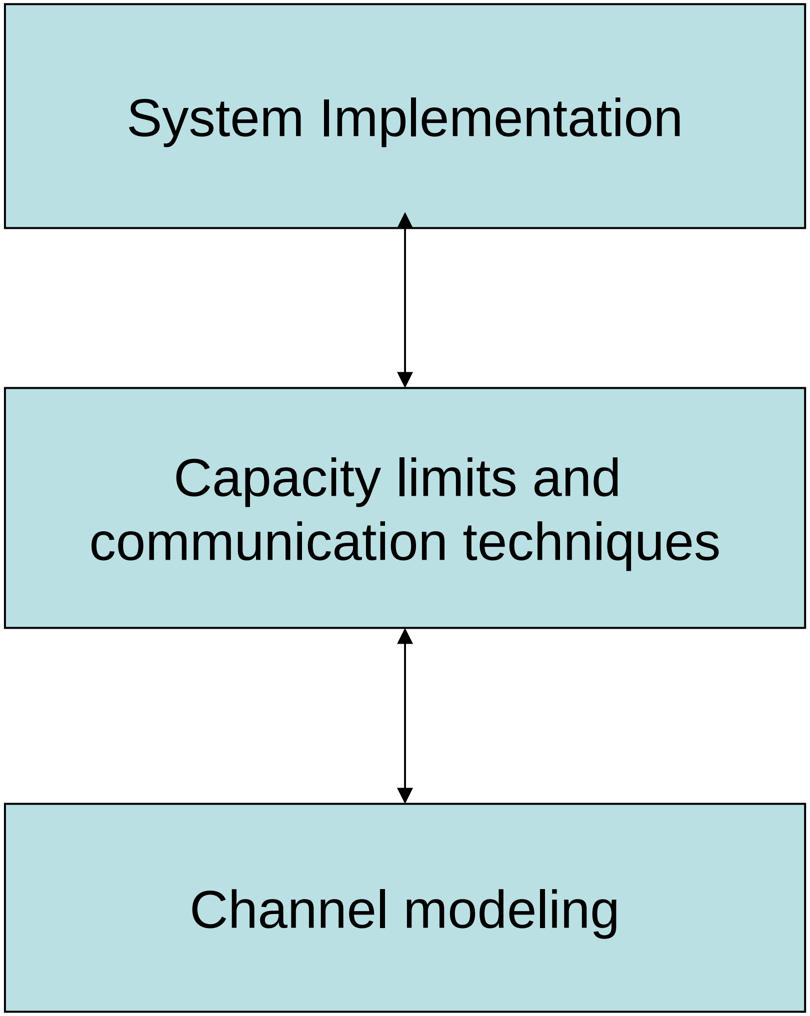
Some concepts of Wireless Communication

Juan Cousseau
Department of Electrical and Computer Engineering
Universidad Nacional del Sur

Lectures Objectives

- Past decade has seen a surge of research activities in the field of wireless communication.
- Emerging from this research thrust are new points of view on how to communicate effectively over wireless channels.
- The goal of these lectures is to study in a unified way the fundamentals and some concepts that lead to new research developments.
- The concepts are illustrated using examples from several modern wireless systems (GSM, IS-95, CDMA 2000 1x EV-DO, Flarion's Flash OFDM, ArrayComm systems.)



System Implementation

Capacity limits and communication techniques

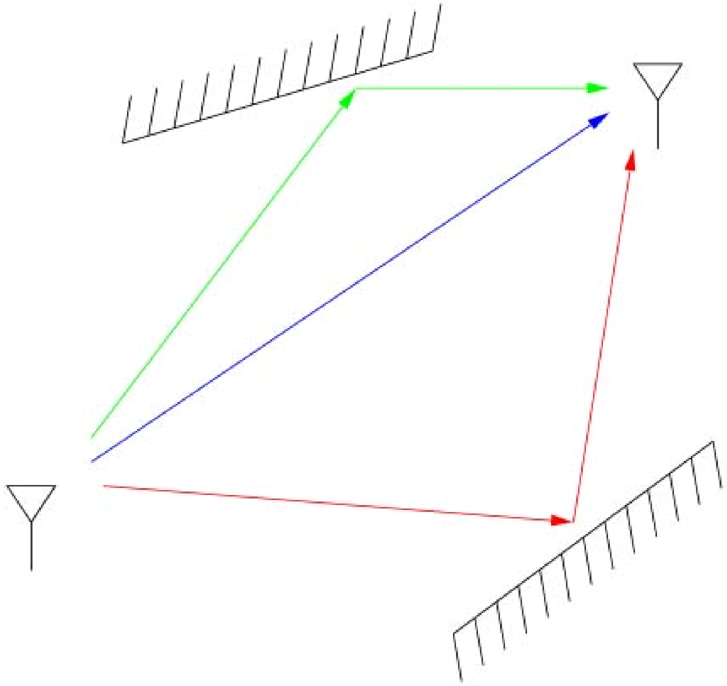
Channel modeling

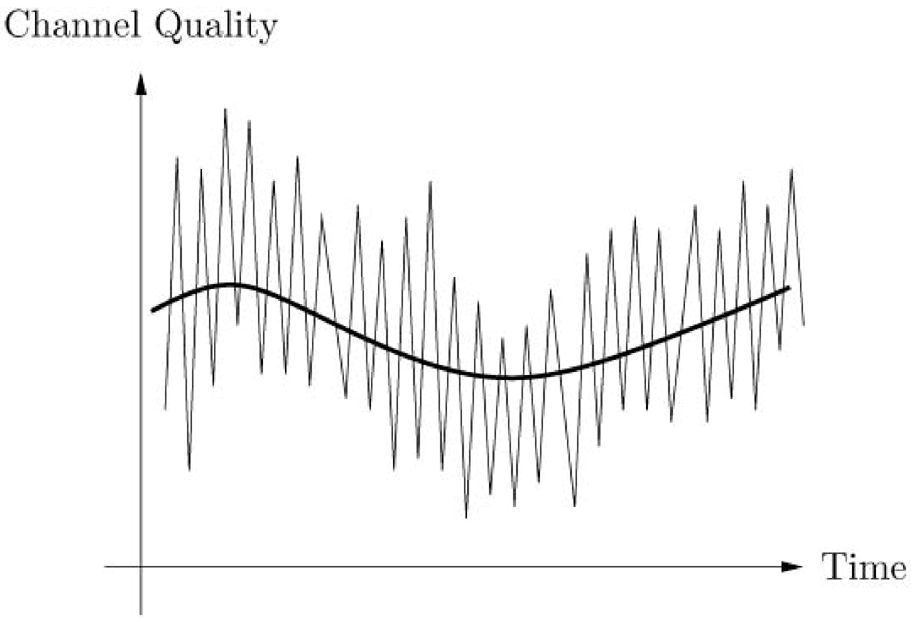
Outline

1. The Wireless Channel
2. Diversity
3. Multiple Access and Interference Management
4. Capacity of Wireless Channels

1. The Wireless Channel

Wireless Multipath Channel





Channel varies at two spatial scales:

- large scale fading
- small scale fading

Large-scale fading

- In free space, received power attenuates like $1/r^2$.
- With reflections and obstructions, can attenuate even more rapidly with distance. Detailed modeling complicated.
- Time constants associated with variations are very long as the mobile moves, many seconds or minutes.
- More important for cell site planning, less for communication system design.

Small-scale multipath fading

- Wireless communication typically happens at very high carrier frequency. (eg. f_c = 900 MHz or 1.9 GHz for cellular)
- Multipath fading due to constructive and destructive interference of the transmitted waves.
- Channel varies when mobile moves a distance of the order of the carrier wavelength. This is about 0.3 m for 900 MHz cellular.
- For vehicular speeds, this translates to channel variation of the order of 100 Hz.
- Primary driver behind wireless communication system design.

Physical Models

- Wireless channels can be modeled as linear time-varying systems:

$$y(t) = \sum_i a_i(t) x(t - \tau_i(t))$$

where $a_i(t)$ and $\tau_i(t)$ are the gain and delay of path i.

- The time-varying impulse response is:

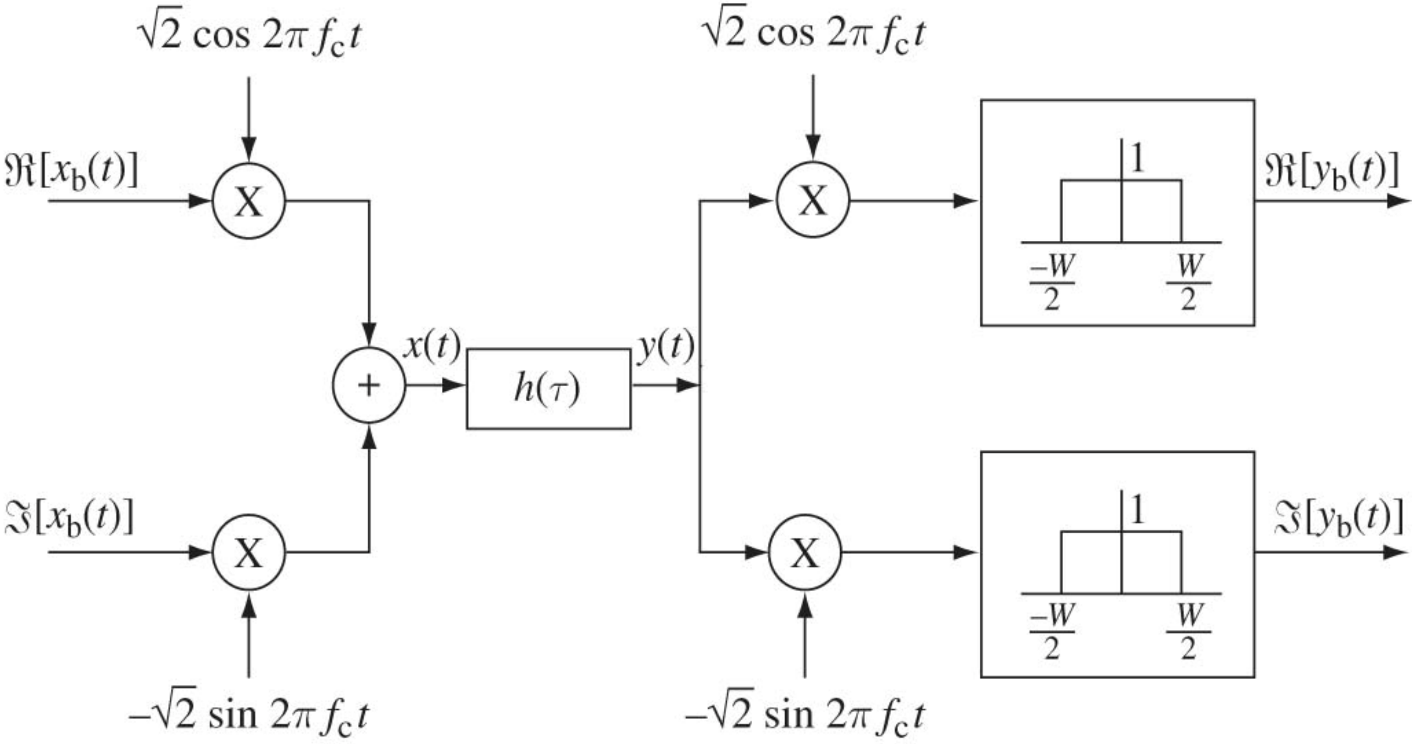
$$h(t,\tau) = \sum_i a_i(t) \delta(\tau - \tau_i(t))$$

- Consider first the special case when the channel is time-invariant:

$$h(\tau) = \sum_i a_i \delta(\tau - \tau_i)$$

Passband to Baseband Conversion

- Communication takes place at $[f_c - W/2, f_c + W/2]$
- Processing takes place at baseband $[-W/2, W/2]$



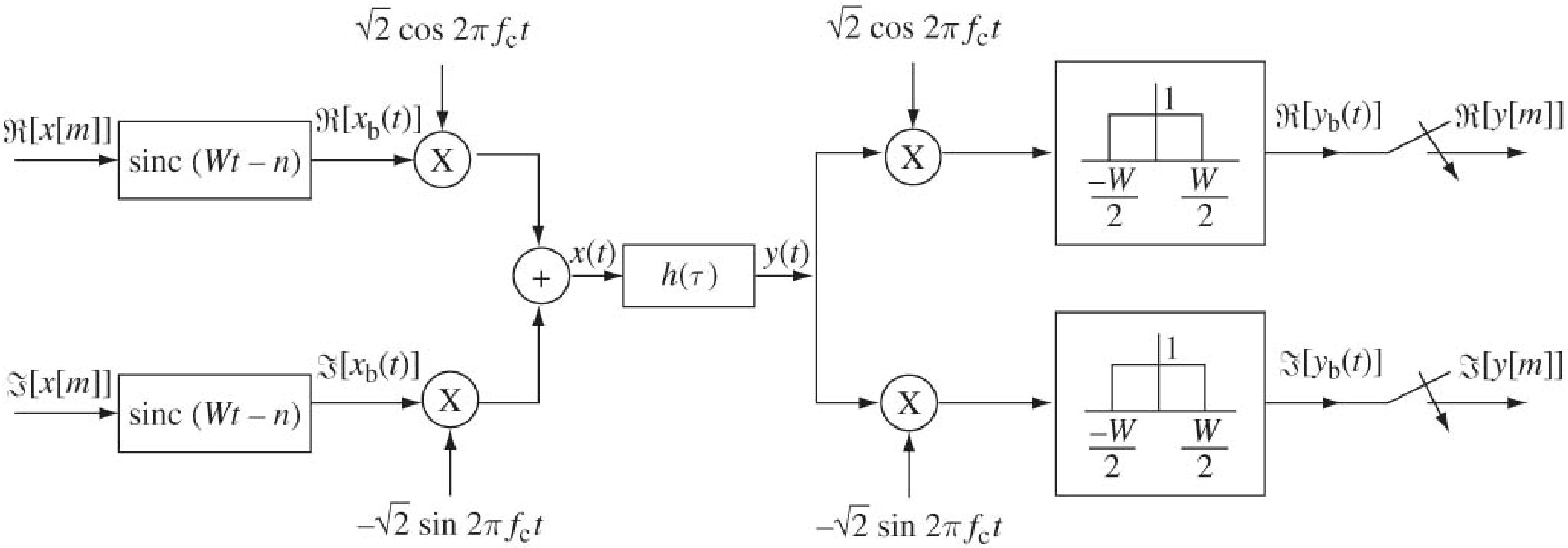
Complex Baseband Equivalent Channel

- The frequency response of the system is shifted from the passband to the baseband.

$$\begin{aligned} H_b(f) &= H(f+f_c) \\ h_b(\tau) &= h(t)e^{-j2\pi f_c t} = \sum_i a_i^b \delta(\tau - \tau_i) \\ \text{where } a_i^b &= a_i e^{-j2\pi f_c \tau_i} \end{aligned}$$

- Each path is associated with a delay and a complex gain.

Modulation and Sampling



Multipath Resolution

Sampled baseband-equivalent channel model:

$$y[m] = \sum_{\ell} h_{\ell}\, x[m-\ell]$$

where h_l is the l th complex channel tap.

$$h_{\ell} \approx \sum_{i} a_i e^{-j2\pi f_c \tau_i}$$

and the sum is over all paths that fall in the delay bin

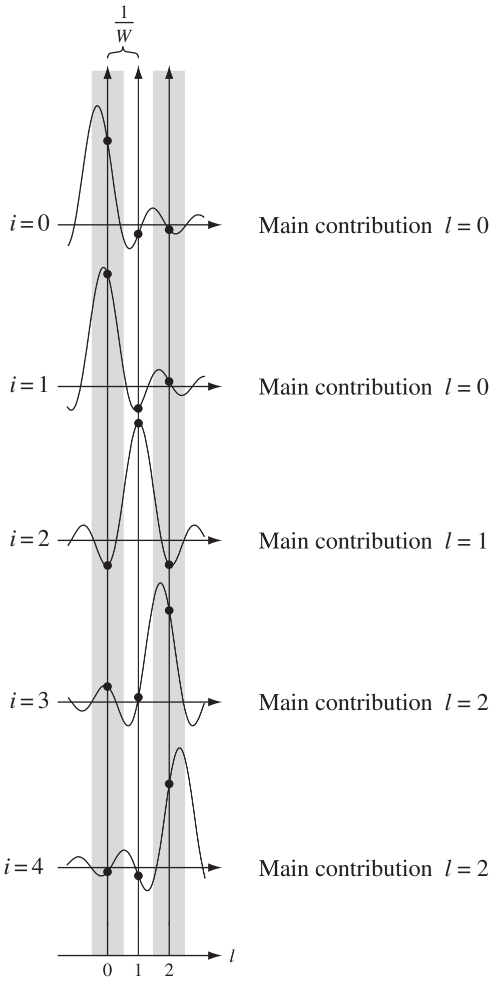
$$\left[\frac{\ell}{W} - \frac{1}{2W}, \frac{\ell}{W} + \frac{1}{2W}\right]$$

System resolves the multipaths up to delays of 1/W .

Sampling Interpretation

- h_l is the l th sample of the low-pass version of the channel response $h_b(\cdot)$.

- Contribution of the i th path is the projection of $a_i^b \, \delta(\tau-\tau_i)$ onto $\mathrm{sinc}(W\tau - l)$.



Flat and Frequency-Selective Fading

- Fading occurs when there is destructive interference of the multipaths that contribute to a tap.

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

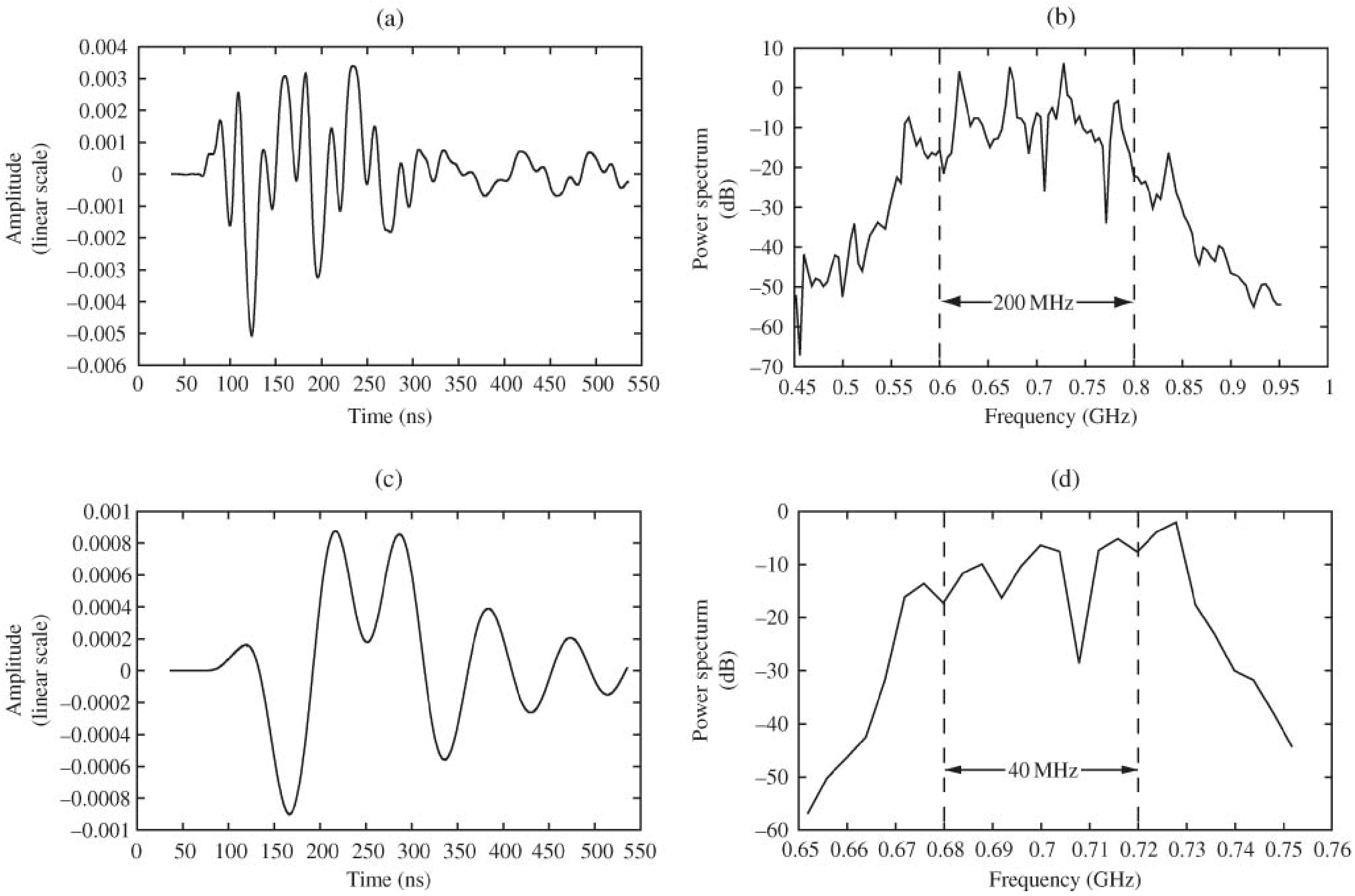
Delay spread $T_d := \max_{i,j} |\tau_i(t) - \tau_j(t)|$

Coherence bandwidth $W_c := \frac{1}{T_d}$

$T_d \ll \frac{1}{W}, W_c \gg W \Rightarrow$ single tap, flat fading

$T_d > \frac{1}{W}, W_c < W \Rightarrow$ multiple taps, frequency selective

1: The Wireless Channel



Effective channel depends on both physical environment and bandwidth!

Time Variations

$$y[m] = \sum_{\ell} h_\ell[m] x[m-\ell]$$

$$h_\ell[m] \approx \sum_i a_i(t) e^{-j2\pi f_c \tau_i(t)}, \qquad t = \frac{m}{W}$$

$f_c \tau_i'(t) =$ Doppler shift of the i th path

Doppler spread $D_s := \mathrm{max}_{i,j} \left| f_c \tau_i'(t) - f_c \tau_j'(t) \right|$

Coherence time $T_c := \frac{1}{D_s}$

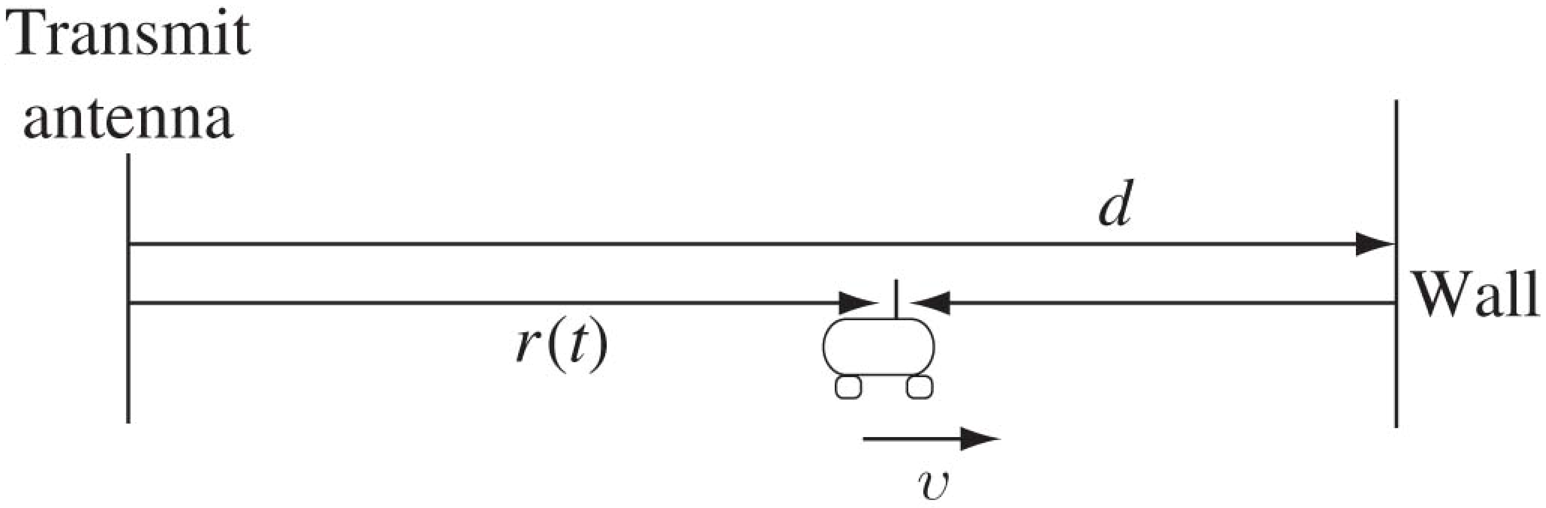
Two-path Example

v= 60 km/h, f_c = 900 MHz:

direct path has Doppler shift of -50 Hz

reflected path has shift of +50 Hz

Doppler spread = 100 Hz



Doppler Spread

$$D_s := \max_{i,j} |f_c\tau_i'(t) - f_c\tau_j'(t)|$$

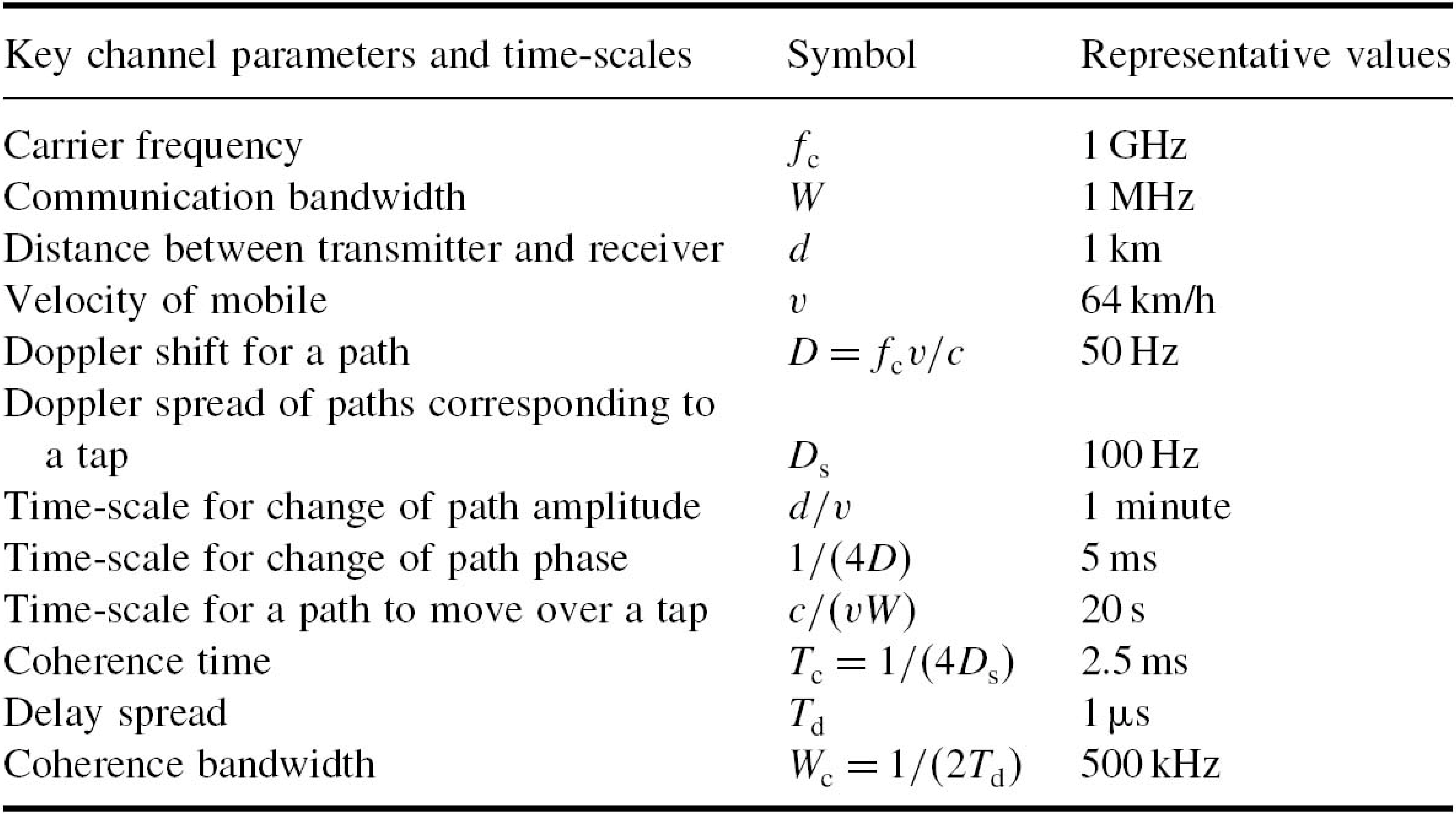
Doppler spread is proportional to:

- the carrier frequency f_c;
- the angular spread of arriving paths.

$$\tau_i'(t) = \frac{v}{c}\cos\theta_i$$

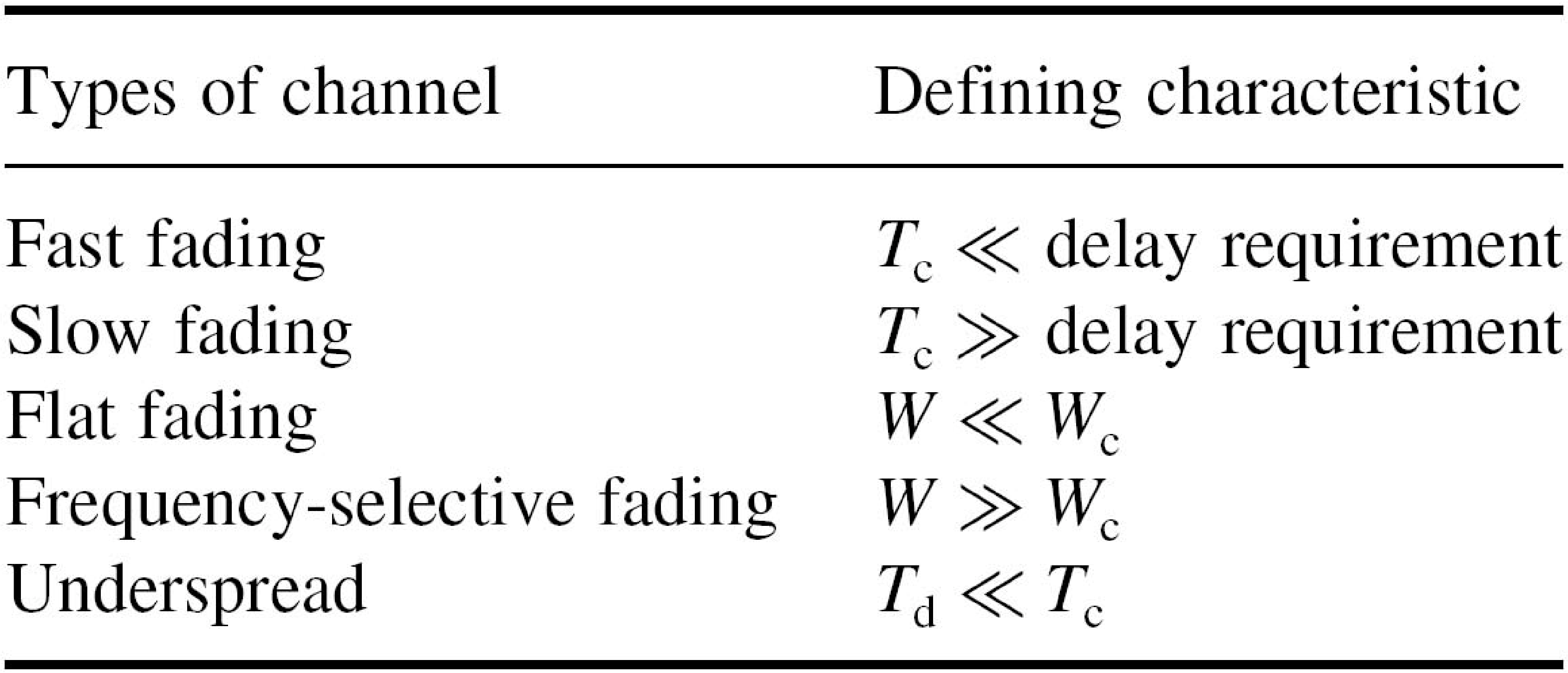
where θ_i is the angle the direction of motion makes with the i th path.

1: The Wireless Channel



Key channel parameters and time-scales	Symbol	Representative values
Carrier frequency	f_c	1 GHz
Communication bandwidth	W	1 MHz
Distance between transmitter and receiver	d	1 km
Velocity of mobile	v	64 km/h
Doppler shift for a path	$D = f_c v/c$	50 Hz
Doppler spread of paths corresponding to a tap	D_s	100 Hz
Time-scale for change of path amplitude	d/v	1 minute
Time-scale for change of path phase	$1/(4D)$	5 ms
Time-scale for a path to move over a tap	$c/(vW)$	20 s
Coherence time	$T_c = 1/(4D_s)$	2.5 ms
Delay spread	T_d	1 μs
Coherence bandwidth	$W_c = 1/(2T_d)$	500 kHz

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	$T_d \ll T_c$

Typical Channels are Underspread

- Coherence time T_c depends on carrier frequency and vehicular speed, of the order of milliseconds or more.
- Delay spread T_d depends on distance to scatterers, of the order of nanoseconds (indoor) to microseconds (outdoor).
- Channel can be considered as time-invariant over a long time scale.

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 .

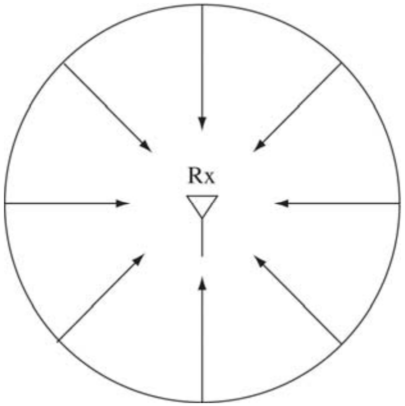
Squared magnitude is exponentially distributed.

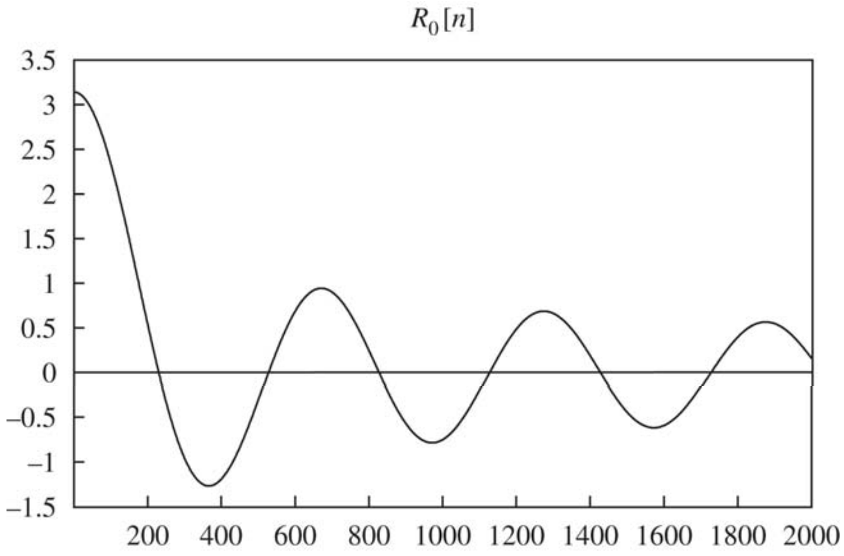
- Rician model: 1 line-of-sight plus scattered paths

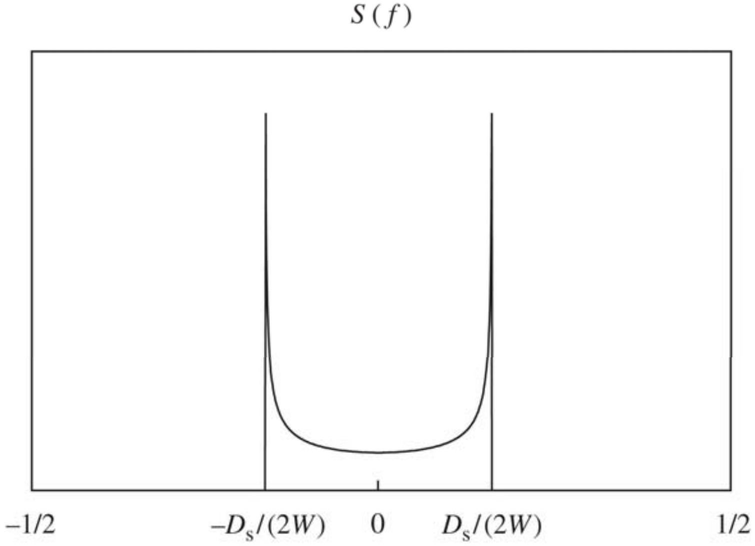
$$h[m] \sim \sqrt{\kappa} + \mathcal{CN}(0, 1)$$

Correlation over Time

- Specified by autocorrelation function and power spectral density of fading process.
- Example: Clarke’s (or Jake’s) model.







Additive Gaussian Noise

- Complete baseband-equivalent channel model:

$$y[m] = \sum_{\ell} h_{\ell}[m]x[m-\ell] + w[m]$$

$$w[m] \sim \mathcal{CN}(0, N_0)$$

- Special case: flat fading:

$$y[m] = h[m]x[m] + w[m]$$

- Will use this throughout these lectures.

Summary

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

- We have come up with statistical channel models that are useful for analysis and design.