Cooperative Communications and Networking

Chapter 1

Introduction

Outline

- **Wireless Channels**
  - **Additive White Gaussian Noise**
  - **Large Scale Propagation Effects**
  - **Small Scale Propagation Effects**
  - **Power Delay Profile**
  - **Uniform Scattering Environment Models**
  - **Other Channel Coefficients Models**
- **Characterizing Performance through Channel Capacity**
- **Orthogonal Frequency Division Multiplexing – OFDM**
- **Diversity in Wireless Channels**
  - **Time Diversity**
  - **Frequency Diversity**
  - **MIMO Systems**
- **Cooperation Diversity**

The Wireless Channel

- **Wireless channel introduces:**
  - **Noise (e.g. AWGN)**
  - **Attenuation**
  - **Distortion**
  - **Interference**

- **Additive White Gaussian Noise:**
  - **The relation between an output $y(t)$ and an input $x(t)$ for transmission over a channel with additive noise $n(t)$ is**

$$y(t) = \frac{x(t)}{\sqrt{\Gamma}} + n(t)$$

(Γ is the loss in power of the transmitted signal)

  - **The additive noise $n(t)$ is a random process with each realization modeled as a random variable with a Gaussian distribution.**

Large Scale Propagation Effects -Path Loss Γ_{dB}

$$\Gamma_{dB} = 10\nu \log(d/d_0) + c$$

- **Constant:** determined by system physical setup (e.g. signal wavelength, antennas height, etc.)

- **Distance to a power measurement reference point.**

- **Path loss exponent:**
  - characterizes the rate of decay of the signal power with the distance.
  - taking values in the range of 2 (propagation in free space) to 6.

- **Distance between transmitter and receiver.**

Shadowing

- **Attenuation due to the random presence of obstructions in the signal path.**

- **Path loss now becomes:**

$$\Gamma_{dB} = 10\nu \log(d/d_0) + \underset{\downarrow}{S} + c$$

- **Shadowing**

- **Shadowing:**
    - Zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (also measured in dB).
    - S is a random value that follows a log-normal distribution.

Small Scale Propagation Effects - Multipath Channels

- **Due to the presence of multiple random reflectors and scatterers during signal propagation.**
- **Observed as multiple copies of the signal arriving at the receiver at different times and with different power.**
- **The multiple copies of the transmitted signal, each having a different amplitude, phase and delay are added at the receiver creating either constructive or destructive interference.**
- **Due to the presence of motion at the transmitter, the receiver or the surrounding objects, the multipath channel changes over time.**

Small Scale Propagation Effects - Multipath Channels

- **Input-output relation at time t :**

$$y(t) = \sum_{i=1}^{L} h_i(t)x(t - \tau_i(t)),$$

- Number of resolvable paths
- Path delay
- Output
- Input
- Channel impulse response with delay $\tau_i(t)$

- **With $x(t) = \delta(t)$ the channel impulse response is:**

$$h(t,\tau) = \sum_{i=1}^{L} h_i(t)\delta(t - \tau_i(t)).$$

Small Scale Propagation Effects - Multipath Channels

- If it is safe to assume that the channel does not change over time, the received signal is:

$$y(t) = \sum_{i=1}^{L} h_i x(t - \tau_i).$$

- And the channel impulse response is:

$$h(t) = \sum_{i=1}^{L} h_i \delta(t - \tau_i).$$

Small Scale Propagation Effects - Multipath Channels

- **Discrete-time baseband-equivalent model of the channel:**

$$y[m] = \sum_{k=l}^{L} \underset{\downarrow}{h_k}[m]x[m-k].$$

- Channel coefficients

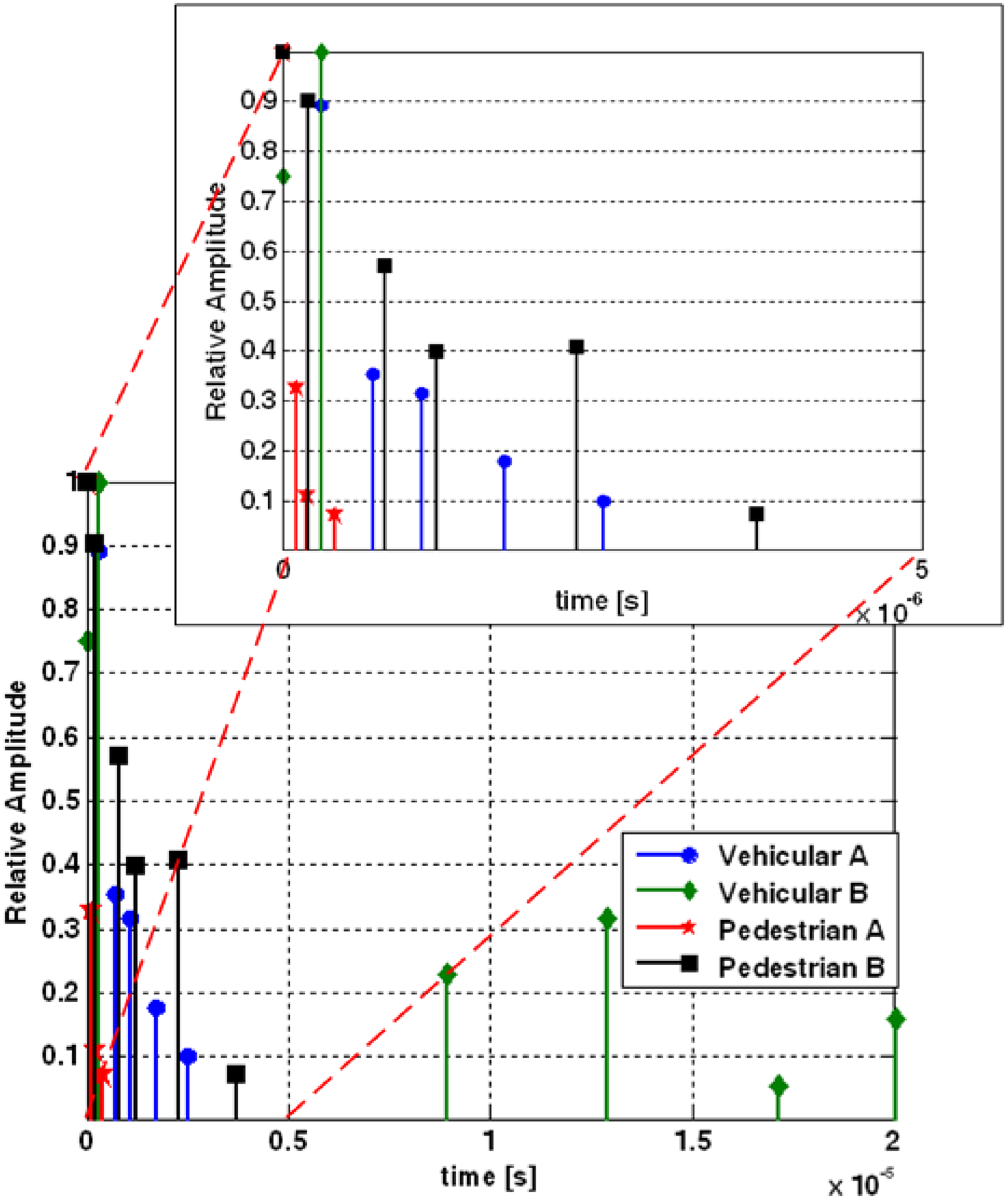
- **The model combines all the paths with arrival time within one sampling period into a single channel response coefficient** $h_k[m]$ **.**

- **Channel coefficients are random processes.**

Multipath Channels – Power Delay Profile

- **Power delay profile:** function determined by the average power associated with each path. Several parameters are derived from the power delay profile or its spectral response:
  - **Channel delay spread:** time difference between the arrival of the first measured path and the last. If the duration of the transmitted symbol exceeds the delay spread, then the symbols will suffer from *inter-symbol interference (ISI)*.
  - **Coherence bandwidth:** range of frequencies over which the amplitude of two spectral components of the channel response are correlated. The coherence bandwidth provides a measurement of the *range of frequencies over which the channel shows a flat frequency response (non-frequency selective)*, i.e. all the spectral components have approximately the same amplitude and a linear change of phase.

Multipath Channels - Examples

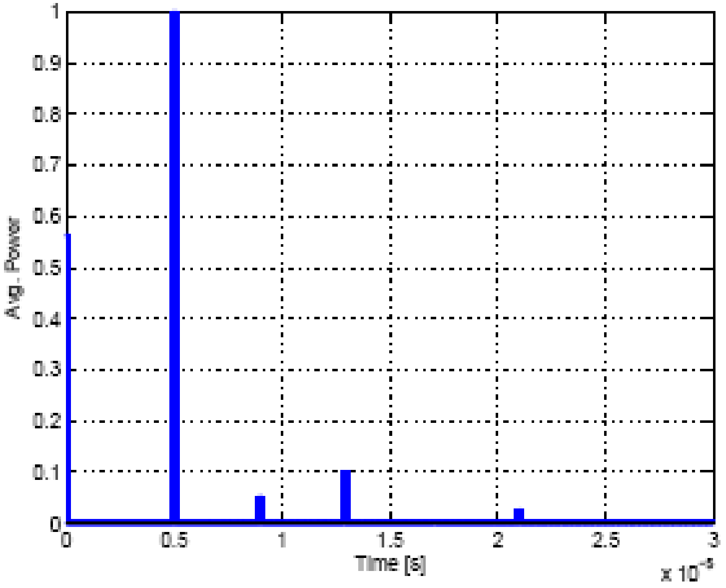


- Relative amplitude of the different paths for the multipath channels defined in the ITU recommendation M.1225

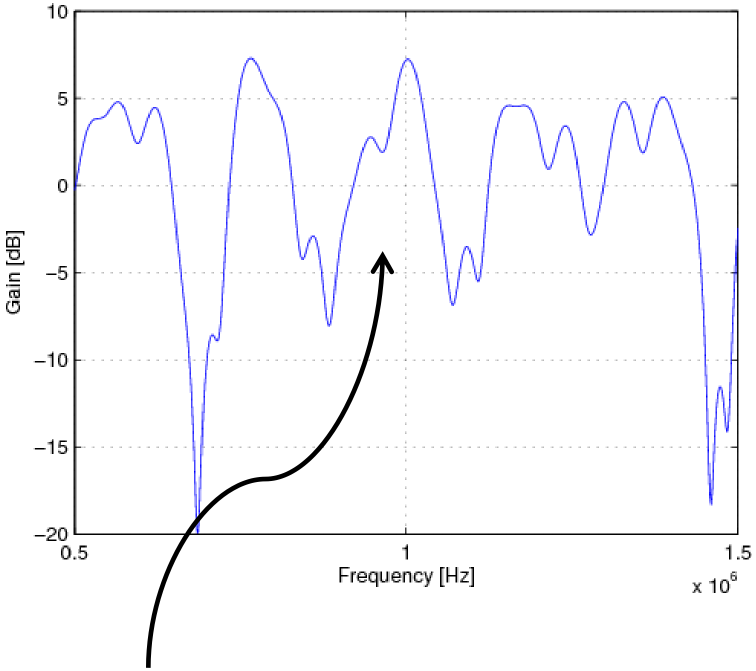
Multipath Channels - Classification

- **Depends** on both the **channel delay spread** and the **signal** being used during transmission.

Power delay profile



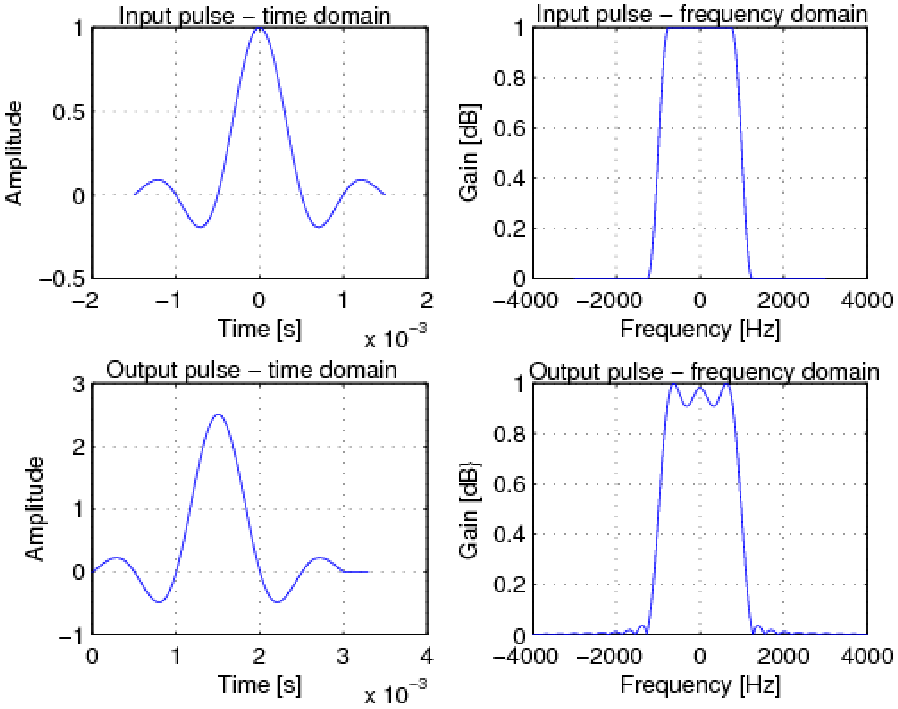
Section of spectral response



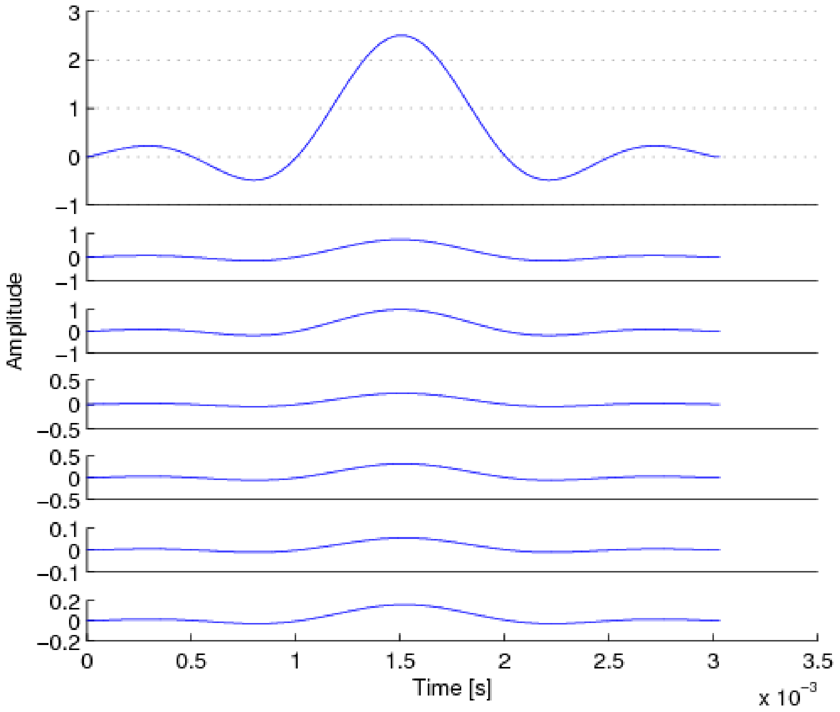
- Spectral components of the transmitted signal separated by more than a few tens of kHz will be affected differently by the channel.

Multipath Channels -Non-Frequency Selective (Flat) Channel

- **Transmitted pulse bandwidth less than the channel coherence bandwidth.**
- **The delay of some paths is much smaller than the symbol duration. There is no intersymbol interference (ISI).**



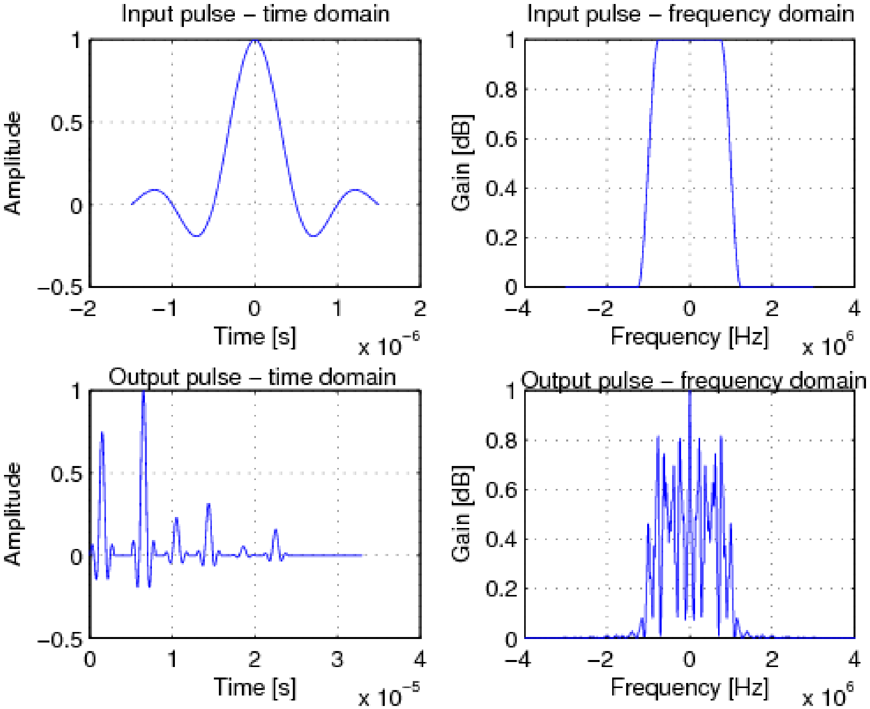
The input and output pulses to a non-frequency selective channel



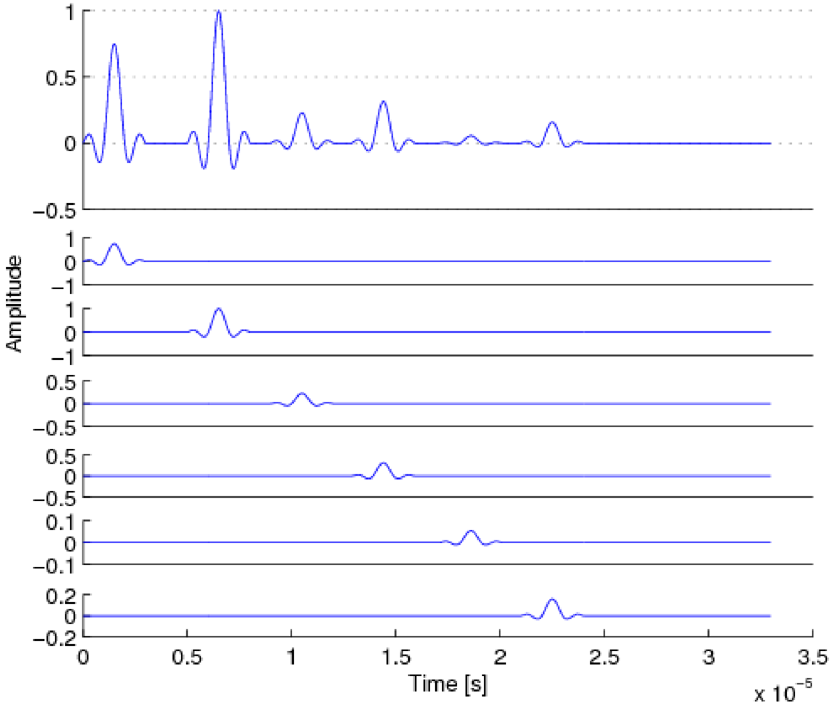
The pulse at the output of a non-frequency selective channel and each of the component pulses due to multipath

Multipath Channels - Frequency Selective Channel

- Transmitted pulse bandwidth exceeds the channel coherence bandwidth.
- The delay of some paths is larger than the symbol period. There is intersymbol interference (ISI)



The input and output pulses to a frequency selective channel



The pulse at the output of a frequency selective channel and each of the component pulses due to multipath

Multipath Channels – Doppler Shift Effect

- Introduced due to motion of transmitter, receiver or reflectors. Characterized in terms of *Channel Coherence Time*.

- **Channel coherence time:** time range over which the correlation between the average power associated with a given multipath delay at two different time instants is approximately zero.

- **Doppler power spectrum:** Fourier transform of the channel coherence time.

- **Doppler spread:** range of frequencies over which the Doppler power spectrum is non-zero.

Multipath Channels - Doppler Shift Effect

- **Doppler spread is the inverse of Channel coherence time.**

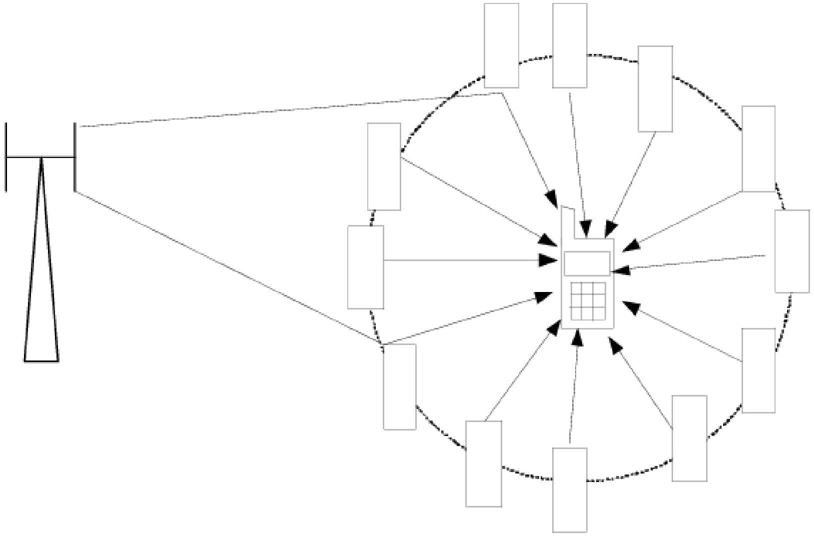
- **Slow fading channel:** if channel coherence time > transmitted signal symbol period. Equivalently if Doppler spread < signal bandwidth.

- **Fast fading channel:** if channel coherence time < transmitted signal symbol period. Equivalently if Doppler spread > signal bandwidth.

- **Characterization of random variations of the channel coefficients:**
    - Uniform scattering model (Rayleigh distribution).
    - Rician distribution.
    - Nakagami distribution.

Multipath Channels – Uniform Scattering Environment Model

- **In the model:**
  - **A waveform arrives at a receiver after being scattered on a very large number of scatterers.**
  - **The scatterers are assumed to be randomly located on a circle centered on the receiver.**
  - **There is no line-of-sight signal with a power notably larger than the rest.**
  - **The received waveform is made of the superposition of many waveforms arriving from the scatterers at an angle that is uniformly distributed between 0 and π.**



Multipath Channels - Uniform Scattering Environment Model

- **Received signal:** $y(t) = y_I(t)\cos(2\pi f_c t) + y_Q(t)\sin(2\pi f_c t)$

Carrier frequency

$$y_I(t) = \sum_{n=1}^{L} h_n(t)\cos(2\pi f_c \tau_n(t) - \varphi_n)$$

$$y_Q(t) = \sum_{n=1}^{L} h_n(t)\sin(2\pi f_c \tau_n(t) - \varphi_n)$$

  - Both the in-phase and the quadrature components of the received signal are composed of the superposition of multiple copies of the signal arriving with a change of amplitude and phase as determined by each of the channel paths.
  - From Central Limit Theorem: $y_I \sim \mathcal{N}(0, \sigma^2) \quad y_Q \sim \mathcal{N}(0, \sigma^2)$
  - Therefore, the magnitude of y(t) exhibits Rayleigh distribution.

Multipath Channels – Other Fading Models

- Rician fading model:
  - **There is one line-of-sight path (K=0, Rayleigh fading)**
  - **pdf for the envelope of channel coefficients is:**

$$f_r(z) = \frac{z}{\sigma^2} e^{-\left(\frac{z^2}{2\sigma^2}+K\right)} I_o\left(\frac{2Kx}{A}\right), \quad z \geq 0$$

where $I_0(x) = J_0(jx) = \frac{1}{2\pi}\int_0^{2\pi} e^{x\cos\theta}\, d\theta$

modified Bessel function of the first kind and zero order

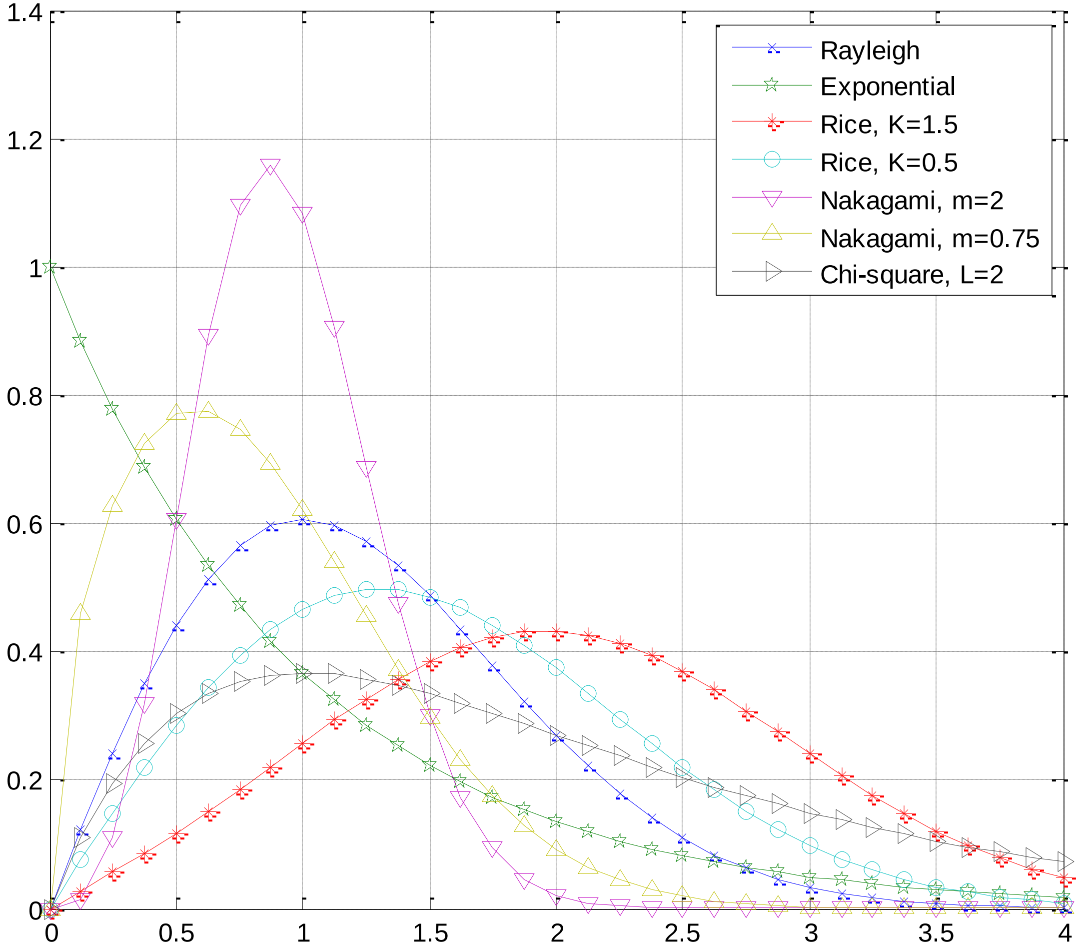
- Nakagami fading model:
  - **A probability density function that can be easily matched to data samples from practical chanels (m=1, Rayleigh fading)**
  - **pdf:**

$$f(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\sigma^{2m}} e^{-mx^2/\sigma^2}, \quad m \geq 1/2$$

Gamma function

parameter used to adjust the pdf to data samples

Multipath Channels - pdf Plot for Different Distributions



Characterizing Performance through Channel Capacity

- **Information** provided by the outcome x of a discrete random variable X:

$$I_X(x) = \log \frac{1}{P[X=x]} = -\log P[X=x]$$

- **Mutual information** – Information shared by two random variables:

$$I(X;Y) = \sum_{x \in X} \sum_{y \in Y} P[X=x, Y=y] \log \frac{P[X=x, Y=y]}{P[X=x]P[Y=y]}$$

- **Entropy** - mean value of the information provided by all the outcomes of a random variable: $H(X) = -\sum_{x \in X} P[X=x] \log P[X=x]$

- **Conditional Entropy** - mean value of the information provided by all the outcomes of a random variable (X) given the outcome of a second random variable (Y). Also, how much uncertainty about a random variable (X) remains after knowing the outcome of a second random variable (Y) :

$$H(X|Y) = -\sum_{x \in X} P[X=x, Y=y] \log P[X=x|Y=y]$$

Channel Capacity

- **Ergodic or Shannon Capacity:** applicable when
  - random variations of the channel are a stationary and ergodic process AND
  - long blocks are used for coding.

- **For AWGN channel with flat fading, where only the receiver has knowledge of the channel state:**

$$C = E[\log(1 + \frac{|h|^2 P}{N_0})]$$

- **Outage Capacity:** applicable when the assumptions required by Shannon capacity do not hold

Outage Capacity

- **Outage event:** set of channel realizations that cannot support reliable transmission at a rate R . Equivalently, is the set of channel realizations with an associated capacity less than a transmit rate R .

- **Outage condition for a realization of the fading:**

$$\log\left(1 + \frac{|h_i|^2 P}{N_0}\right) < R.$$

- **Outage probability:**

$$P_{out} = \mathsf{P}\left[\log\left(1 + \frac{|h|^2 P}{N_0}\right) < R\right]$$

- P_{out} **Outage Capacity:** information rate that can be reliably communicated with a probability $1 - P_{out}$

$$\mathsf{P}[C \leq C_{out}] = P_{out}.$$

Shannon capacity

Outage capacity

Orthogonal Frequency Division Multiplexing - OFDM

- **OFDM is a form of *multicarrier modulation*.**
- ***Multicarrier modulation* combats the effects of a frequency selective channel by dividing the *high bandwidth* signal to be transmitted over multiple mutually *orthogonal* signals of a *bandwidth small* enough such that the channel appears as *non-frequency selective*.**
- **In OFDM, the orthogonal signals used for multicarrier modulation are truncated complex exponentials:**

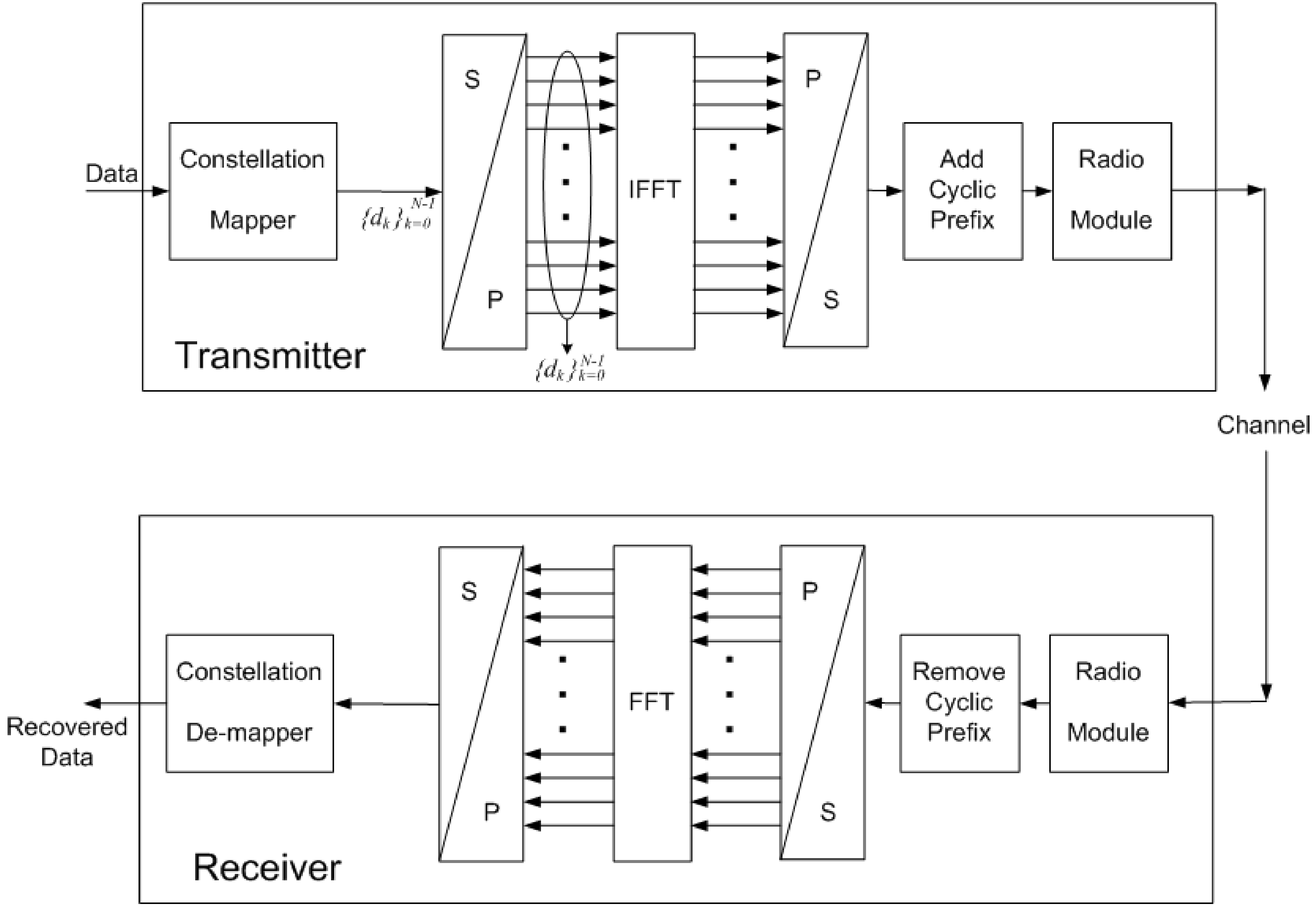
$$\phi_k(t) = \begin{cases} e^{j2\pi f_k t} & \text{if } 0 \leq t \leq T_s \\ 0 & \text{else.} \end{cases}$$

- **An OFDM symbol:**

$$s(t) = \sum_{k=0}^{N-1} d_k \phi_k(t) = \sum_{k=0}^{N-1} d_k e^{j2\pi f_k t},$$

where $\{d_k\}_{k=0}^{N-1}$ are the N complex symbols that are input to the OFDM modulator.

OFDM Transmitter and Receiver Block Diagram



Diversity in Wireless Channels

- **Diversity Techniques:** techniques that aim at providing multiple, ideally independent, signal paths.

Why?
By providing more than one copies of signal information between source and destination, the overall reliability of the link can be significantly improved.

How?
By constructively combining the received signals from multiple sources of signal copies.

Maximum Ratio Combiner (MRC): linearly combines the signals so that the SNR is maximized at the resulting signal.

$$y_M = \sum_{k=0}^{L-1} c_k e^{-j\phi_k} y_k,$$

signal sample from each path.

co-phasing factor.

MRC coefficients: $c_k = \frac{h_k}{\sqrt{N_o}}$

Path envelope

Noise power density

Diversity Gain

- **Diversity gain:**

$$m = -\lim_{\gamma\to\infty}\frac{\log P_{SER}}{\log \gamma}$$

Probability of symbol error

channel SNR

- **Diversity gain: the larger, the better since it means that probability of symbol error is reduced at a faster rate.**

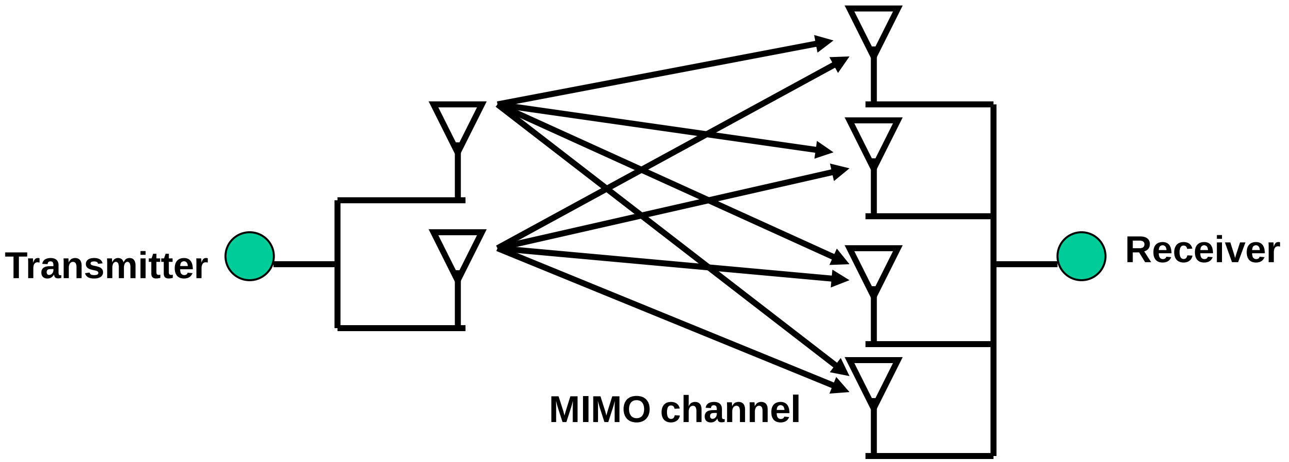
Diversity Techniques

- **Time Diversity**:
  - Used in cases where the channel coherence time equals or exceeds several symbol transmission periods.
    - This implies that two symbols transmitted with a separation in time longer than the coherence time will experience channel realizations that are highly uncorrelated and can be used to obtain diversity.
    - Diversity gain could equal the number of times a data symbol is repeated.

- **Frequency Diversity**:
  - Analogous to time diversity but now by using channels that are a partition of the available bandwidth and that are separated by more than the channel coherence bandwidth.
  - Used in those wideband systems where the available bandwidth exceeds the channel coherence bandwidth.

MIMO Diversity

- **A MIMO system is one where both transmitter and receiver have multiple antennas**



- **The signal present at each receive antenna is the combination of signals from the transmit antennas after each having traveled through their different fading channel.**

MIMO Diversity

- **MIMO performance improvement:**
  - **Antenna gain:** increase in average received SNR by achieving coherent combining of received signals.
  - **Interference reduction:** shaping of the energy emitted to each receiver in such a way that most of the energy is useful and not interference.
  - **Diversity gain:** taking advantage of the multiple channels between the transmitter and receiver and combine the differently-affected signals in such a way that resulting signal shows better quality and less amplitude variability.
  - **Spatial multiplexing:** transmit independent data signals though each transmit antennas, which can be separated at the receiver through MIMO.

Capacity of MIMO Systems

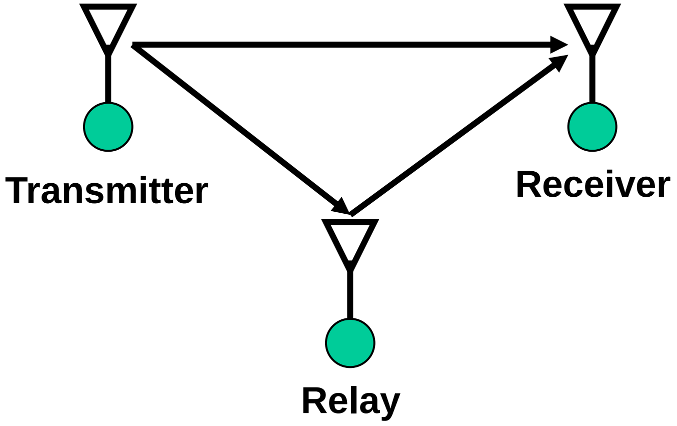
- **Notation:**
  - Number of transmit antennas M_t
  - Number of receive antennas M_r

- **Channels with flat fading, known at receiver only:** ergodic capacity can be found by averaging over the fading realizations. At High SNR:

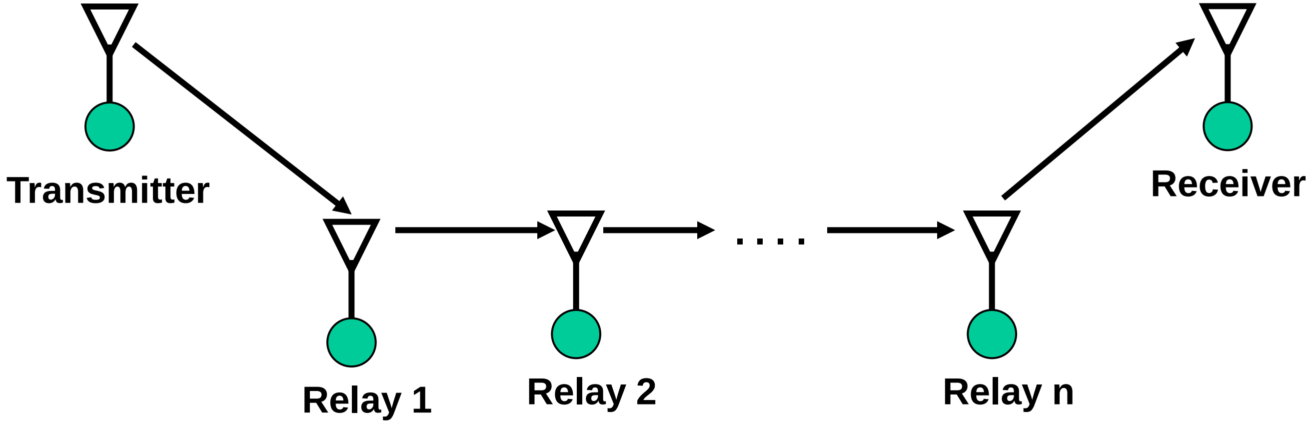
$$C = \min(M_r, M_t)\log_2 \underset{\downarrow\ \text{SNR}}{\gamma} + \mathcal{O}(1),$$

Relay Channel

- **What is it:** a three-terminal network where, in addition to the usual transmitter and receiver nodes, there is an extra node named the relay node.
- **Importance:** First to introduce idea of relay, ancestor of user cooperation.

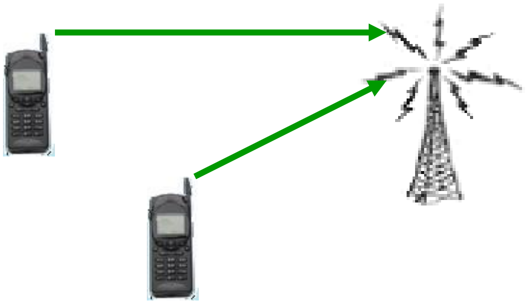


- **Multihop channel:** a multi-relay network where there is no direct path between transmitter and receiver.



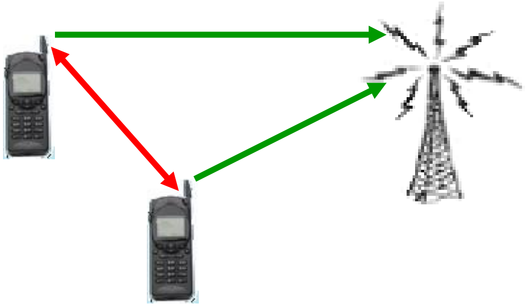
User-Cooperation Communications: a New Paradigm

- **Traditional peer-to-peer networks:**



- **Most of the transmitted power (energy) is not received at the destination antenna.**
- **Mobility / size / complexity constraints prevent the use of directional or multiple antenna at transmitters.**

- **User-cooperative networks:**



- **Take advantage of broadcast nature of wireless communication.**
- **Associate users so that they collaborate in forwarding information for each other over different paths.**