ECE5984

Orthogonal Frequency Division Multiplexing and Related Technologies

Fall 2007

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Fading Channels

Major Learning Objectives

- Upon successful completion of the course the student will be able to:
- Describe the complete architecture of an OFDM system, (serial to parallel, FFT/IFFT, Cyclic prefix, Modulation techniques, coding techniques)
- Evaluate the response of OFDM in Gaussian channels and fading channels.
- Design and analyze standards using OFDM such as IEEE 802.11a,g and IEEE 802.16
- Define the problems associated of using multi-carrier in time varying channels and how to mitigate these problems.
- Describe the principle mechanisms by which multiple access techniques are supported using OFDM.
- Able to categorize the different type of MC-CDMA and the degree of flexibility provided by each type.
- Able to simulate the basic and advanced techniques used in OFDM systems

Textbook

- OFDM and MC-CDMA: A Primer by Lajos Hanzo (Author), Thomas Keller (Author), ISBN-10: 0470030070

- Additional Readings:

- Richard van Nee and Ramjee Prasad, OFDM for Wireless Multimedia Communications, Artech House: 2000 (ISBN: OR90065306)
- Orthogonal Frequency Division Multiplexing for Wireless Communications by Ye (Geoffrey) Li (Editor), Gordon L. Stuber (Editor), ISBN 0387290958
- Ahmad Bahai and Burton Saltzberg, Multi-Carrier Digital Communications: Theory and Applications of OFDM, Plenum Publishing Corporation: 1999, ISBN: 0306462966.

Syllabus

- Wireless channels characteristics **(7.5%)** 1
  - wireless channel modeling and characteristics
    - Large scale and small scale models
    - Common channel models
    - Channel categories and parameter calculation.
    - Prob. of error calculations
- OFDM Basics **(10%)** 1
  - History of OFDM
  - OFDM System model
  - Discrete-time signals & systems and DFT
  - Generation of subcarriers using the IFFT
  - Guard time, cyclic extension
  - Windowing
  - Choice of OFDM parameters & OFDM signal processing
  - Implementation complexity of OFDM versus single carrier modulation
- Modulation and Coding **(10%)** 2
  - Linear and nonlinear modulation
  - Interleaving and channel coding
  - Optimal bit and power allocation
  - Adaptive modulation

Syllabus

- Analysis of OFDM systems **(15%)** 2
  - RF subsystems, amplifier classification and distortion
  - Crest factor (PAPR) reduction techniques
    - Pre-distortion & adaptive pre-distortion techniques
    - clipping
    - coding techniques
    - partial transmit sequences (PTS) & modified PTS v. selective mapping
    - nonlinear quantization (companding)
  - Phase noise and I&Q imbalance for QAM
  - Performance of OFDM in Gaussian channels
  - Performance of OFDM in Wide-band channels
- Synchronization and Estimation **(15%)** 2
  - ICI and OISI problems
  - Timing estimation
  - Frequency synchronization
  - Frequency error estimation algorithms
  - Carrier phase tracking
  - Frequency domain and time domain approaches for channel estimation
    - coherent detection
    - differential detection

Syllabus

- Multi-user OFDM Techniques **(10%)** **2**
  - Adaptive modulations in OFDM
  - Power and bit allocations in OFDM
  - Scalable OFDM
  - Flash OFDM
- Diversity **(7.5%)** 1
  - Limits of capacity in fading environments
  - Channel models for multiple-input-multiple-output (MIMO) system
  - Receiver diversity techniques
  - Transmit diversity techniques and design criteria for fading channels
  - Block, trellis and layered space-time codes
- Multi-carrier CDMA **(10%)** **1**
  - MC-CDMA versus DS-CDMA
  - MC-CDMA versus orthogonal frequency division multiple access (OFDMA)
  - OFDMA and MC-CDMA performance evaluation in wide-band channels

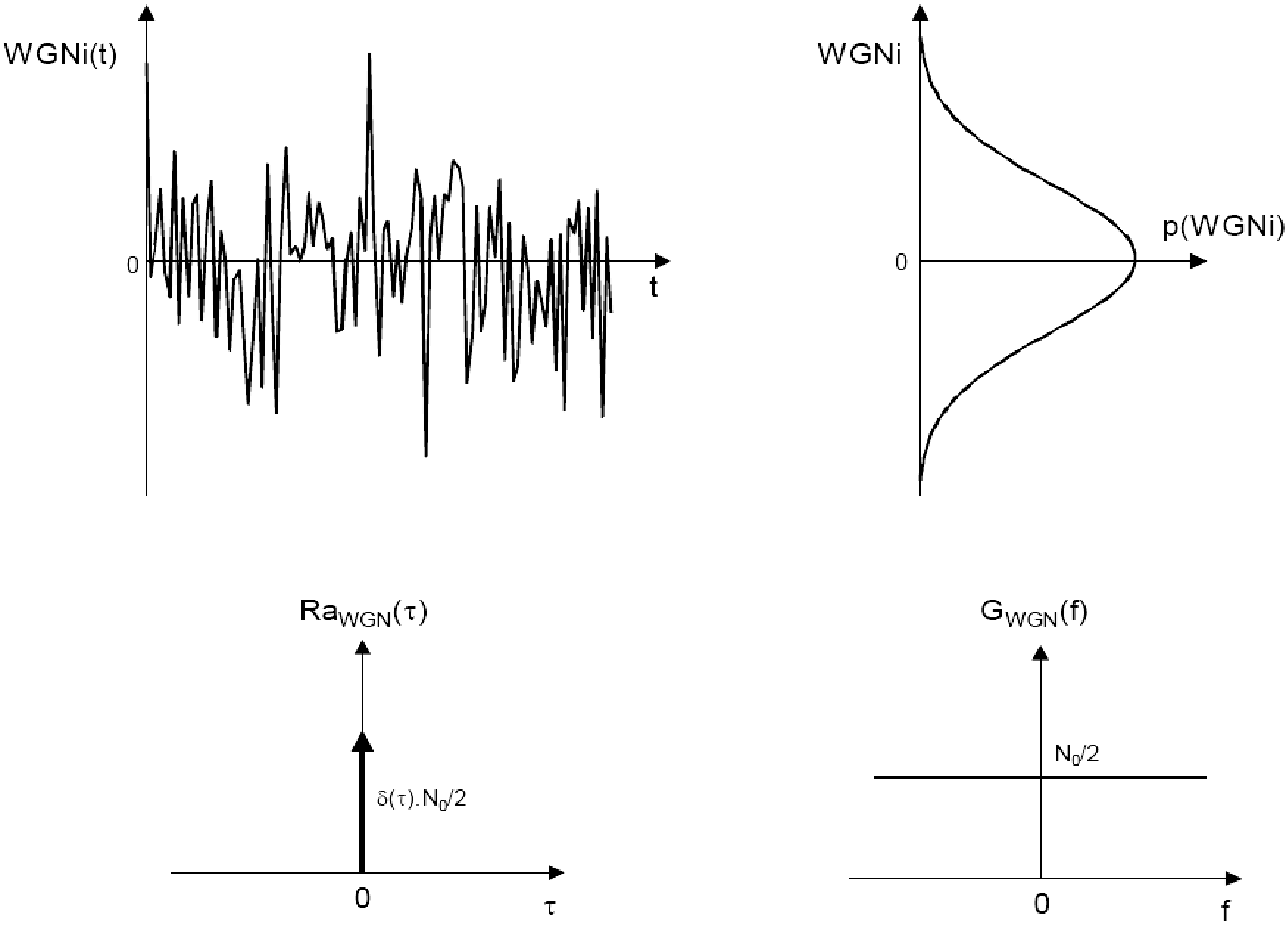
Syllabus

- Physical and Medium Access Control (MAC) for IEEE 802.11 Networks **(7.5%)** 1
  - Physical modeling of 802.11 networks
  - MAC system architecture
  - Frame exchange with RTS/CTS
  - Power management
  - Synchronization
- Physical and Medium Access Control (MAC) for IEEE 802.16 Networks **(7.5%)** **1**
  - Physical modeling of 802.16 networks
  - MAC system architecture
  - QoS guarantees in Wimax
  - Power management
  - Synchronization

Grading

Type of assignment	**Percent of Grade**
Home works	20%
Matlab Assignments	20%
Midterm	20%
Final project presentation and term paper	20%
Final Exam	20%

Fading channels


WGNi(t)
0
t
WGNi
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p(WGNi)
Ra_WGN(τ)
δ(τ).N0/2
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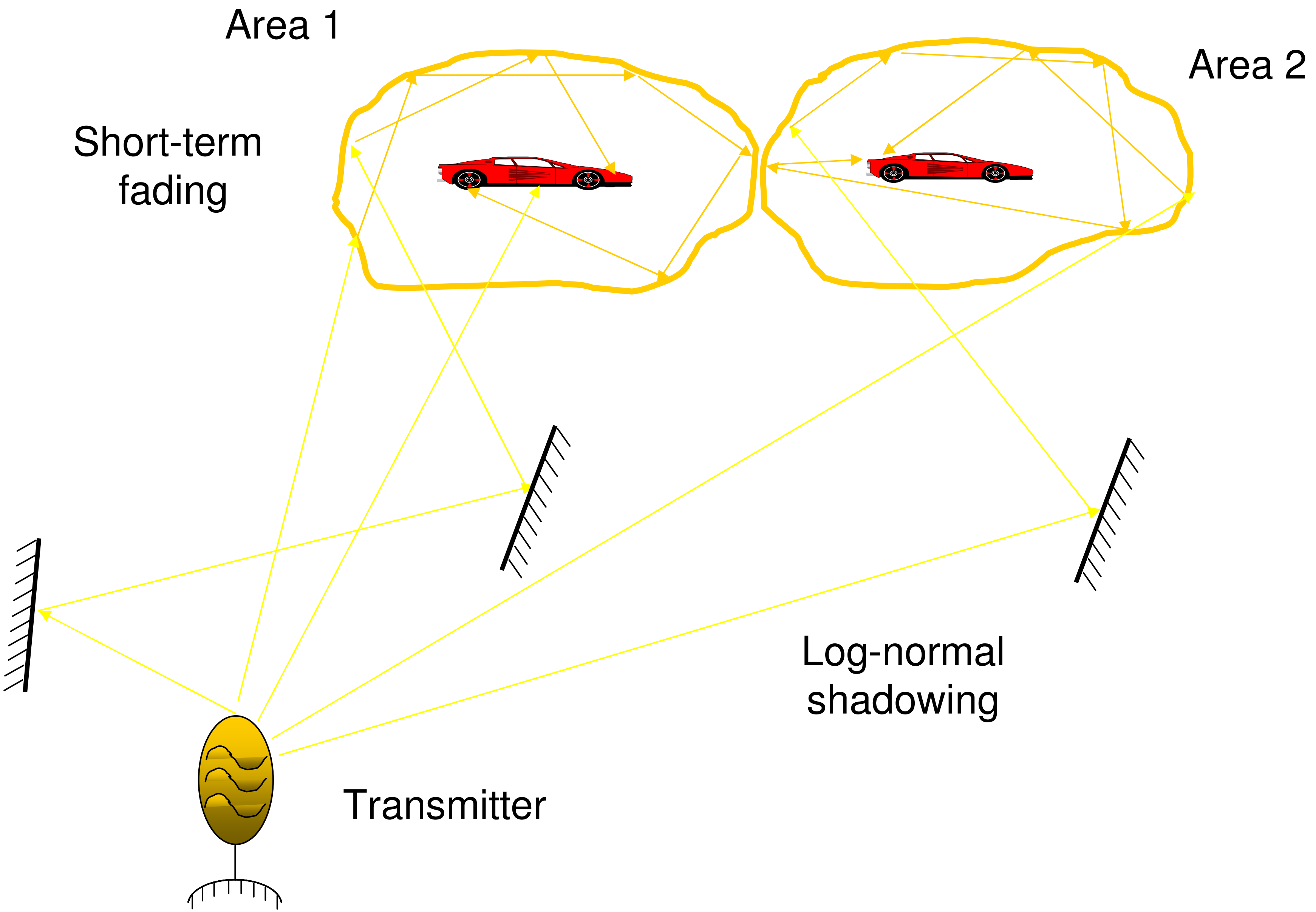
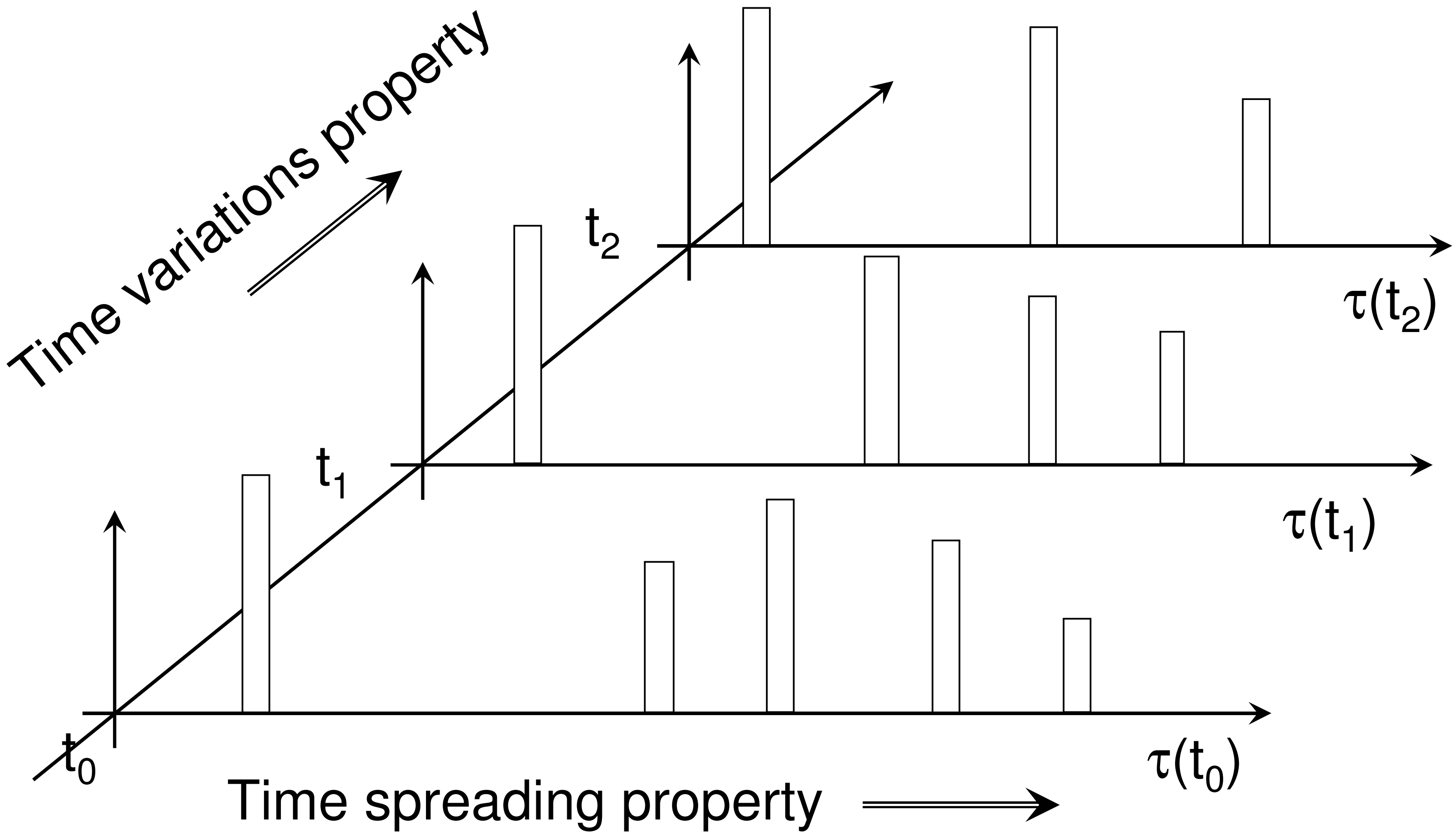
τ
G_WGN(f)
N0/2
0
f

Large and Small Scale Propagation Models



Impulse Response Characterization



- Impulse response: Time-spreading : multipath

  and time-variations: time-varying environment

Low-pass equivalent (LPE) signal

RF carrier frequency

$$s(t) = \mathrm{Re}\left\{ z(t) e^{j2\pi f_c t} \right\}$$

Real-valued RF signal

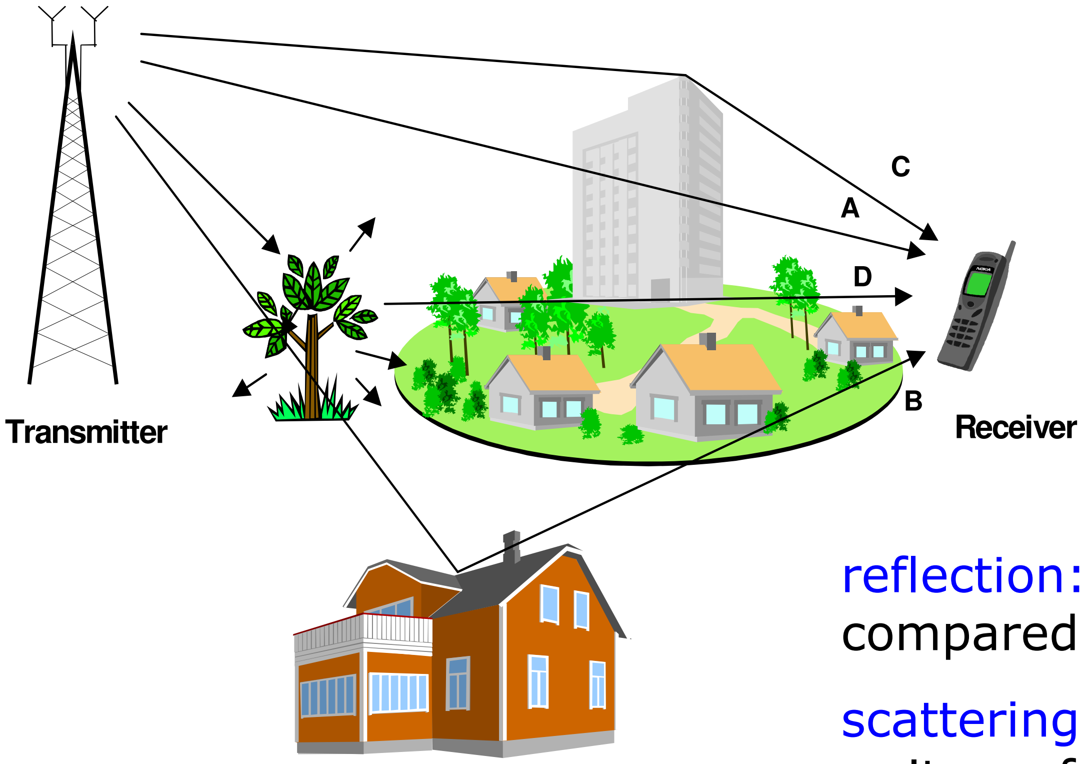
Complex-valued LPE signal

$$z(t) = x(t) + j y(t) = c(t) e^{j\phi(t)}$$

In-phase signal component

Quadrature component

Propagation mechanisms



A: free space
B: reflection
C: diffraction
D: scattering

reflection: object is large compared to wavelength

scattering: object is small or its surface irregular

Countermeasures: narrowband fading

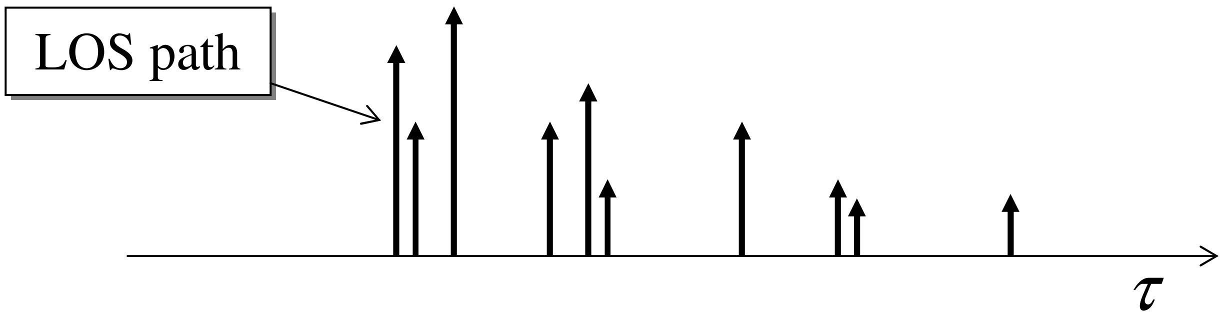
- Diversity (transmitting the same signal at different frequencies, at different times, or to/from different antennas)
  - will be investigated in later lectures
  - wideband channels => multipath diversity
- Interleaving (efficient when a fade affects many bits or symbols at a time), frequency hopping
- Forward Error Correction (FEC, uses large overhead)
- Automatic Repeat reQuest schemes (ARQ, cannot be used for transmission of real-time information)

CIR of a wideband fading channel

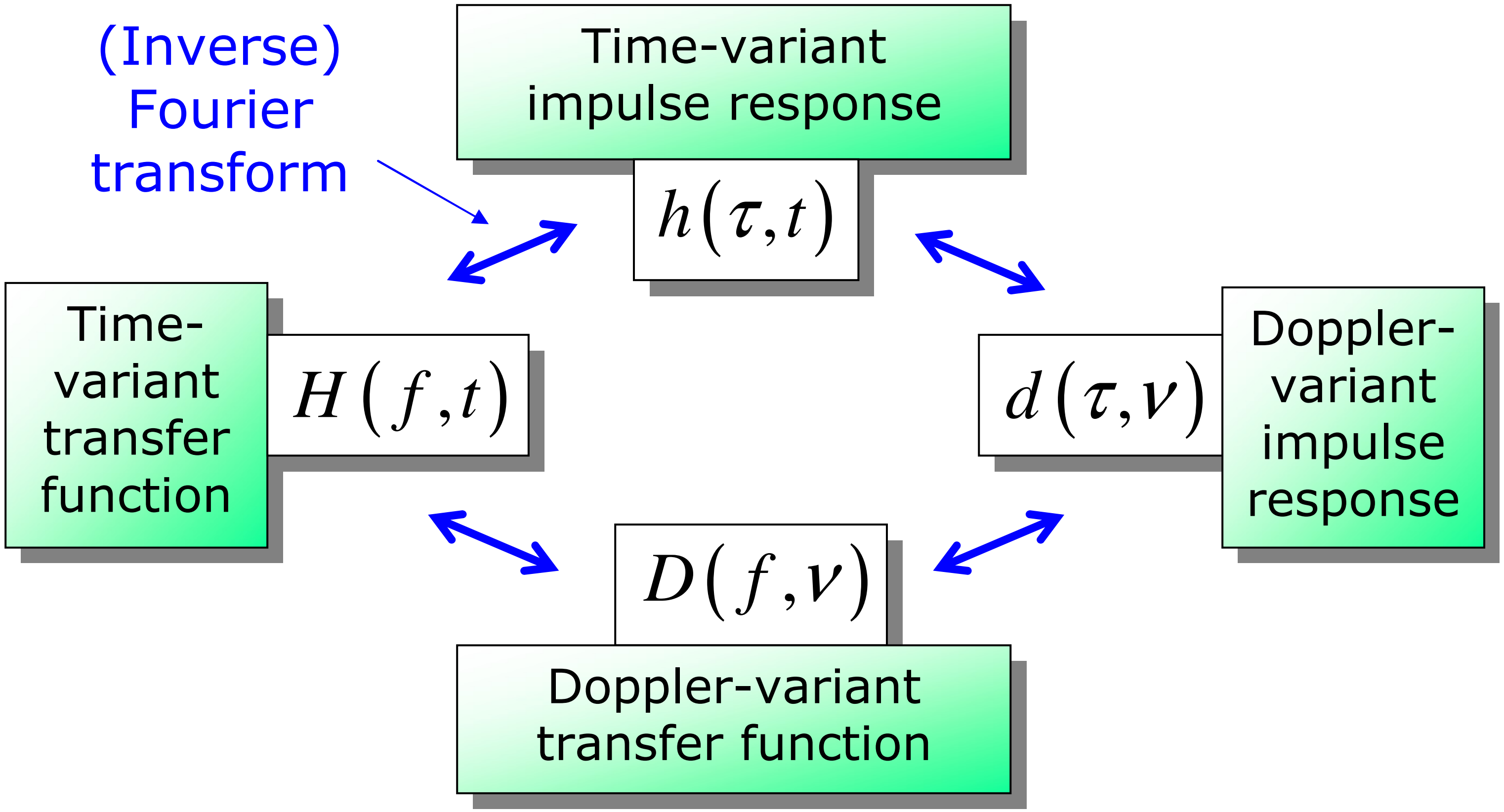
The CIR consists of L resolvable propagation paths

$$h(\tau,t)=\sum_{i=0}^{L-1} a_i(t)\, e^{j\phi_i(t)}\,\delta(\tau-\tau_i)$$

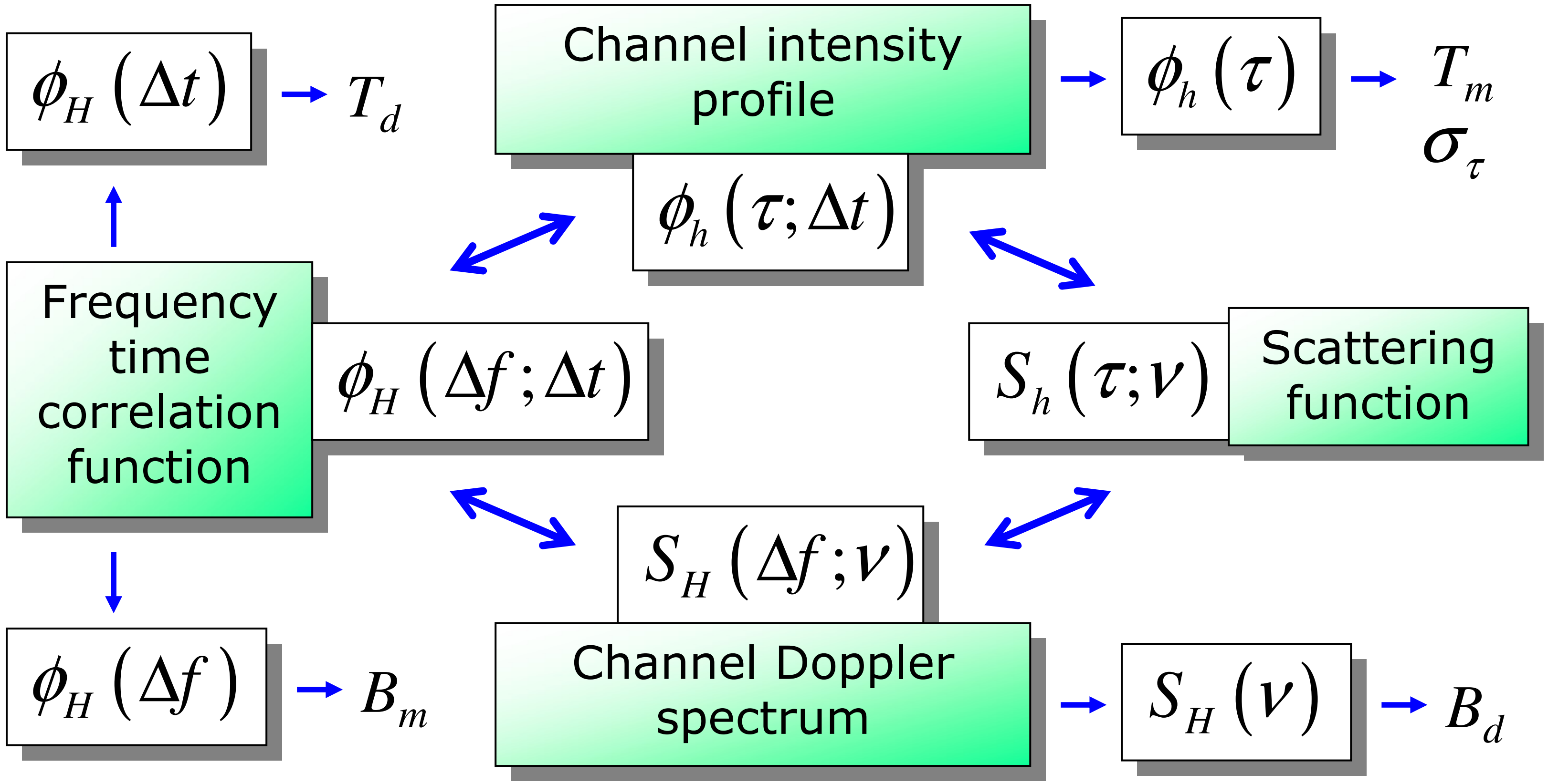
path attenuation | path phase | path delay



Deterministic channel functions



Stochastical (WSSUS) channel functions

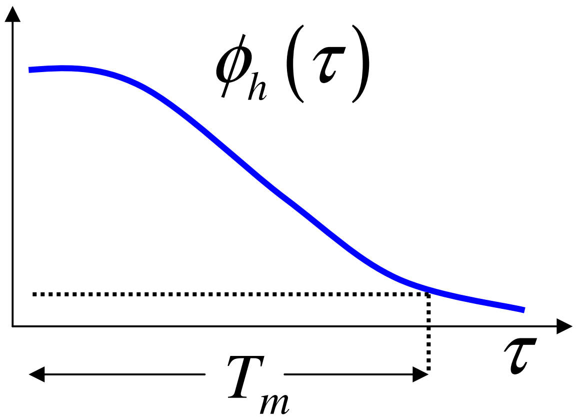


Stochastical (WSSUS) channel variables

Maximum delay spread: T_m

Maximum delay spread may be defined in several ways.

For this reason, the RMS delay spread is often used instead:

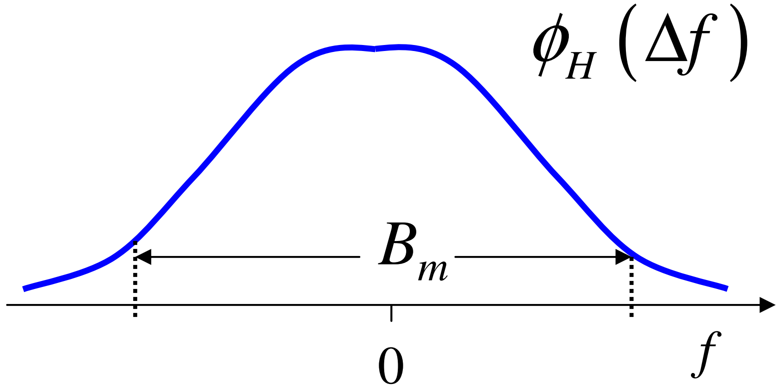


$$\sigma_\tau = \sqrt{\frac{\int \tau^2 \phi_h(\tau)\,d\tau}{\int \phi_h(\tau)\,d\tau} - \left[\frac{\int \tau \phi_h(\tau)\,d\tau}{\int \phi_h(\tau)\,d\tau}\right]^2}$$

Stochastical (WSSUS) channel variables

Coherence bandwidth of channel:

$$B_m \approx 1/T_m$$



Implication of coherence bandwidth:

If two sinusoids (frequencies) are spaced much less apart than B_m , their fading performance is similar.

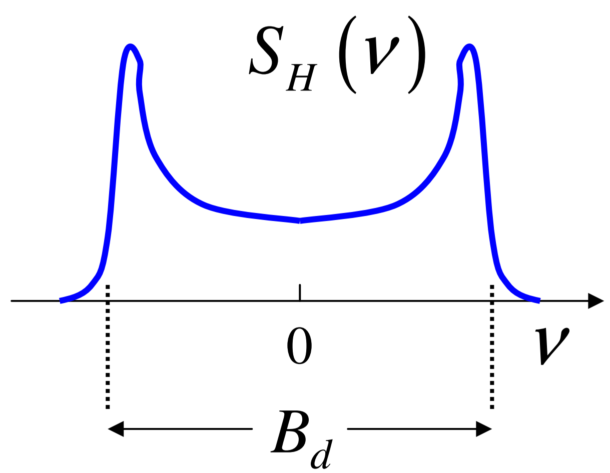
If the frequency separation is much larger than B_m , their fading performance is different.

Stochastical (WSSUS) channel variables

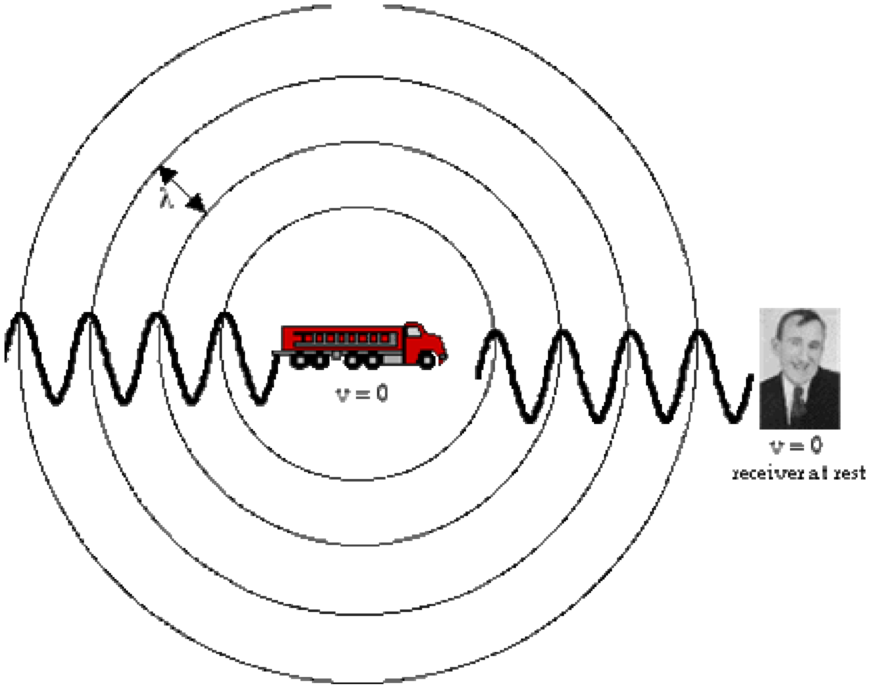
Maximum Doppler spread: B_d

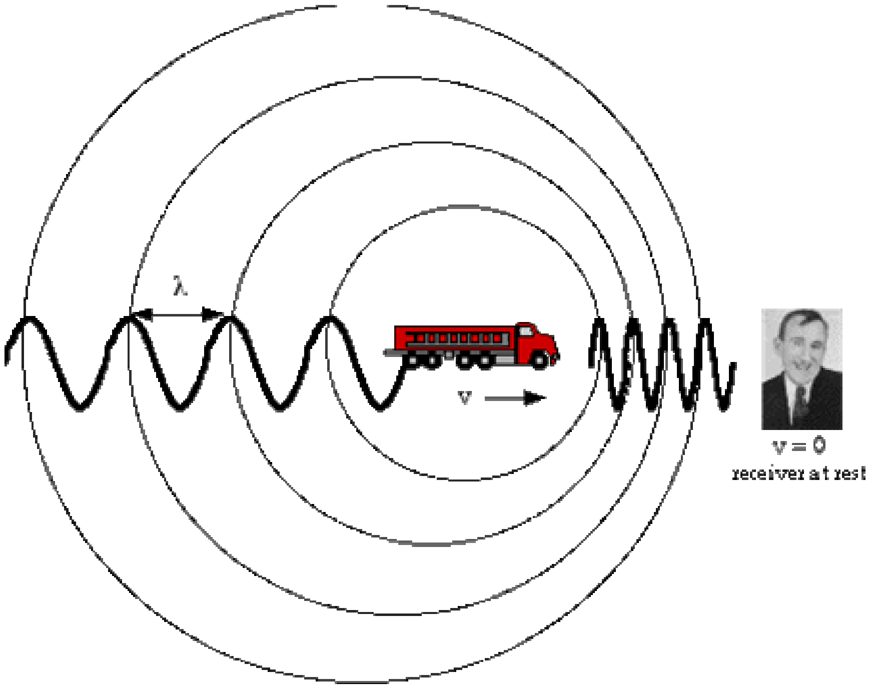
The Doppler spectrum is often U-shaped (like in the figure on the right). The reason for this behaviour is the relationship

$$\nu = \frac{V}{\lambda}\cos\alpha = f_d \cos\alpha$$

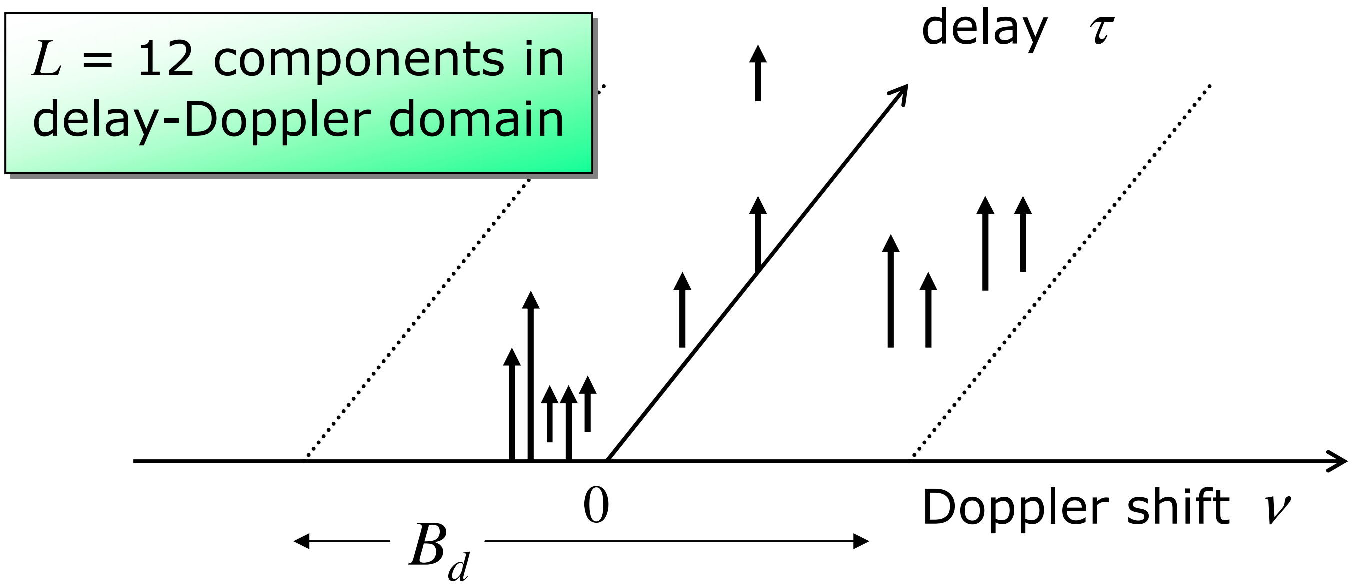


Physical interpretation of Doppler shift





Delay - Doppler spread of channel



$$h(\tau,t)=\sum_{i=0}^{L-1} a_i(t)\,e^{j(2\pi\nu_i t+\phi_i)}\,\delta(\tau-\tau_i)$$

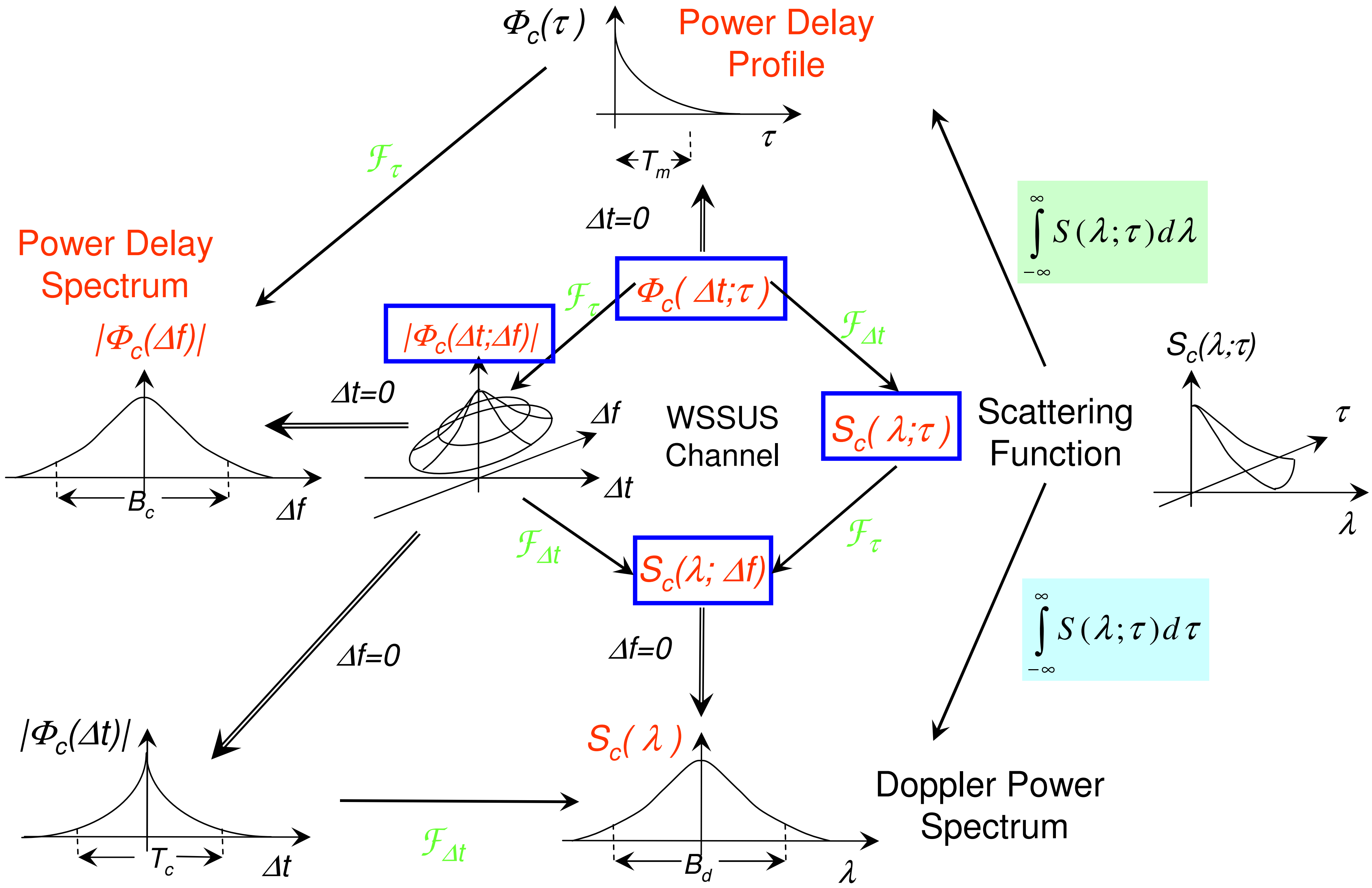
Channel Autocorrelation Functions

- Time-spreading: Multipath characteristics of channel
  - Multi-path delay spread, T_m
    - Characterizes time dispersiveness of the channel,
    - Obtained from power delay-profile, $\Phi_c(\tau)$
    - Indicates delay during which the power of the received signal is above a certain value.
  - Coherence bandwidth, B_c approx. $1/T_m$
    - Indicates frequencies over which the channel can be considered flat
    - Two sinusoids separated by more than B_c: affected differently by the channel
    - Indicates frequency selectivity during transmission.

Channel Autocorrelation Functions

- Time variations of channel: Frequency-spreading
  - Doppler Spread, B_d
    - Characterizes frequency dispersiveness of the channel, or the spreading of transmitted frequency due to different Doppler shifts
    - Obtained from Doppler spectrum, $S_c(\lambda)$
    - Indicates range of frequencies over which the received Doppler spectrum is above a certain value
  - Coherence time, T_c approx. $1/B_d$
    - Time over which the channel is time-invariant
    - A large coherence time: Channel changes slowly

Channel Autocorrelation Functions



Statistical Models

- Design and performance analysis based on statistical ensemble of channels rather than specific physical channel.

$$h_\ell[m] \approx \sum_i a_i e^{-j2\pi f_c \tau_i}$$

- Rayleigh flat fading model: many small scattered paths

$$h[m] \sim \mathcal{N}(0, \frac{1}{2}) + j\mathcal{N}(0, \frac{1}{2}) \sim \mathcal{CN}(0,1)$$

Complex circular symmetric Gaussian .

Squared magnitude is exponentially distributed.

- Rician model: 1 line-of-sight plus scattered paths

$$h[m] \sim \sqrt{\kappa} + \mathcal{CN}(0,1)$$

Fading distributions (Rayleigh)

In a flat fading channel, the (time-variant) CIR reduces to a (time-variant) complex channel coefficient:

$$c(t) = a(t)e^{j\phi(t)} = x(t) + j\,y(t) = \sum_i a_i(t)e^{j\phi_i(t)}$$

When the quadrature components of the channel coefficient are independently and Gaussian distributed, we get:

$$p(a) = \frac{a}{\sigma^2}e^{-a^2/2\sigma^2} \qquad p(\phi) = \frac{1}{2\pi}$$

Rayleigh distribution

Uniform distribution

Fading distributions (Rice)

In case there is a strong (e.g., LOS) multipath component in addition to the complex Gaussian component, we obtain:

$$c(t) = a_0 + a(t)e^{j\phi(t)} = a_0 + \sum_i a_i(t)e^{j\phi_i(t)}$$

From the joint (magnitude and phase) pdf we can derive:

$$p(a) = \frac{a}{\sigma^2} e^{-\left(a^2 + a_0^2\right)/2\sigma^2} I_0\left(\frac{a a_0}{\sigma^2}\right)$$

Rice distribution

Modified Bessel function of first kind and order zero

Types of Channels

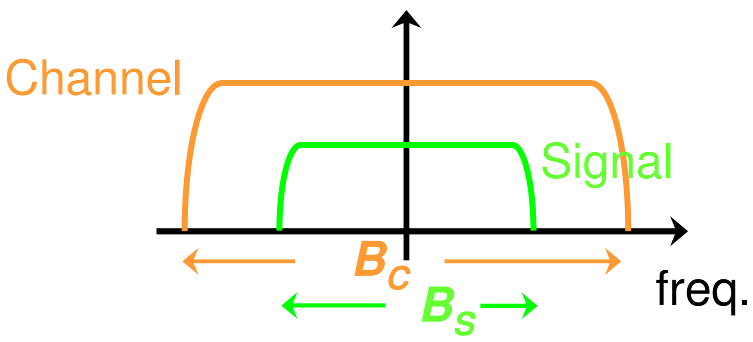
Types of channel	Defining characteristic
Fast fading	$T_c \ll$ delay requirement
Slow fading	$T_c \gg$ delay requirement
Flat fading	$W \ll W_c$
Frequency-selective fading	$W \gg W_c$
Underspread	$T_d \ll T_c$

Channel Classification

- Based on Time-Spreading

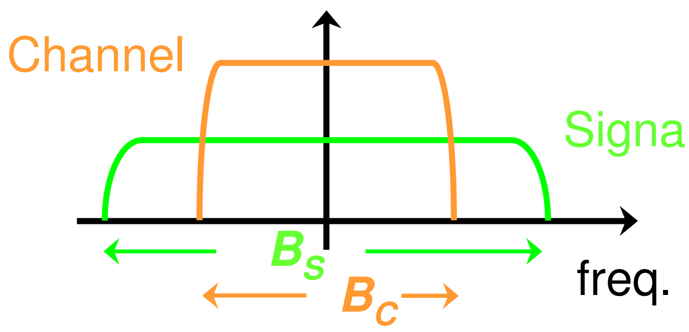
Flat Fading

1. $B_S < B_C \Leftrightarrow T_m < T_s$
2. Rayleigh, Ricean distrib.
3. Spectral char. of transmitted signal preserved



Frequency Selective

1. $B_S > B_C \Leftrightarrow T_m > T_s$
2. Intersymbol Interference
3. Spectral chara. of transmitted signal not preserved
4. Multipath components resolved

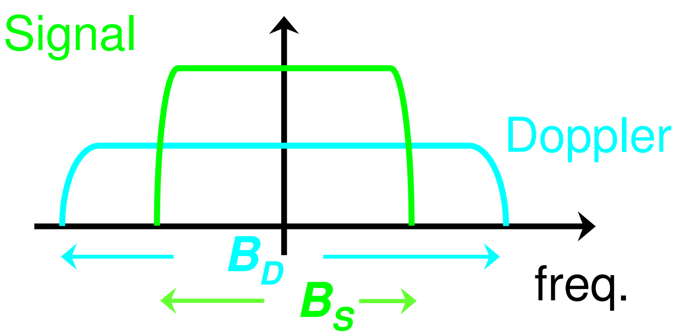


Channel Classification

- Based on Time-Variations

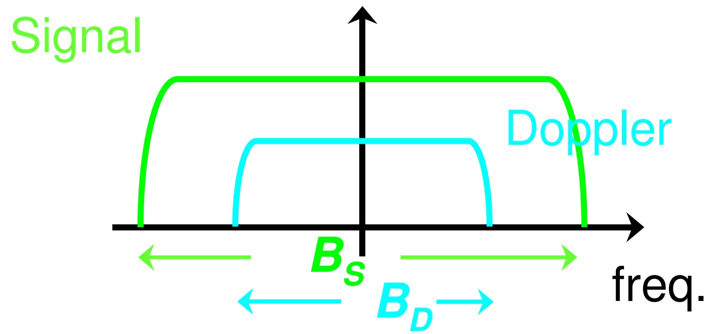
Fast Fading

1. High Doppler Spread
2. $1/B_d \cong T_C < T_s$



Slow Fading

1. Low Doppler Spread
2. $1/B_d \cong T_C > T_s$



Channel Classification

- Underspread channel: $T_m B_d << 1$

  Channel characteristics vary slowly (B_d small) or paths obtained within a short interval of time (T_m small).

  Easy to extract channel parameters.

- Overspread channel: $T_m B_d >> 1$

  Hard to extract parameters as channel characteristics vary fast and channel changes before all paths can be obtained.