Basic Principles of Wireless Networks (I)

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CHALMERS

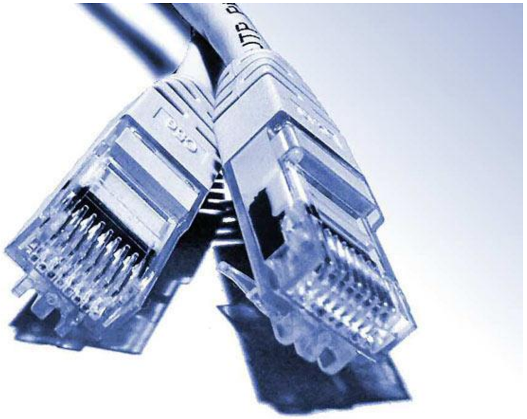
Based on slides prepared by Nima Seifi at Chalmers, based on slides from P. Viswanath/Tse, A. Goldsmith, Shiv Kalyanaraman, Tae Hyun Kim, David Gesbert & textbooks by Tse/Viswanath, A. Goldsmith, J. Andrews et al.

Outline

- Wireless channel
- Physical layer
- Mitigating the wireless channel impairments
  - Equalization
  - Spread spectrum
  - Multicarrier modulation and OFDM
  - Antenna solutions
- Multi-antenna techniques

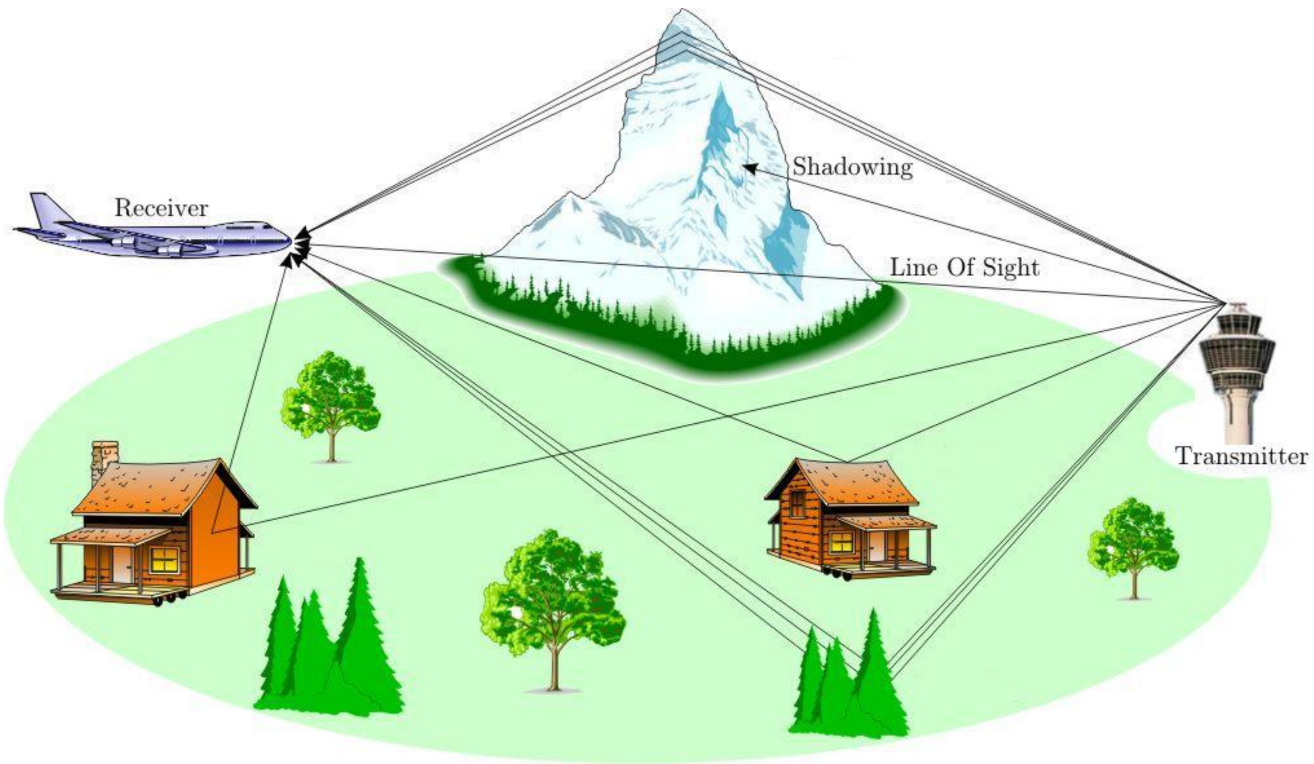
Wireless Channel

Wireless Channel is Very Different!



Wired	Wireless
Each cable is a different channel	One media (cable) shared by all
Signal attenuation is low	High signal attenuation
Small (no) interference	High interference noise; co-channel interference; adjacent channel interference

Wireless Multipath Channel

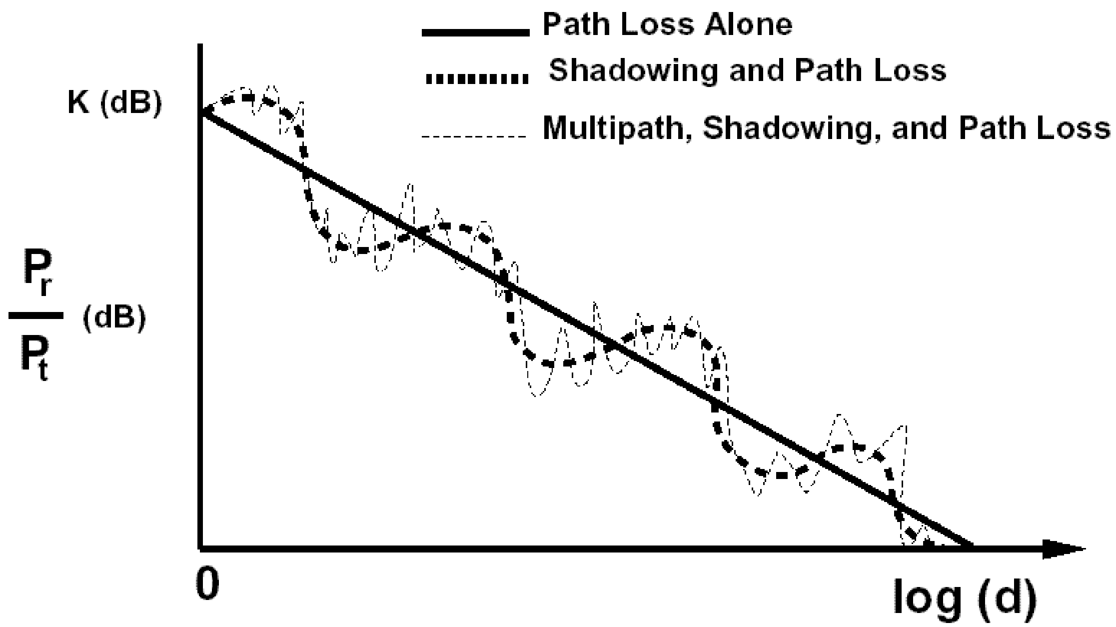


Channel varies at two spatial scales:

- Large scale fading: path loss, shadowing
- Small scale fading: Multi-path fading, Doppler

Path Loss, Shadowing, Fading

- Variable decay of signal due to environment, multipaths, mobility



Source: A. Goldsmith book

Path Loss Modeling

- Maxwell's equations
  - Complex and impractical
- Free space path loss model
  - Too simple
- Ray tracing models
  - Requires site-specific information
- Empirical Models
  - Don't always generalize to other environments
- Simplified power falloff models
  - Main characteristics: good for high-level analysis
  - A simple model for path loss, L, is

$$L = \frac{\bar{P}_r}{P_t} = K \left(\frac{d_0}{d} \right)^{\gamma}$$

- γ is the path loss exponent
- P_t transmit power
- $\bar{P}_r$ local mean receive power
- d_0 reference distance
- d transmit-receive distance
- K transmission constant

Shadowing

- The received signal is shadowed by obstructions such as hills and buildings.
- This results in variation in the local mean received signal power

$$P_r(dB) = \bar{P}_r(dB) + \chi \quad where\ \chi \sim \mathcal{N}(0, \sigma), 4 \leq \sigma \leq 10\ dB$$

- Implications:
  - nonuniform coverage
  - increases the required transmit power

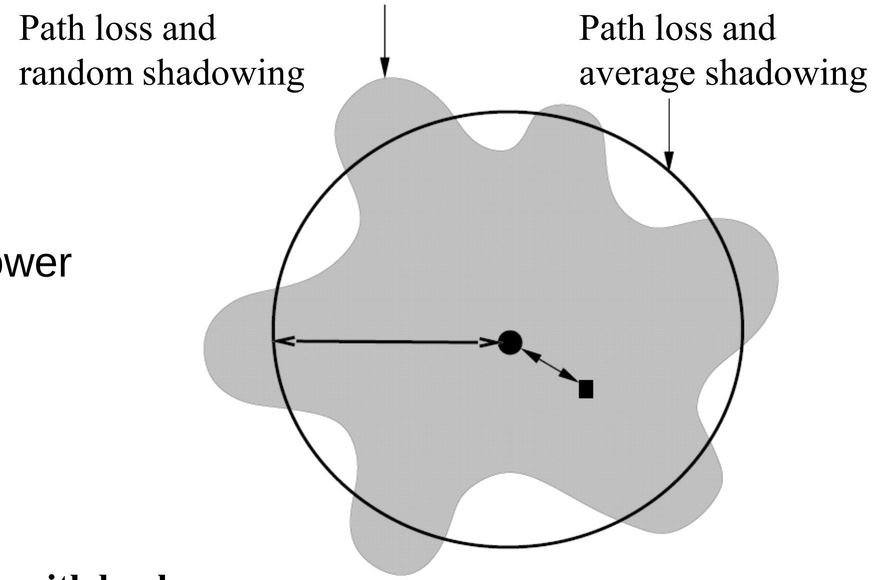


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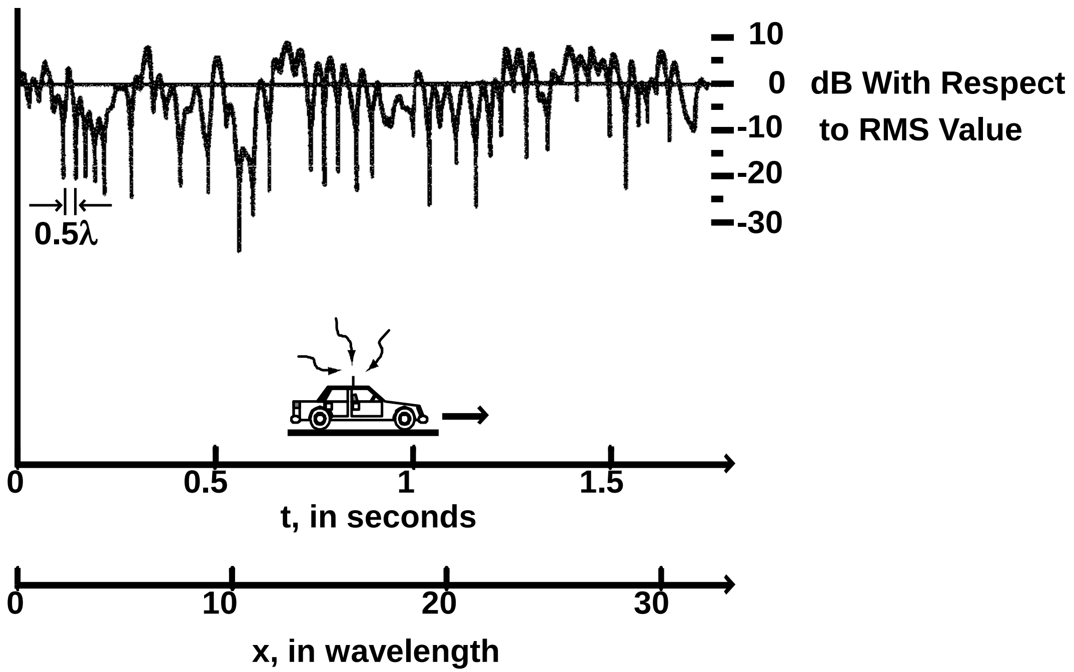
Figure 2.10: Contours of Constant Received Power.

Small-scale Multipath fading

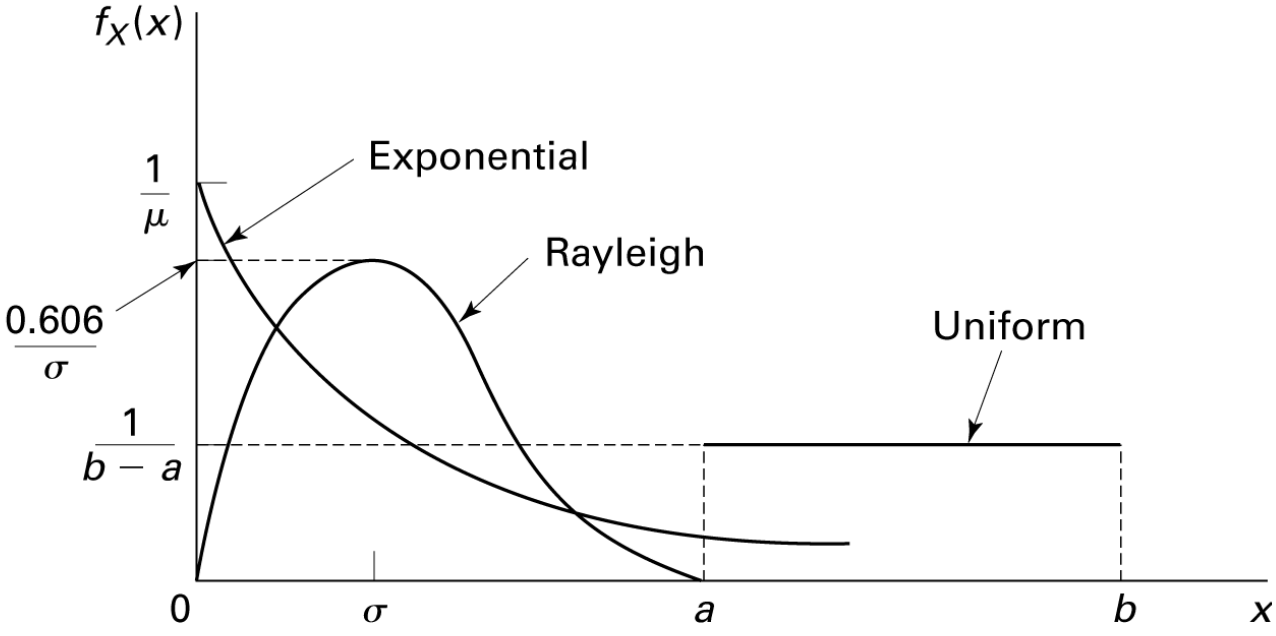
- Multipath fading due to constructive and destructive interference of the transmitted waves.



Single-Tap Channel: Rayleigh Fading

- Path loss, shadowing => average signal power loss
  - Fading around this average.
  - Subtract out average => fading modeled as a zero-mean random process
- Narrowband Fading channel: Each symbol is long in time
- Fading w/ many scatterers: Central Limit Theorem
  - In-phase (cosine) and quadrature (sine) components of the snapshot r(0), denoted as $r_I(0)$ and $r_Q(0)$ are independent Gaussian random variables.
  - Envelope Amplitude: $|r| = \sqrt{r_I^2 + r_Q^2}$ is Rayleigh.
  - Received Power: $|r|^2 = r_I^2 + r_Q^2$ is exponentially distributed.

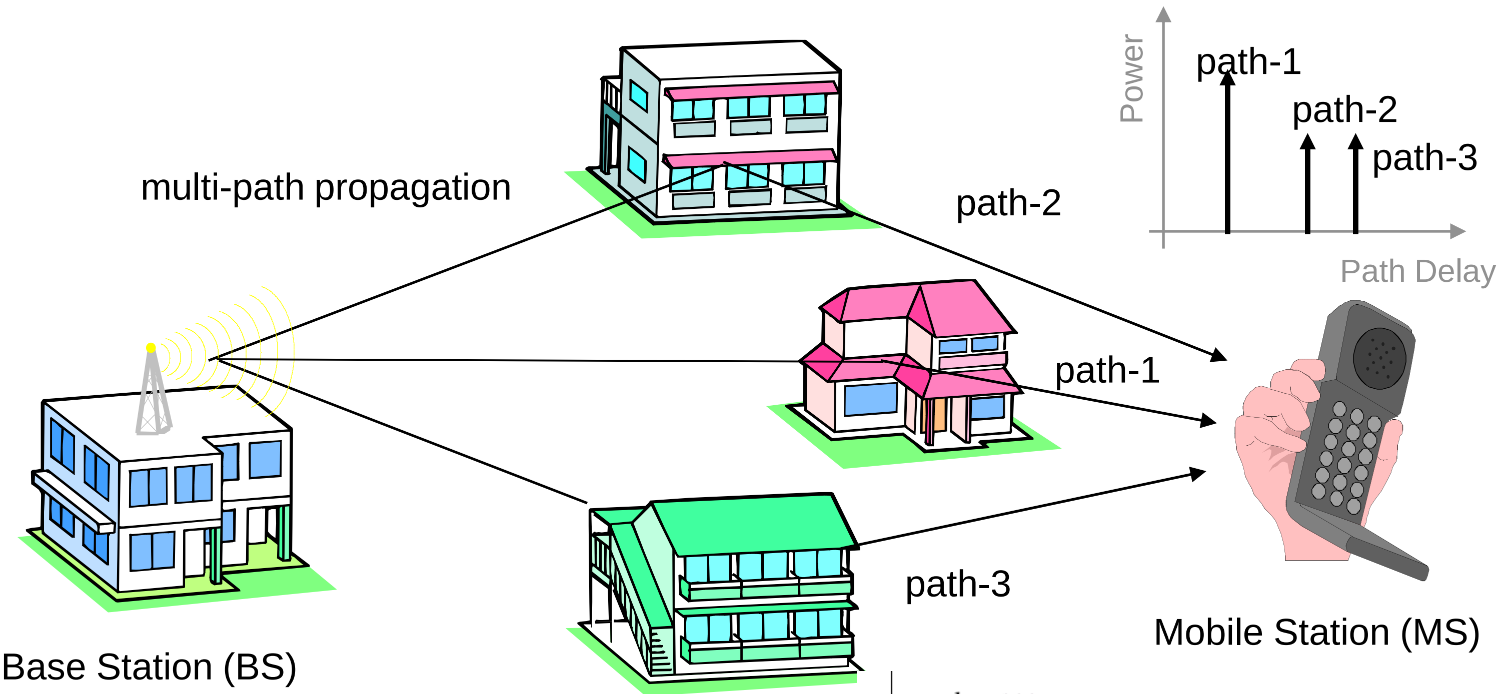
Normal Vector R.V, Rayleigh, Chi-Squared



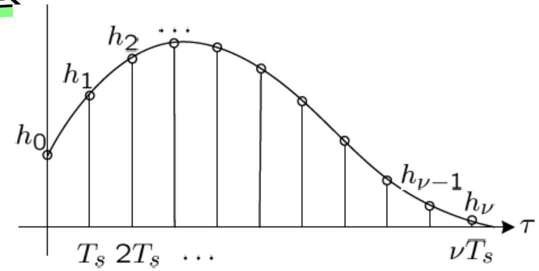
The rayleigh, exponential, and uniform pdf 's.

$X = [X_1, \ldots, X_n]$ is **Normal random *vector***
$||X||$ is **Rayleigh** { eg: *magnitude* of a complex gaussian channel $X_1 + jX_2$ }
$||X||^2$ is **Chi-Squared w/ *n*-degrees of freedom**
When n = 2, chi-squared becomes **exponential**. {eg: *power* in complex gaussian channel: sum of squares…}

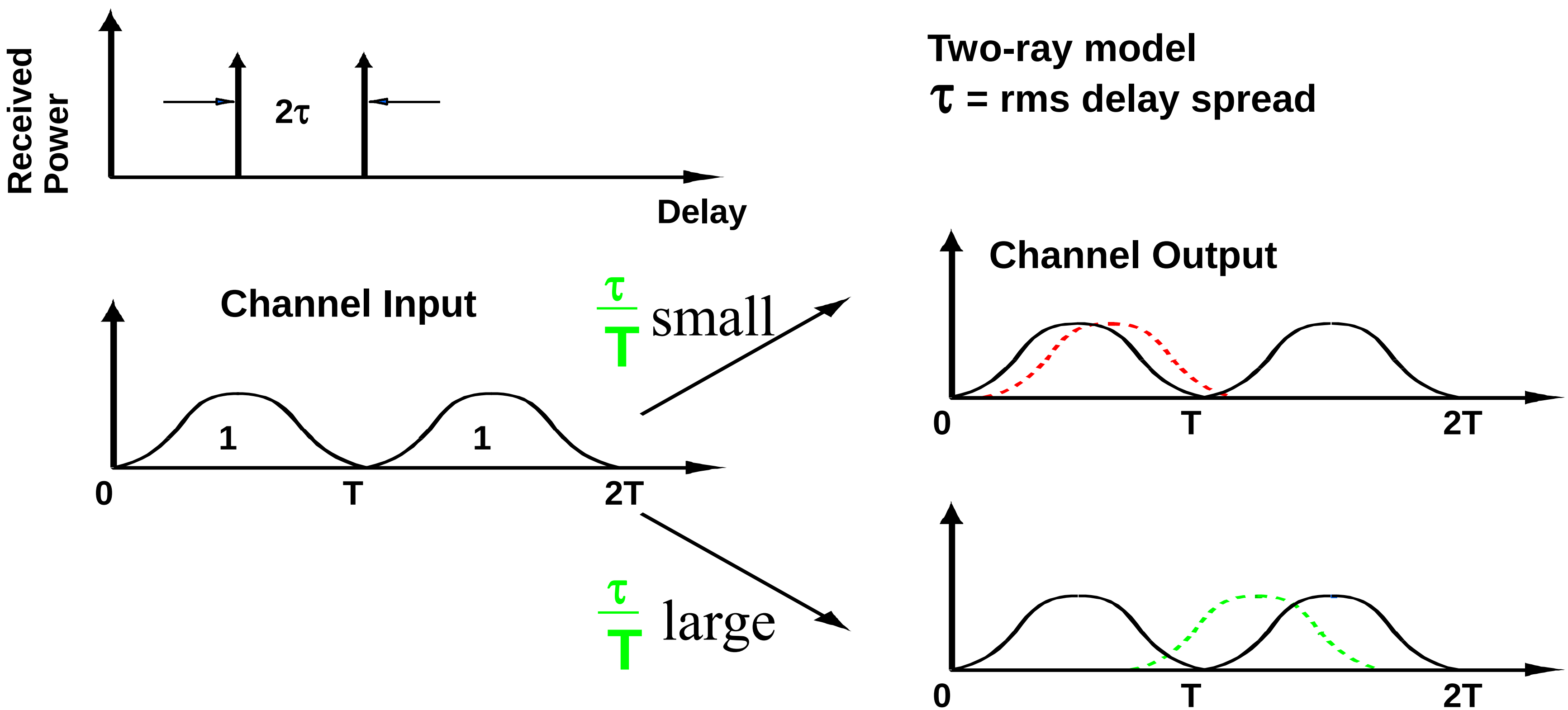
Multipaths: Power-Delay Profile



Channel Impulse Response:
Channel amplitude |h| <u>correlated</u> at delays τ.
Each "tap" value @ kTs Rayleigh distributed
(actually the sum of several sub-paths)



Delay Spread: Time Domain Interpretation



- $\frac{\tau}{T}$ small $\Longrightarrow$ negligible intersymbol interference
- $\frac{\tau}{T}$ large $\Longrightarrow$ significant intersymbol interference, which causes an irreducible error floor

Dispersion-Selectivity Duality

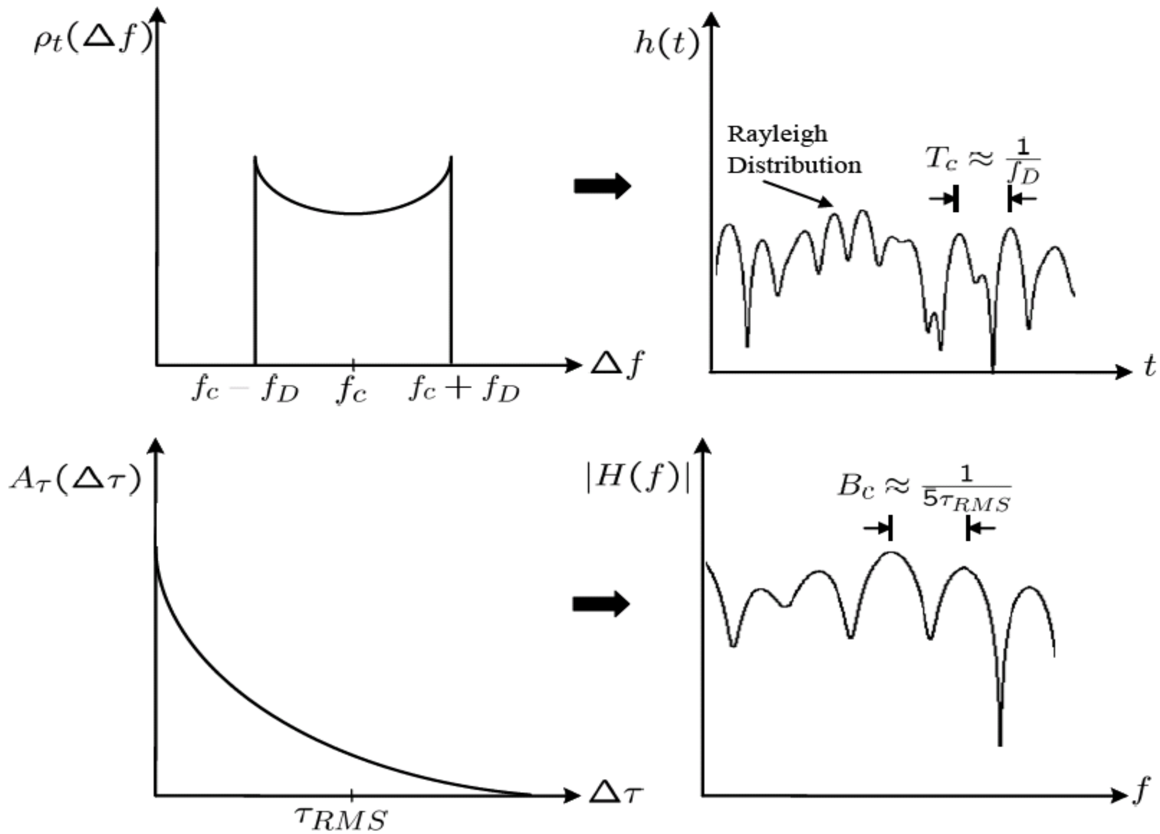


Figure 3.18: The shape of the Doppler power spectrum $\rho_t(\Delta f)$ determines the correlation envelope of the channel in time (top). Similarly, the shape of the multipath intensity profile $A_\tau(\Delta\tau)$ determines the correlation pattern of the channel frequency response (bottom)

Fading: Jargon

- **Flat fading**: no multipath ISI effects.
  - Eg: narrowband, indoors
- **Frequency-selective fading:** multipath ISI effects.
  - Eg: broadband, outdoor.

- **Slow fading:** no Doppler effects.
  - Eg: indoor Wi-fi home networking
- **Fast Fading:** Doppler effects, time-selective channel
  - Eg: cellular, vehicular
  - Doppler: *not an LTI system*

- Broadband cellular + vehicular => Fast + frequency-selective

Summary of Wireless Channel

- We have discussed the concepts of path loss, shadowing, fading (multipath, Doppler), and some of their design impacts.

- We have discussed how time and frequency selectivity of wireless channels depend on key physical parameters.

Physical Layer

Physical Layer Issue

- **Link Performance Measures**
- **Modulation Tradeoffs**
- **Flat Fading Countermeasures**
- **Delay Spread Countermeasures**

Link Performance Measures

PROBABILITY OF BIT/ BLOCK ERROR

- The bit error probability (BER), P_b, in a radio environment is a random variable.
  - Average P_b, $\overline{P}_b$
  - Outage P_b, $P_{out} = \Pr[P_b > P_{b,target}]$

- Similarly, the block error probability (BLER), P_{bl}, in a radio environment is a random variable.
  - Average P_{bl}, $\overline{P}_{bl}$
  - Outage P_{bl}, $P_{out} = \Pr[P_{bl} > P_{bl,target}]$

Link Performance Measures

EFFICIENCY

- Spectral Efficiency
  - A measure of data rate per unit bandwidth for a given bit error probability and transmitted power.
- Power Efficiency
  - A measure of required transmit power to achieve a given data rate for a given bit error probability and bandwidth.

What is Modulation?

- Encoding information in a manner suitable for transmission.
  - Translate baseband source signal to bandpass signal
  - Bandpass signal: “modulated signal”

- How?
  - Vary amplitude, phase or frequency of a carrier

- Demodulation
  - Extract baseband message from carrier

Digital Modulation

- Any modulated signal can be represented as

$$s(t) = \underset{\text{amplitude}}{A(t)} \cos [\omega_c t + \underset{\text{phase or frequency}}{\phi(t)}]$$

$$= \underbrace{A(t) \cos \phi(t)}_{\text{in-phase}} \cos \omega_c t - \underbrace{A(t) \sin \phi(t)}_{\text{quadrature}} \sin \omega_c t$$

- Linear versus nonlinear modulation
- Constant envelope versus non-constant envelope

Linear Modulation Techniques

$$s(t) = \underbrace{\left[\sum a_n\, g(t-nT)\right]}_{I(t),\ \text{in-phase}} \cos \omega_c t - \underbrace{\left[\sum b_n\, g(t-nT)\right]}_{Q(t),\ \text{quadrature}} \sin \omega_c t$$

LINEAR MODULATIONS

Square Constellations → M-ARY QUADRATURE AMPLITUDE MOD. (M-QAM)

M-ARY PHASE SHIFT KEYING (M-PSK) ← Circular Constellations

$M \neq 4$

M=4 (4-QAM = 4-PSK)

$M \neq 4$

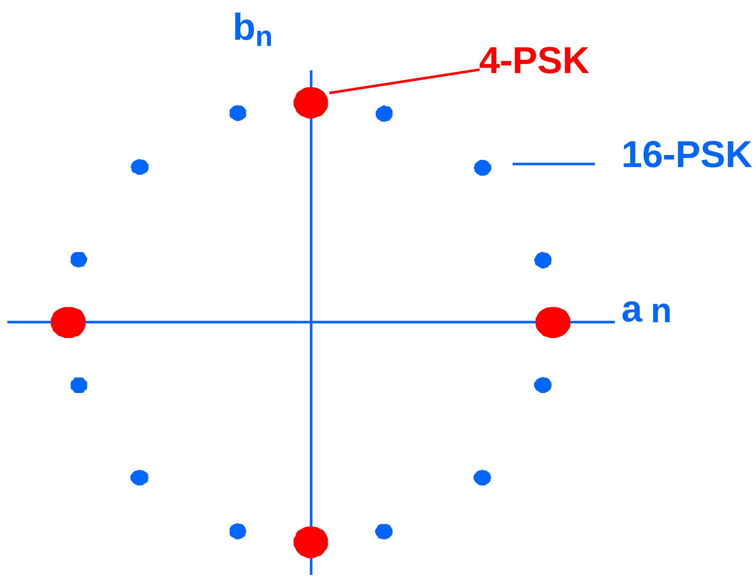
CONVENTIONAL 4-PSK (QPSK)

OFFSET 4-PSK (OQPSK)

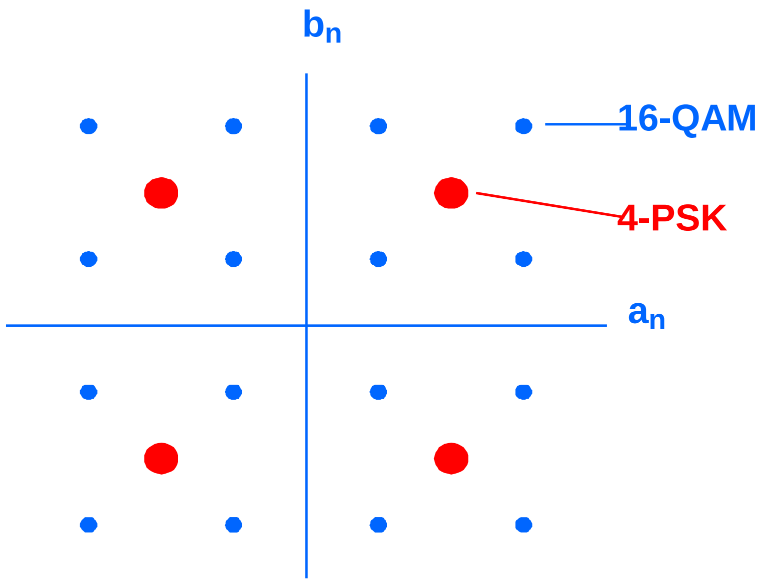
DIFFERENTIAL 4-PSK (DQPSK, $\pi/4$-DQPSK)

Signal Constellation

M-PSK (Circular Constellations)



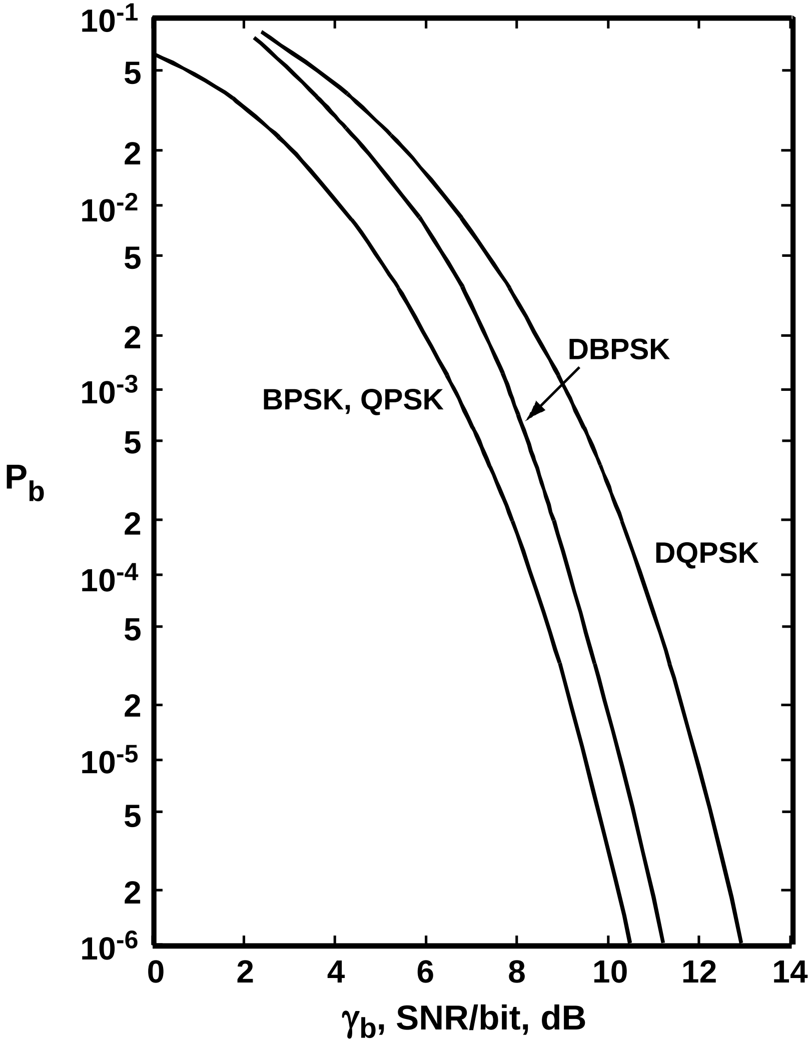
M-QAM (Square Constellations)



Demodulation

- Coherent detection requires a coherent phase reference.
  - difficult to obtain in a rapidly fading environment
  - increases receiver complexity
- Differential detection uses the previous symbol for the reference signal.
  - eliminates need for coherent reference
  - Doppler causes irreducible error floor, typically small for high bit rates

Bit Error Rate (BER): AWGN

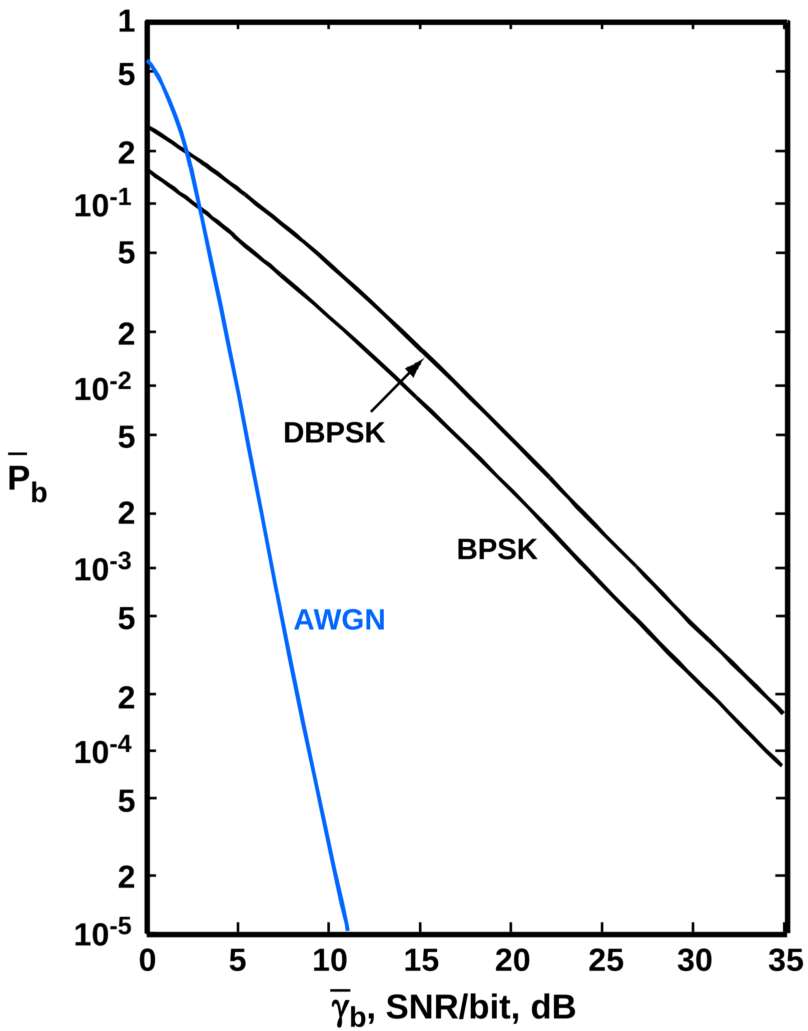


For $P_b = 10^{-3}$

BPSK 6.5 dB
QPSK 6.5 dB
DBPSK ~8 dB
DQPSK ~9 dB

- QPSK is more spectrally efficient than BPSK with the same performance.
- There is a ~3 dB power penalty for differential detection.

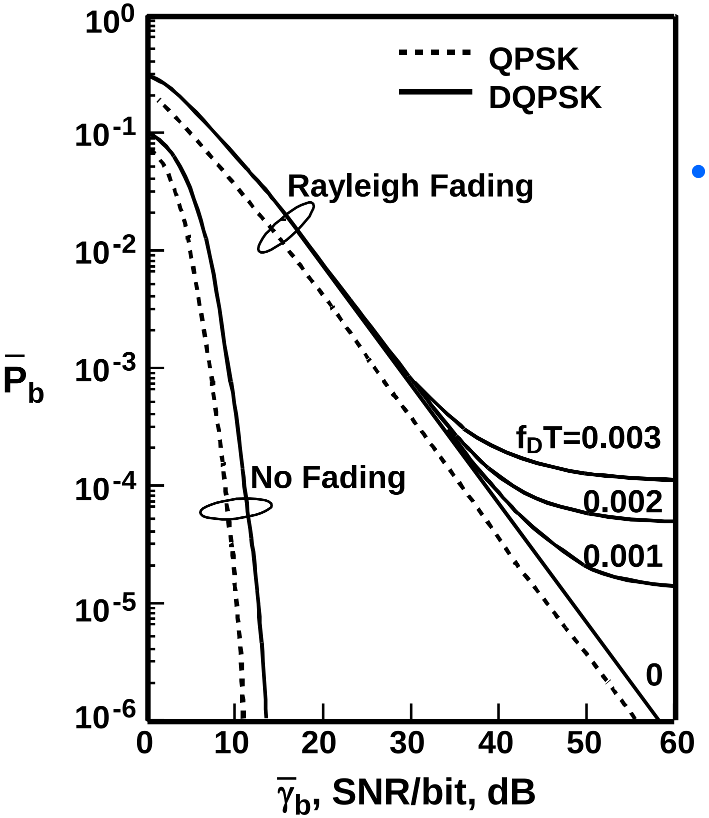
Bit Error Rate (BER): Fading Channel



- $\bar{P}_b$ is inversely proportion to the average SNR per bit.
- Transmission in a fading environment requires about 18 dB more power for $\bar{P}_b = 10^{-3}$.

Bit Error Probability (BER): Doppler Effects

- Doppler causes an irreducible error floor when differential detection is used $\Rightarrow$ decorrelation of reference signal and distortion of signal shape.



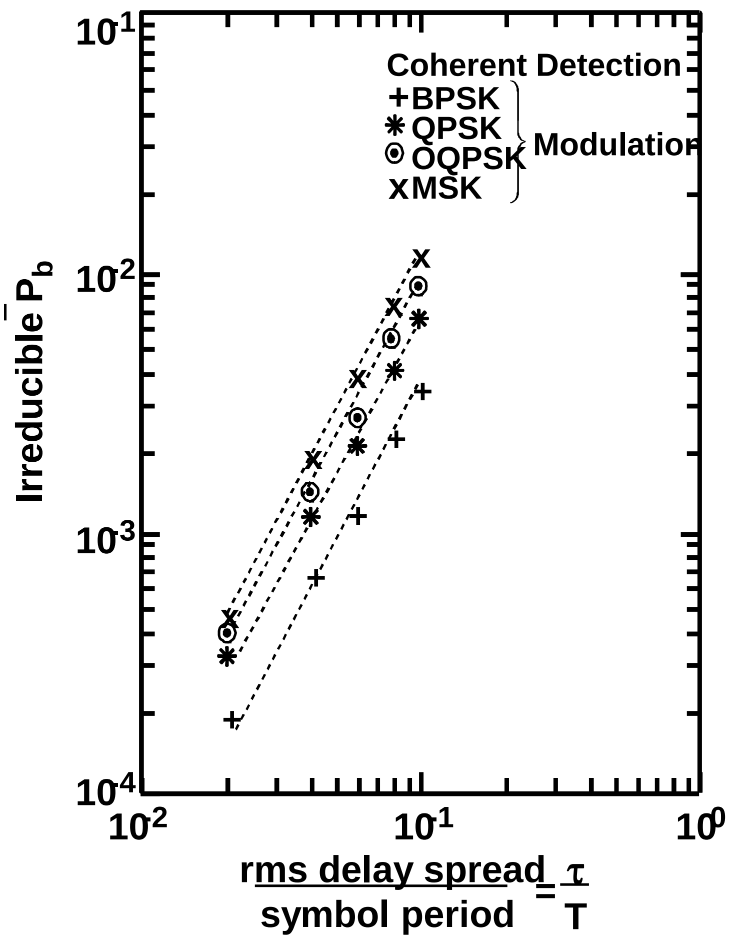
- The irreducible $\bar{P}_b$ depends on the data rate and the Doppler. For f_D = 80 Hz,

data rate	T	$\bar{P}_{b_{floor}}$
10 kbps	10^{-4}s	$3\text{x}10^{-4}$
100 kbps	10^{-5}s	$3\text{x}10^{-6}$
1 Mbps	10^{-6}s	$3\text{x}10^{-8}$

The implication is that Doppler is ***not an issue for high-speed wireless data.***

[M. D. Yacoub, *Foundations of Mobile Radio Engineering* , CRC Press, 1993]

Bit Error Probability (BER): Delay Spread



- ISI causes an irreducible error floor.
- The rms delay spread imposes a limit on the maximum bit rate in a multipath environment.

For example, for QPSK,

	τ	Maximum Bit Rate
Mobile (rural)	25 μsec	8 kbps
Mobile (city)	2.5 μsec	80 kbps
Microcells	500 nsec	400 kbps
Large Building	100 nsec	2 Mbps

[J. C.-I. Chuang, "The Effects of Time Delay Spread on Portable Radio Communications Channels with Digital Modulation," *IEEE JSAC*, June 1987]

Summary of Modulation Issues

- Tradeoffs
  - linear versus nonlinear modulation
  - constant envelope versus non-constant envelope
  - coherent versus differential detection
  - power efficiency versus spectral efficiency
- Limitations
  - flat fading
  - Doppler
  - delay spread