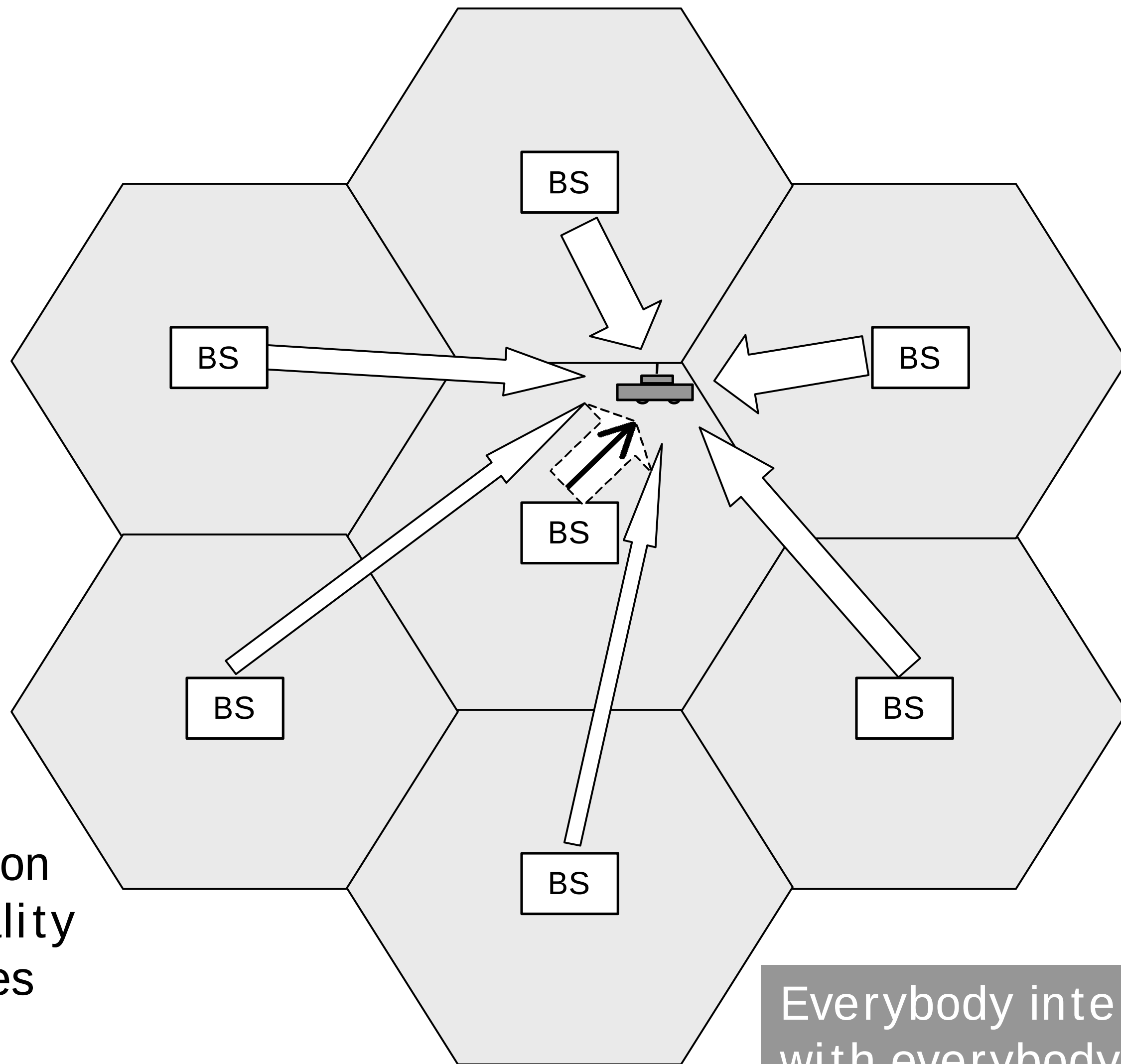
<u>An Example of Importance in Prop. Character.</u>
Interference level strongly dependent on propagation exponent α: $\sim 1/r^{\alpha}$
$\rightarrow$ Major Impact on Frequency Reuse Efficiency

Six Major Interferers of about equal strength

Propagation Scenario for CDMA



Forward Link Signal Reception and Interference Scenario for CDMA



<u>Another Example:</u>
Depends on Multipath Condition
Due to breakage in orthogonality between same cell users' codes
<u>But</u>, Distance Dependent PL not as Important as in AMPS & TDMA

Everybody interferes with everybody else

Cellular Engineering: Coverage Reliability

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Shadow Fading Log-Normal Model

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

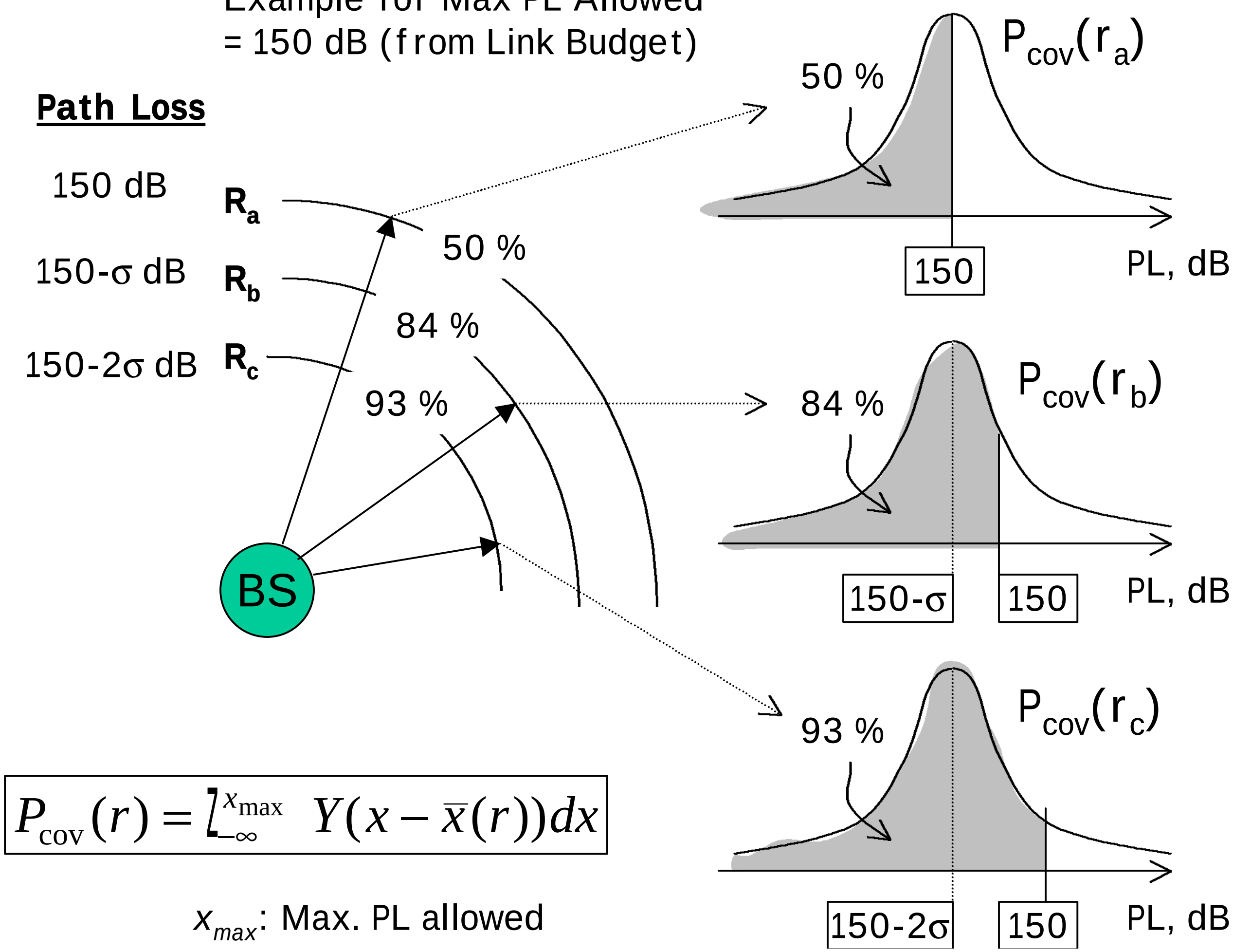
x: PL, $\bar{x}$: mean PL, σ: SF Sigma

Typical Objective for Area Coverage = 90 %

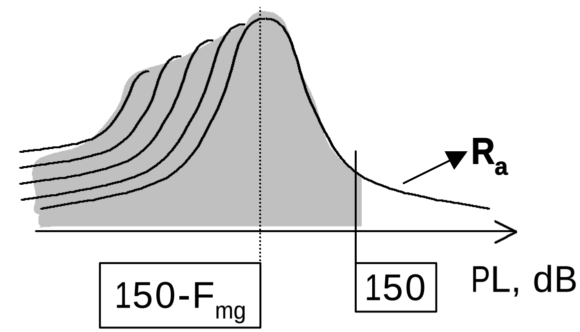
Contour Reliability

Area Reliability

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



Fade Margin: F_{mg}



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

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

x_{max}: Max. PL allowed

$$P_{cov}(A) = 2\pi \int_0^{r_a} P_{cov}(r)\,r\,dr$$

What do Cellular Engineers care about?

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- **Path Loss vs. Distance Model (~ $1/r^{\alpha}$)**
  - Cell Coverage Radius: Noise Limited Area [$\alpha \uparrow \Rightarrow Rc \downarrow$]
  - Cell Radius: Interference Limited Area [$\alpha \uparrow \Rightarrow N_{reuse} \uparrow$]
- **Shadow Fading Model (Log-Normal with σ)**
  - Cell Radius: Link Budget Margin [$\sigma \uparrow \Rightarrow Rc \downarrow$]
  - Correlation over Distance (Exponential) [?] (In HO simulation)
- **Fast Fading Model (Rayleigh Fading)**
  - Min. Required S/N (Eb/No) or S/I (Eb/Io) [$\downarrow \Rightarrow$ Rc, 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

- 1944 — S.O. Rice, "Mathematical Analysis of Random Noise,", "Statistical Properties of a Sine Wave Plus Random Noise," BSTJ
- 1963 — P.A. Bello, "Characterization of Randomly Time-Variant Linear Channels," IEEE T. Comm

→ **Rayleigh & Rice Distributions, GWSSUS Channel**

Fast Fading: Theory and Measurements

- < 1960 — M. Nakagami, "The m-Distribution: A General Formula of Intensity of Rapid Fading," ?
- 1968 — R.H. Clarke, "A Statistical Theory of Mobile-Radio Reception," BSTJ

→ **Rayleigh Dist., Bessel Correl Nakagami, Jake's Model**

W.C. Jakes, Ed. Microwave Mobile Comm, Wiley, 1974

Path Loss: Measurement Based

- 1968 — Y. Okumara, "Field Strength and Its Variability in VHF and UHF LMR Service," Rev. Elec. Comm. Lab, Japan
- 1980 — Hata, "Empirical Formula ffor Propagation Loss in LMR," IEEE T. VT.

→ **Hata/Okumura Model (Cost231 Macro-cell Model)**

Path Loss: Physical Theory Based

- 1984 — F. Ikegami, "Propagation Factors Controlling Mean Field Strength in Urban Streets, " IEEE T. A/P
- 1988 — J. Walfisch & H. Bertoni, "A Theoretical Model of UHF Propagation in Urban Environments, " IEEE T. A/P

→ **Walfisch-Ikegami Model (Cost231 Micro-cell Model)**

Wideband Delay: Early Measurements

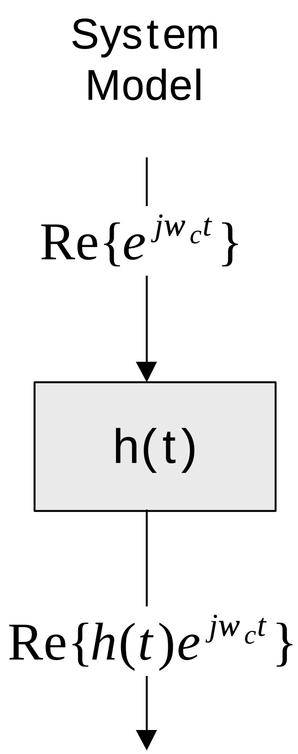
- G. L. Turin, et al., "A Statistical model of urban multipath propagation," IEEE T. VT
- D.C. Cox., "910 MHz Urban Mobile Radio Propagation: Multipath Caracterisics in NYC," IEEE T. Comm

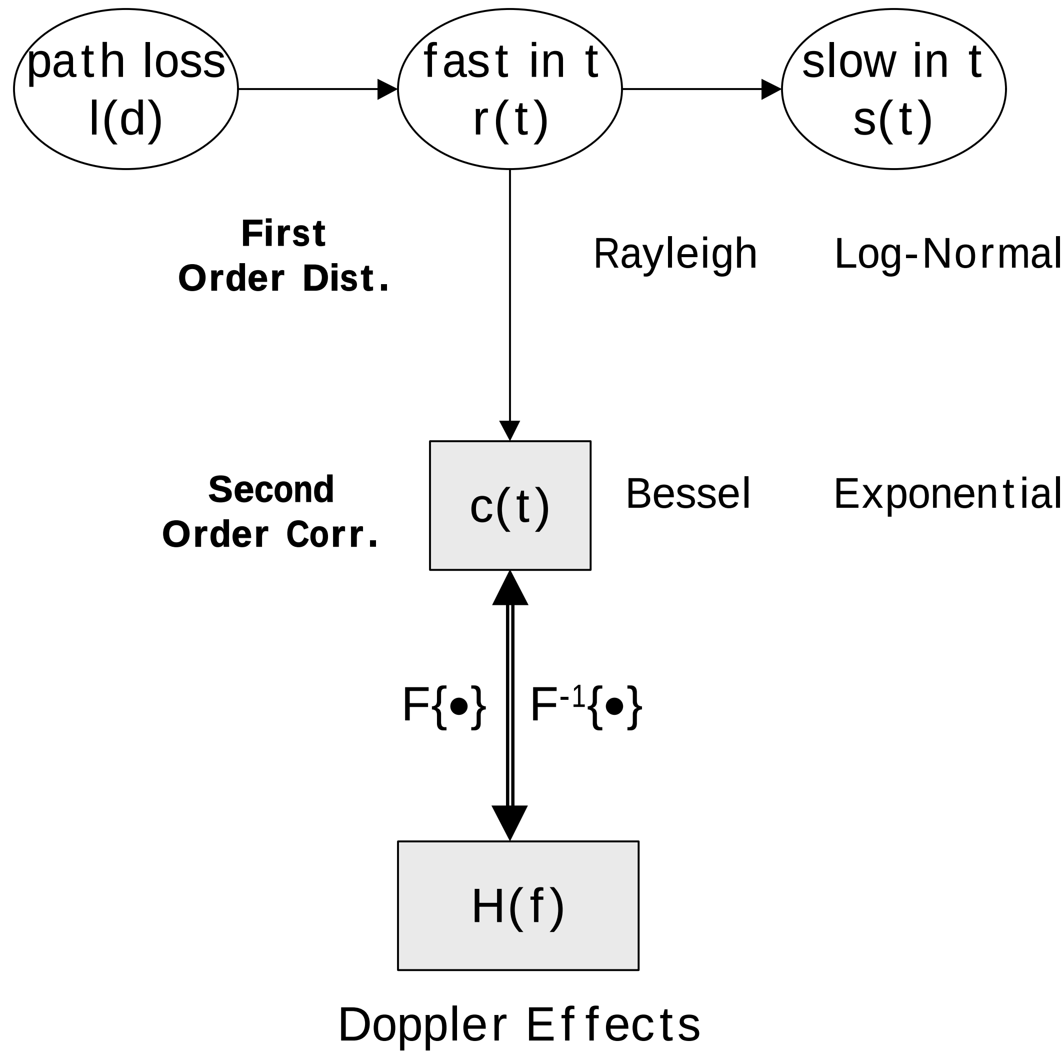
1972,3

Mathematical Model for 1G Analog

<u>Variable:</u>
- Temporal

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





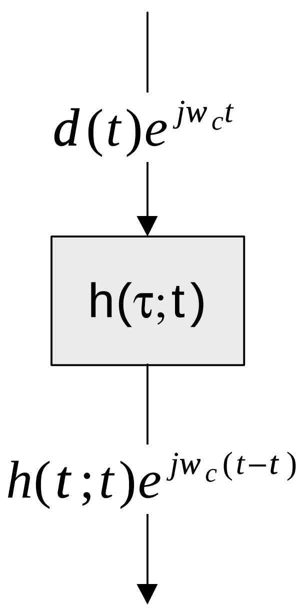
Mathematical Model for 2G Digital

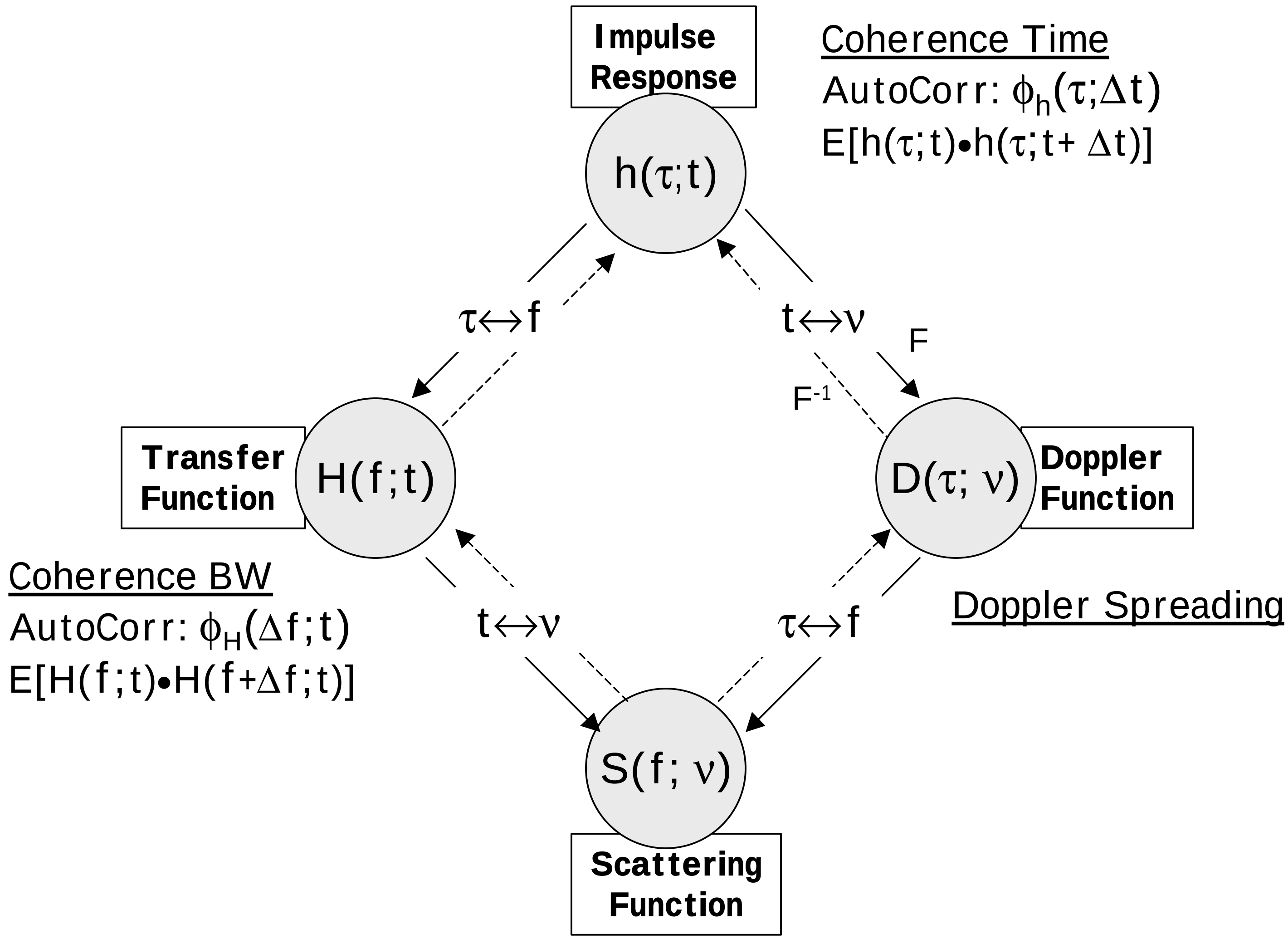
Variables:
- Temporal
- Delay Profile

$$h(t;t) = c(t;t) = \sum_i a_i(t)d(t - t_i)$$

$$h(t) = \int_t^{t_m} c(t;t)dt$$

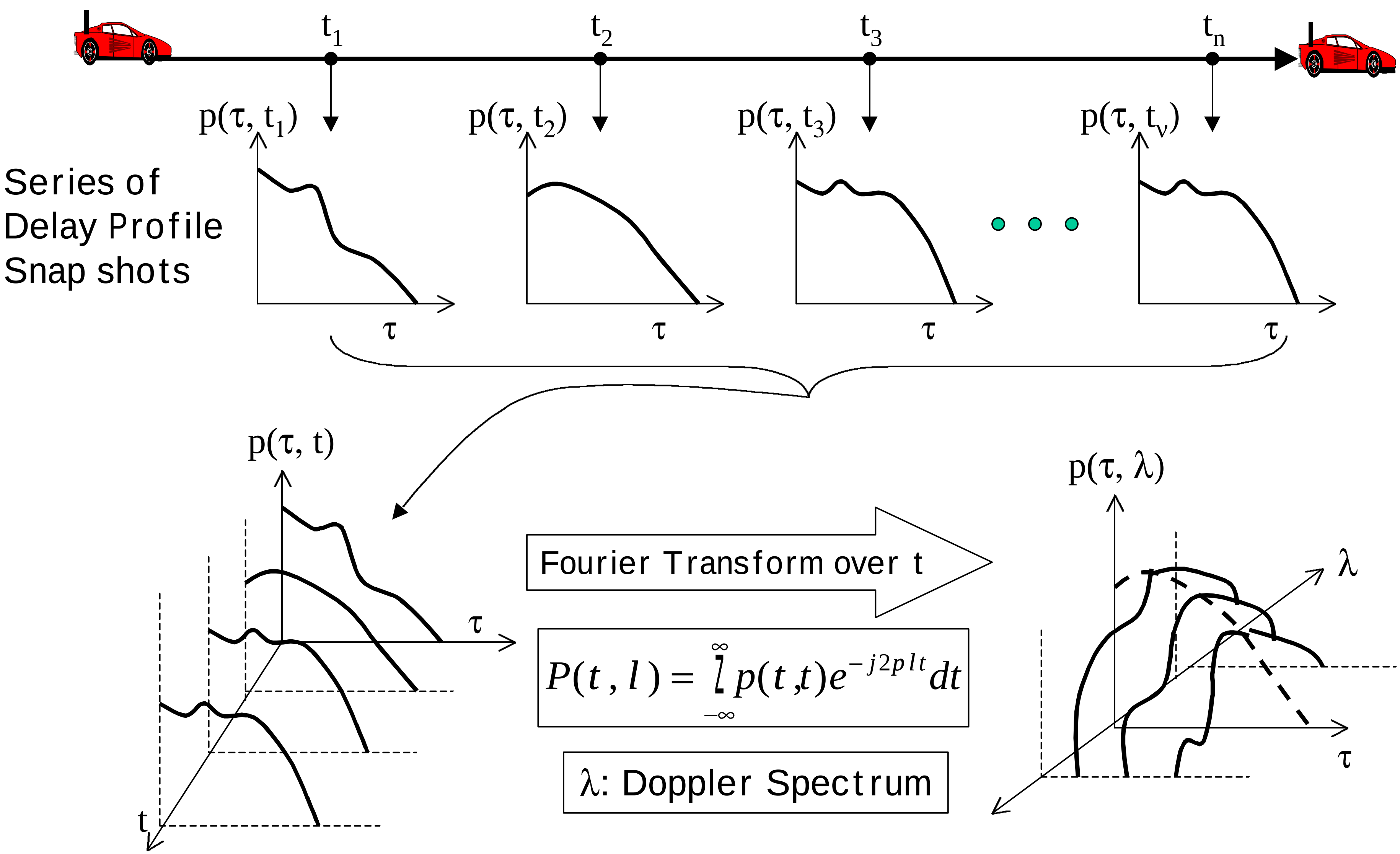
System Model





2D Time Varying Channel Illustration

Illustration



Mathematical Model for 2G+

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Variables:
- Temporal
- Delay Profile
- Spatial

System Model

$d(t)e^{jw_c t}$

h(τ;θ;t)

$h(t-t)\cdot g(q-h)\cdot e^{jw_c(t-t)}$

Industry Accepted Model
which includes angular domain
Yet to Come

●

h(t) ……….. 1D Channel Model

h(τ;t) ………. 2D Channel Model

h(τ;θ;t) ……… 3D 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 ~ τ_o = .2 μsec +
    - K and τ_o essentially not correlated
    - Relatively insensitive to antenna heights and path length
  - Omni case: no such structure found

Case Study, 2: Theory

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$$g(t;t) = \sum_i [A_i + a_i(t)]d(t - t_i) = \sum_i A_i d(t - t_i) + \sum a_i(t) d(t - t_i) = g_F(t) + g_M(t;t)$$

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

Mean Amplitude

$$E[g(t;t)] = E[g_F(t)] + E[g_M(t;t)] = E[\sum_i A_i d(t - t_i))] \xrightarrow{\text{determinstic}} \sum_i A_i$$

(the term $E[g_M(t;t)]$ is struck out with an arrow to 0)

Mean Power

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

Delay Profile

$$P_i = \frac{|A_i|^2 + s_i^2}{\sum_i \left(|A_i|^2 + \sum_i s_i^2 \right)}$$

RMS Delay Spread

$$t_{rms}^2 = \sum_i t_i^2 P_i - \left(\sum_i t_i P_i \right)^2$$

Case Study, 3: Findings and Completeness

General Model

$$g(t;t) = \sum_i A_i d(t - t_i) + \sum a_i(t) d(t - t_i)$$

Directional Antenna Case

Empirical Model based on Measurements: Spike-plus-exponential

$$g(t;t) = A_0 d(t - t_0) + \sum a_i(t) d(t - t_i) = A_0 d(t - t_0) + b \sum_{i=0} e^{-i\Delta/t_m} d(t - i\Delta t_i)$$

- 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