Communication Concepts

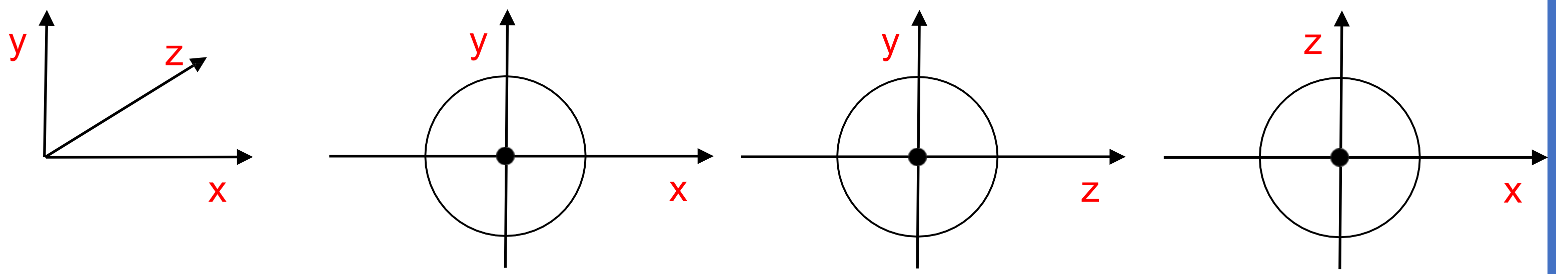
Antenna – The Isotropic Radiator

- Antenna
  - couples wires to space, for electromagnetic (EM) wave transmission or reception

- Radiation pattern
  - pattern of EM radiation around an antenna

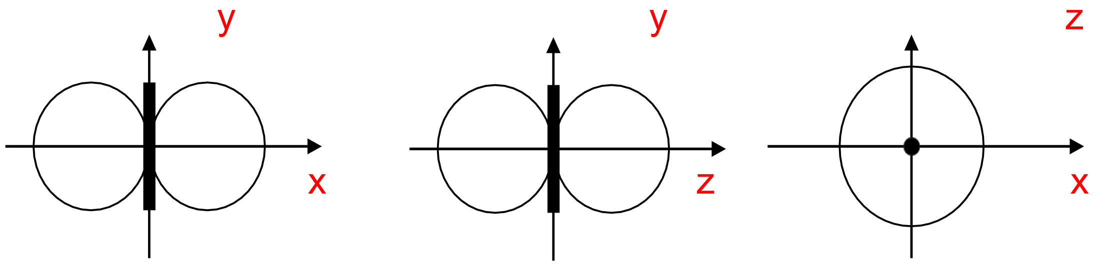
- Isotropic radiator
  - » equal radiation in 3 directions (**x**, **y**, **z**)
  - » theoretical reference antenna

Isotropic radiator

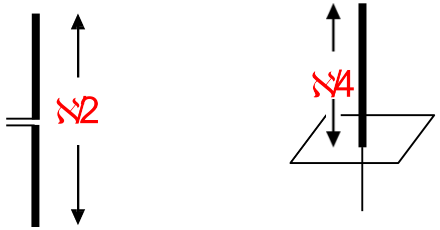


Antennas - Simple Dipoles

- Real antennas are **not** isotropic radiators
- Simple antenna dipoles
  - » Length H/2: Hertzian dipole
  - » Length H/4: on car roofs
- Shape of antenna proportional to H

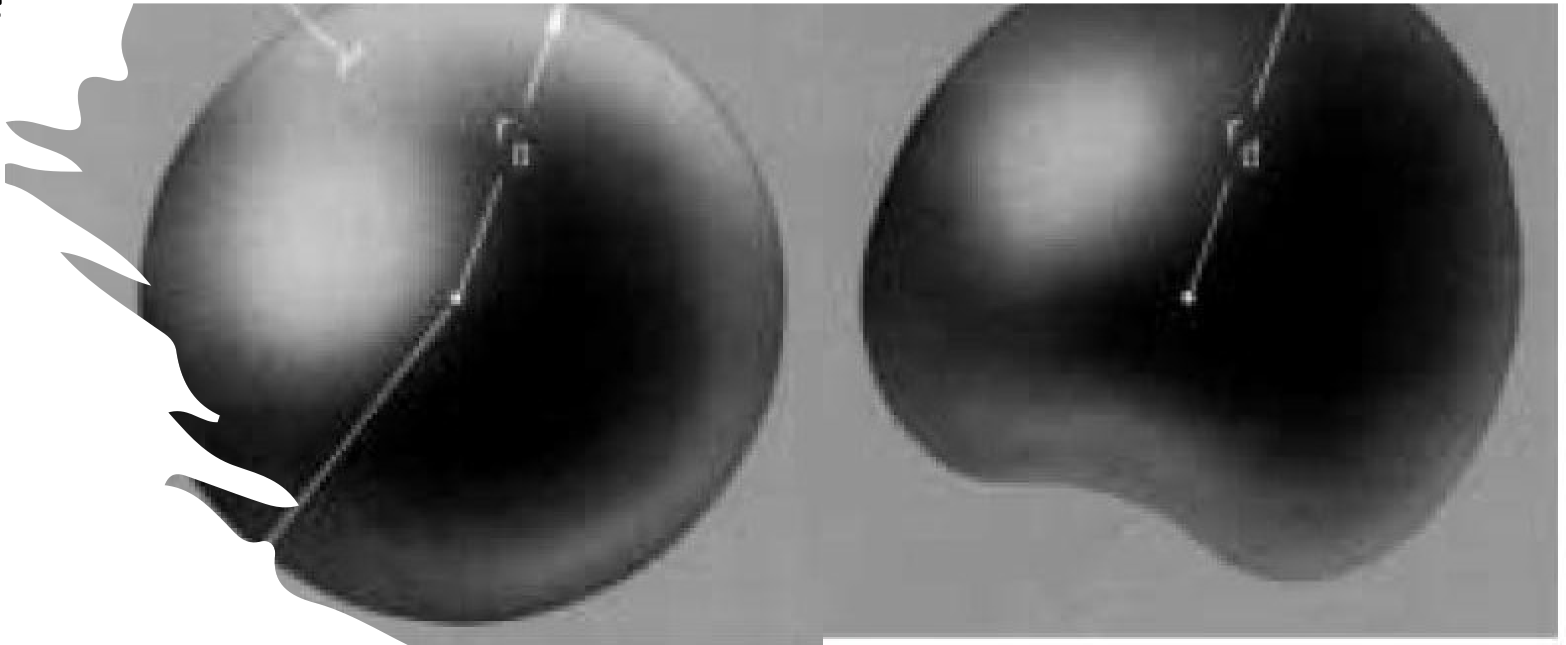


- Radiation pattern of a simple Hertzian dipole



Antenna Gain, EIRP

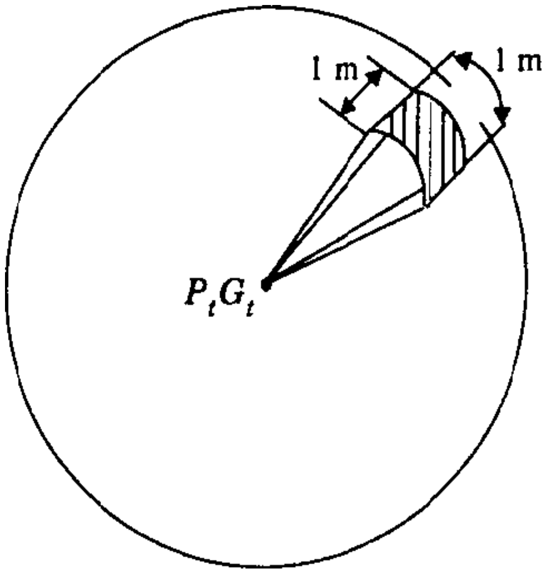
- Antenna Gain
  - maximum power in direction of the main lobe (P_{main_lobe}), compared to power of an isotropic radiator (P_t) transmitting the same average power baloon
- *Effective Isotropic Radiate Power (EIRP)*
  - $EIRP = P_t\, G_t$
  - Maximum radiated power in the direction of maximum antenna gain



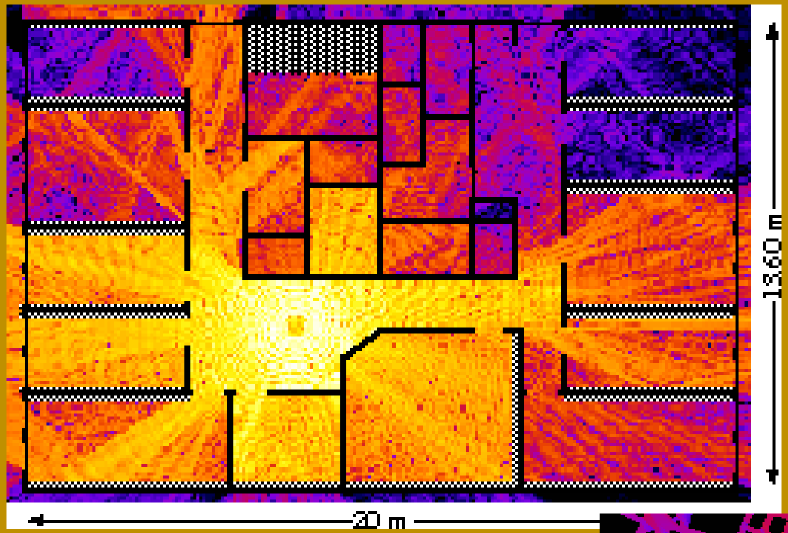
Received Power at Distance d: $P_r(d)$

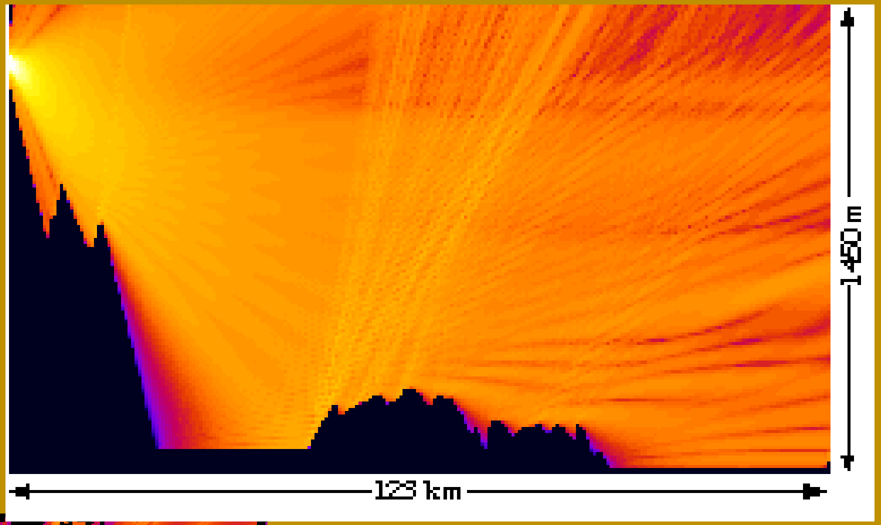
- Depends on Power flow density $\boldsymbol{P_d}$ (W/m²)

$$P_d = \frac{EIRP}{4\pi d^2}$$



Real World Examples





Transmit and Receive Signal Models

- Transmitted signal modeled as

$$
\begin{aligned}
s(t) &= \Re\left\{u(t)e^{j2\pi f_c t}\right\} \\
&= \Re\{u(t)\}\cos(2\pi f_c t) - \Im\{u(t)\}\sin(2\pi f_c t) \\
&= s_I(t)\cos(2\pi f_c t) - s_Q(t)\sin(2\pi f_c t)
\end{aligned}
$$

- The received signal

$$
r(t) = \Re\left\{v(t)e^{j2\pi f_c t}\right\},
$$

- if *s(t)* is transmitted through a time-invariant channel ***c*** then

$$
v(t) = u(t) * c(t), \qquad V(f) = H_l(f)U(f).
$$

where

» $c(t)=h_l(t)$ is the equivalent lowpass impulse response of the channel

» $H_l(f)$ is the equivalent lowpass frequency response of the channel

Doppler Frequency Shift

- The received signal may have a Doppler shift of

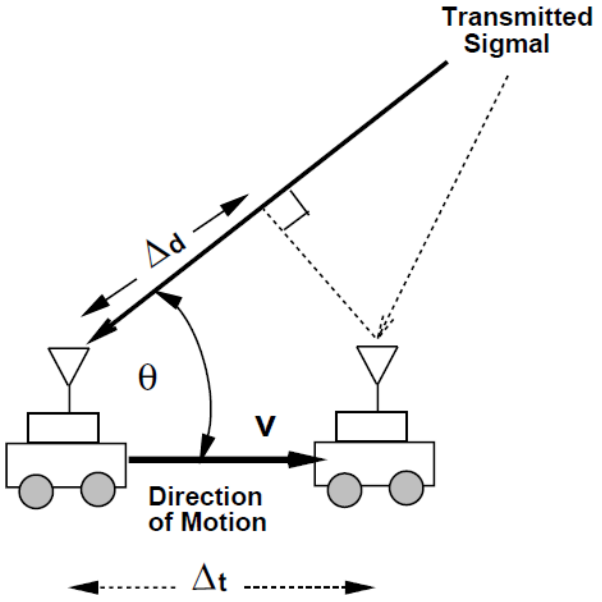
$$\Delta d = v\Delta t \cos\theta$$

$$\Delta\phi = 2\pi\frac{\Delta d}{\aleph} = 2\pi\frac{v\Delta t\cos\theta}{\aleph}$$

- Doppler frequency, f_D

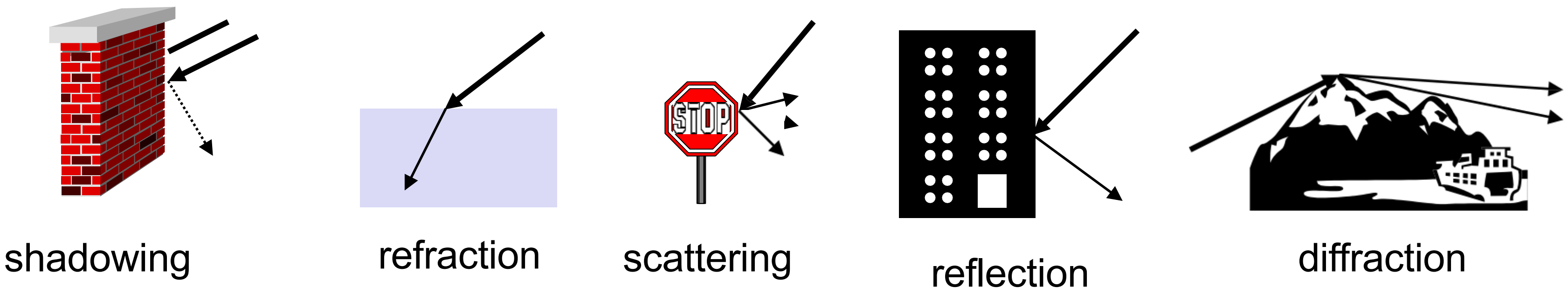
$$\Delta\phi = 2\pi f_D \Delta t$$

$$f_D = \frac{1}{2\pi}\frac{\Delta\phi}{\Delta t} = v\cos\theta/\lambda$$



Signal Propagation – Key Concepts

Propagation often modeled as rays (light)	
Line-of-Sight (LOS) – direct ray receiver gets from transmitter	
Relevant concepts	» Shadowing, Reflection è caused by objects much larger than the wavelength » Refraction è caused by different media densities » Scattering è caused by surfaces in the order of wavelengths » Diffraction è similar to scattering; deflection at the edges



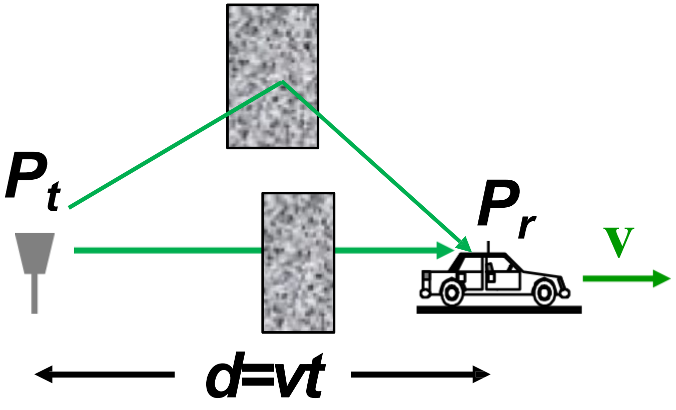
Signal Propagation and Wireless Channels

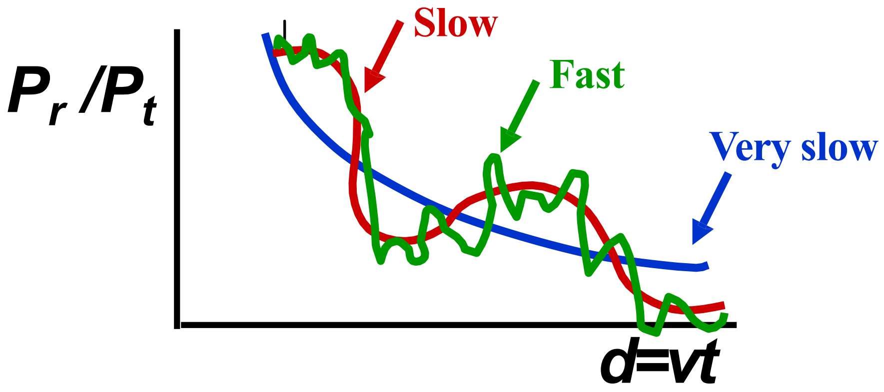
Received Power can be influenced by 3 factors

- **Path loss**
  - **Dissipation of radiated power**; depends on the sender-receiver distance
- **Shadowing**
  - caused by the obstacles between the transmitter and the receiver
  - attenuates the signal
- **Multipath**
  - constructive and destructive **addition of multiple signal components**

Path Loss Models

- Free space path loss model
  - Too simple
- Ray tracing models
  - Demand site-specific information
- Empirical models
  - Do not generalize to other environments
- Simplified model
  - Good for high-level analysis





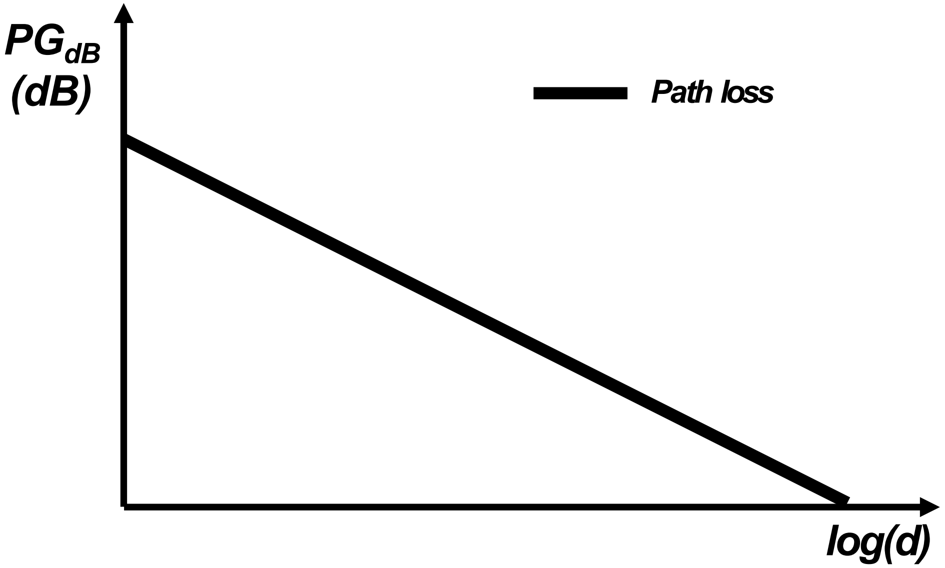
Path Loss - Free Space (LOS) Model

- Path loss (PL) for unobstructed LOS path
- Power falls off
  - » Proportional to $1/d^2$
  - » Proportional to $\aleph$ (inversely proportional to f^2)

$$P_r/P_s = \left[\frac{\lambda\sqrt{G_l}}{4\pi d}\right]^2 \qquad G_l = \sqrt{G_s G_r}$$

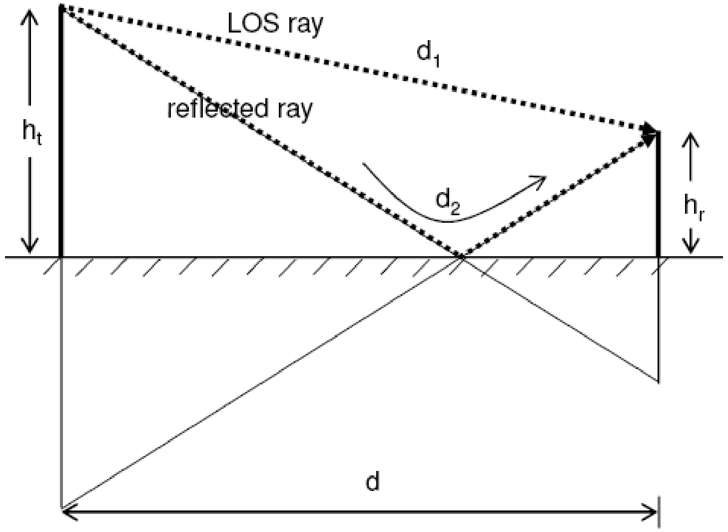
$$PG_{dB} = 10\ log(Pr/Ps)$$

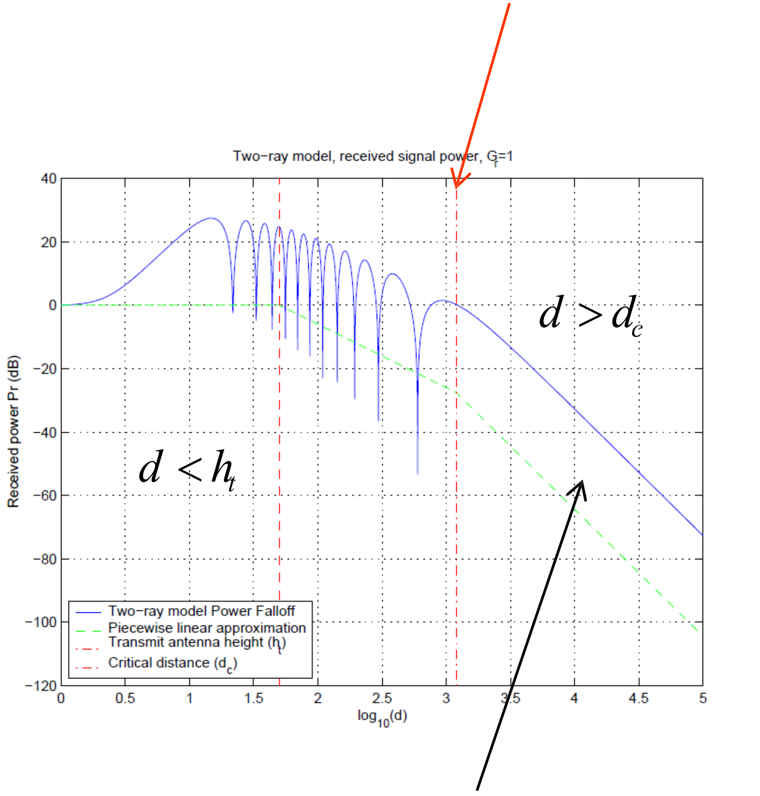
$$PG_{dB} = 20.\log\left(\frac{\aleph\sqrt{G_l}}{4\pi}\right) - 20.\log(d)$$



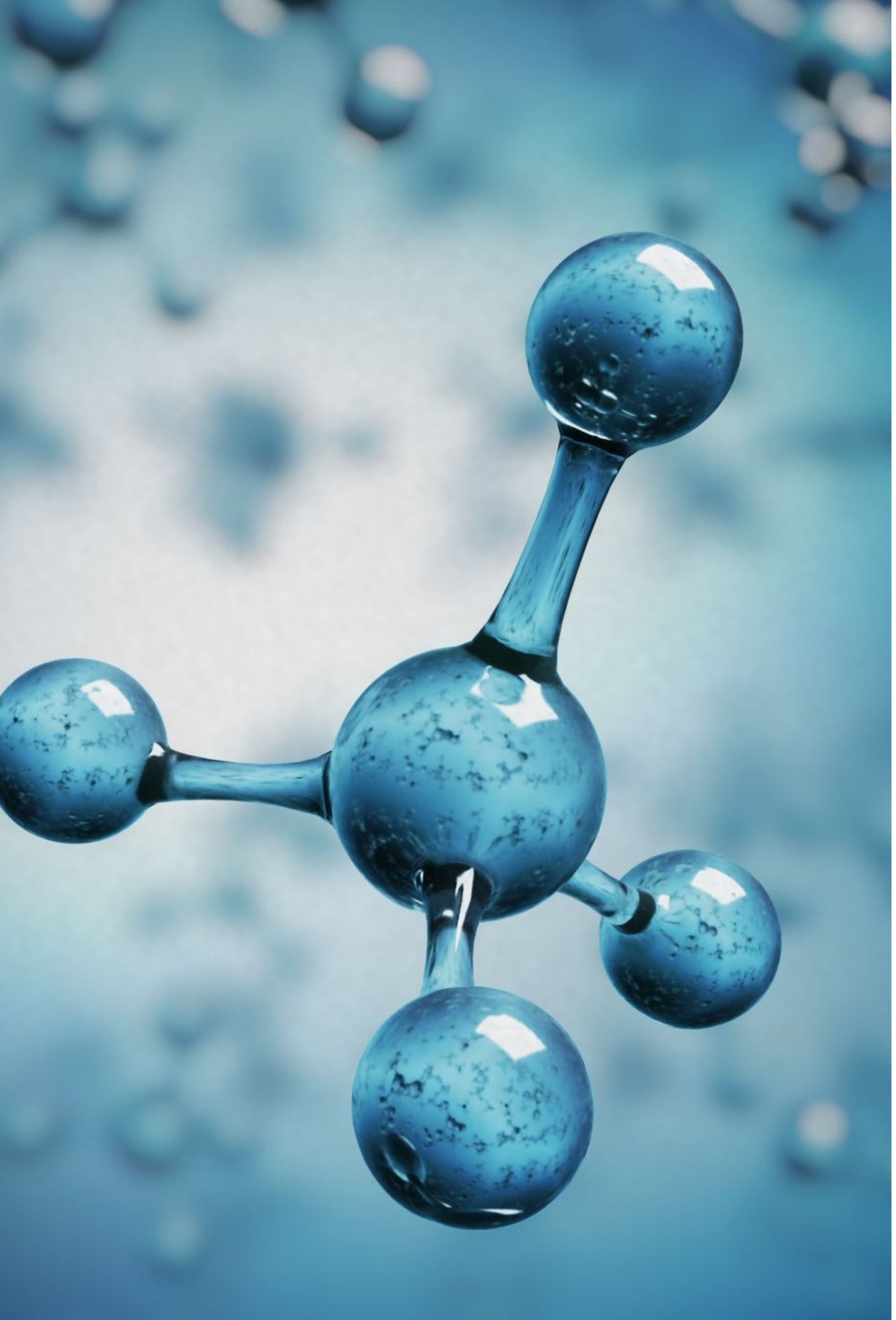
Example of More Complex Path Loss – Two-Ray Model

- One LOS ray + one ray reflected by ground
- Ground ray cancels LOS path above critical distance $d_c=4h_th_r/\lambda$
- Power falls off
  - » Proportional to d^2 ($h_t < d < d_c$)
  - » Proportional to d^4 ($d > d_c$)





$$P_r \text{ dBm} = P_t \text{ dBm} + 10\log_{10}(G_l) + 20\log_{10}(h_t h_r) - 40\log_{10}(d)$$



Path – Loss Empirical Models

- Okumura model
  - » Empirically based (site/freq specific); 150-1500 MHz, Tokyo
  - » Empirical plots
- Hata model
  - Analytical approximation to Okumura model
- Cost 231 Model
  - Extension Hata model to higher frequency (1.5 GHz < f_c < 2 GHz)
- Walfish/Bertoni
  - Extends Cost 231 to include diffraction from rooftops

Path Loss – Indoor Factors

Partition	Loss (dB)
hollow brick	8
concrete wall	13
aluminum siding	20
window	6
floor	10

- Walls, floors, layout of rooms, location and type of objects
- » Impact on the path loss
- » The losses introduced **must be added** to the free space losses

Path Loss - Simplified Model

- Used when path loss is dominated by reflections

$$P_r = P_s K \left(\frac{d_0}{d}\right)^{\psi}, \qquad 2 \leq \psi \leq 8$$

$$P_{r_{dBm}} = P_{s_{dBm}} + K_{dB} - 10\ \gamma\ log\left[\frac{d}{d_0}\right]$$

$$d_0 \approx 1.0\ \aleph$$

Environment	γ
Urban macrocells	3.7 - 6.5
Urban microcells	2.7 - 3.5
Office building	1.6 - 3.5
Store	1.8 - 2.2
Factory	1.6 - 3.3
Home	3

- Constant K
  - » determined by measurement at $d = d_0 \Rightarrow \quad K_{dB} = P_{r_{dBm}} - P_{s_{dBm}}$
  - » or, $K_{dB} = 10\ log\left[\frac{\lambda}{4\pi d_0}\right]^2$
- Path loss exponent ψ is determined empirically

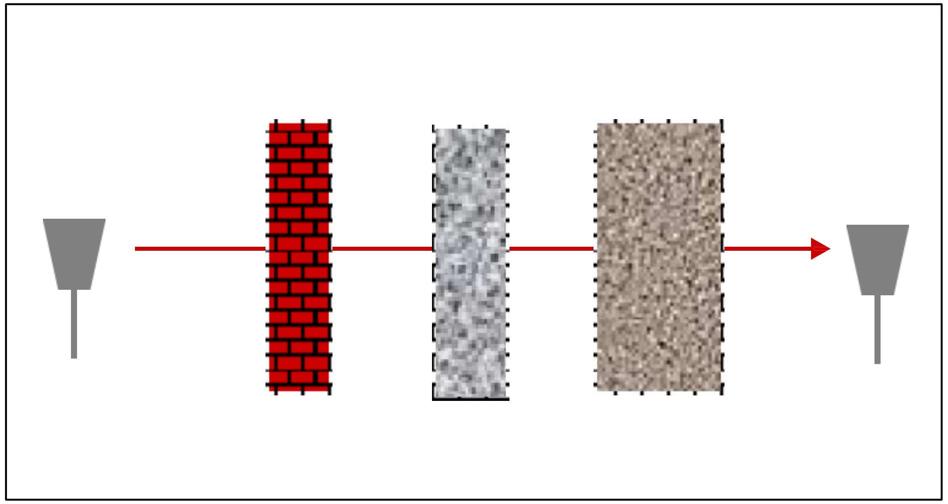
Obstructions

- Models attenuation introduced by obstructions
- Random due to random number and type of obstructions ➔ ψ

$$\left(\frac{P_r}{P_s}\right)_{dB} = 10\ logK - 10\gamma\ log\frac{d}{d_0} - \psi_{dB}$$

where ψ_{dB} is a Gaussian distributed random variable

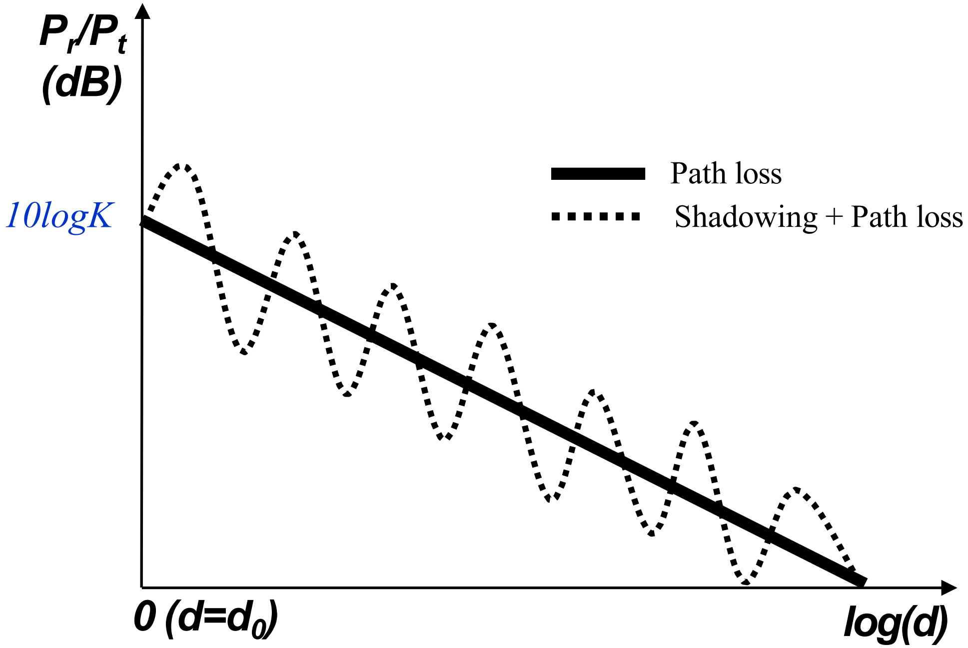
characterized by $\mu_{\psi_{dB}} = 0$ and $\sigma_{\psi_{dB}}$



Combined Path Loss and Shadowing

$$\frac{P_r}{P_s}(dB) = 10\log_{10} K - 10\psi\log_{10}\left(\frac{d}{d_0}\right) - \psi_{dB},$$

$$\psi_{dB} \sim N(0, \sigma_\psi^2)$$

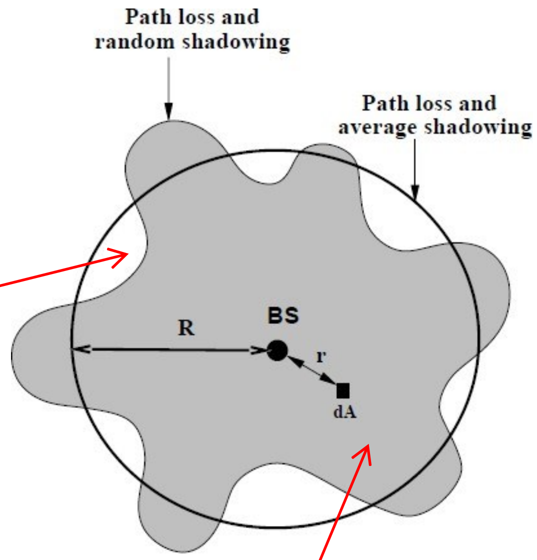


Outage Probability and Cell Coverage Area

- Path loss model ➔ circular cells
- Path loss + shadowing ➔ amoeba cells

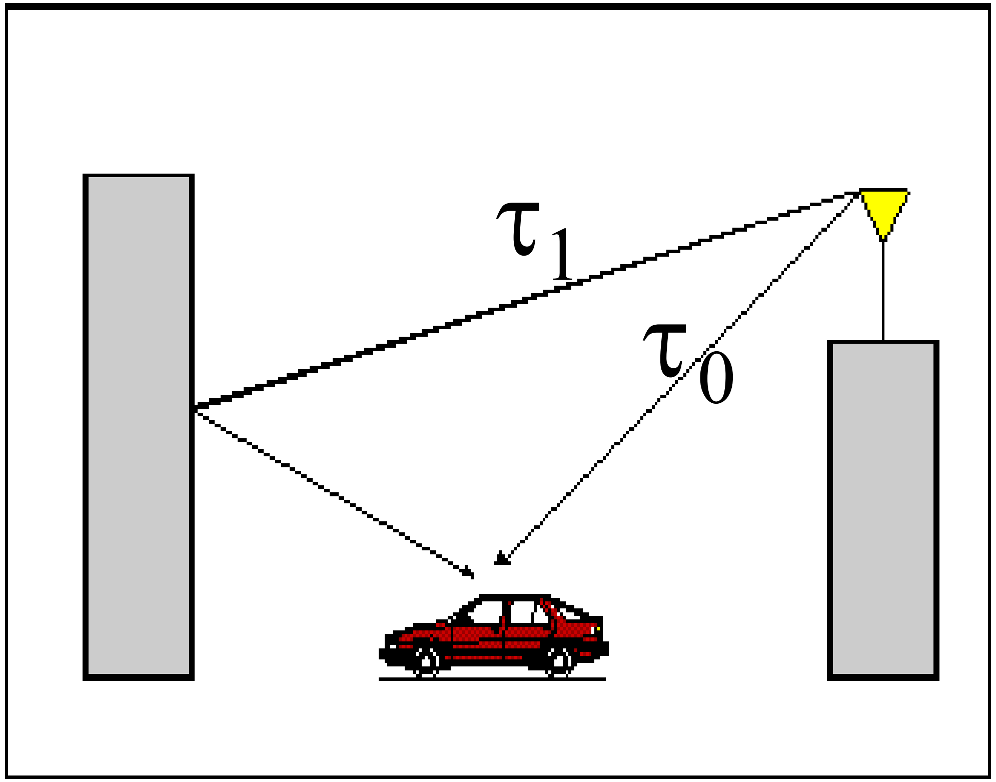
  tradeoff between coverage and interference
- Outage probability

  Probability received power below given minimum
- Cell coverage area ➔ % of cell locations at desired power
  - » Increases as shadowing variance (σ_ψ) decreases
  - » Large % indicates interference to other cells



Statistical Multipath Model

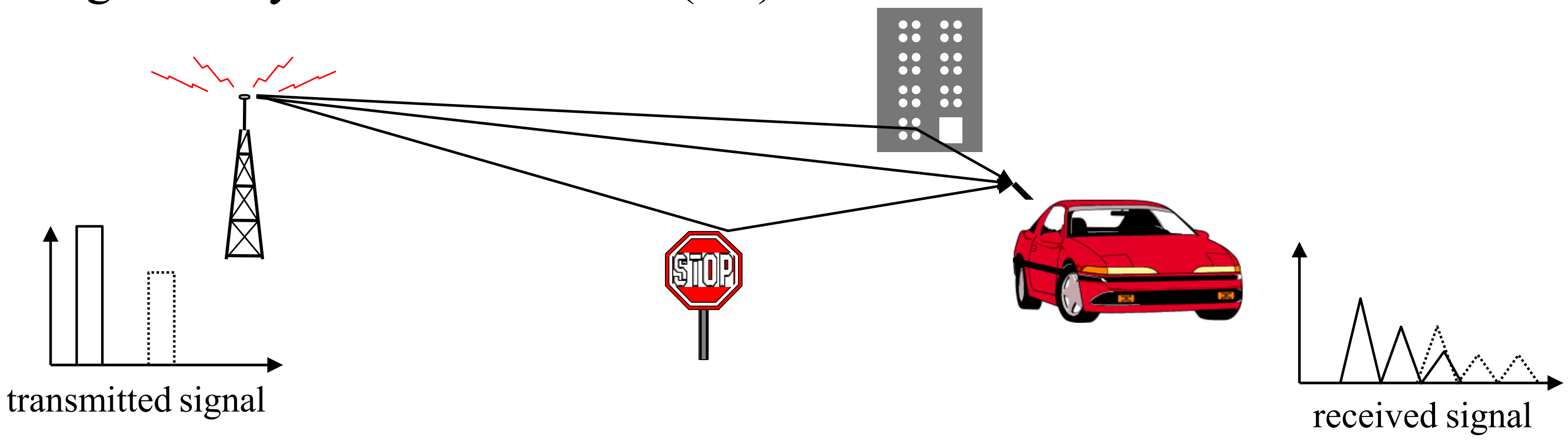
- Multipath → multiple rays
  - » multiple delays from transmitter to receiver → τ_i
  - » time delay spread $T_m = max_n|\tau_n - \tau_0|$
- Multipath channel has a time-varying gain
  - » caused by the transmitter / receiver movements
  - » location of reflectors which originate the multipaths



Multipath – Wideband Channel

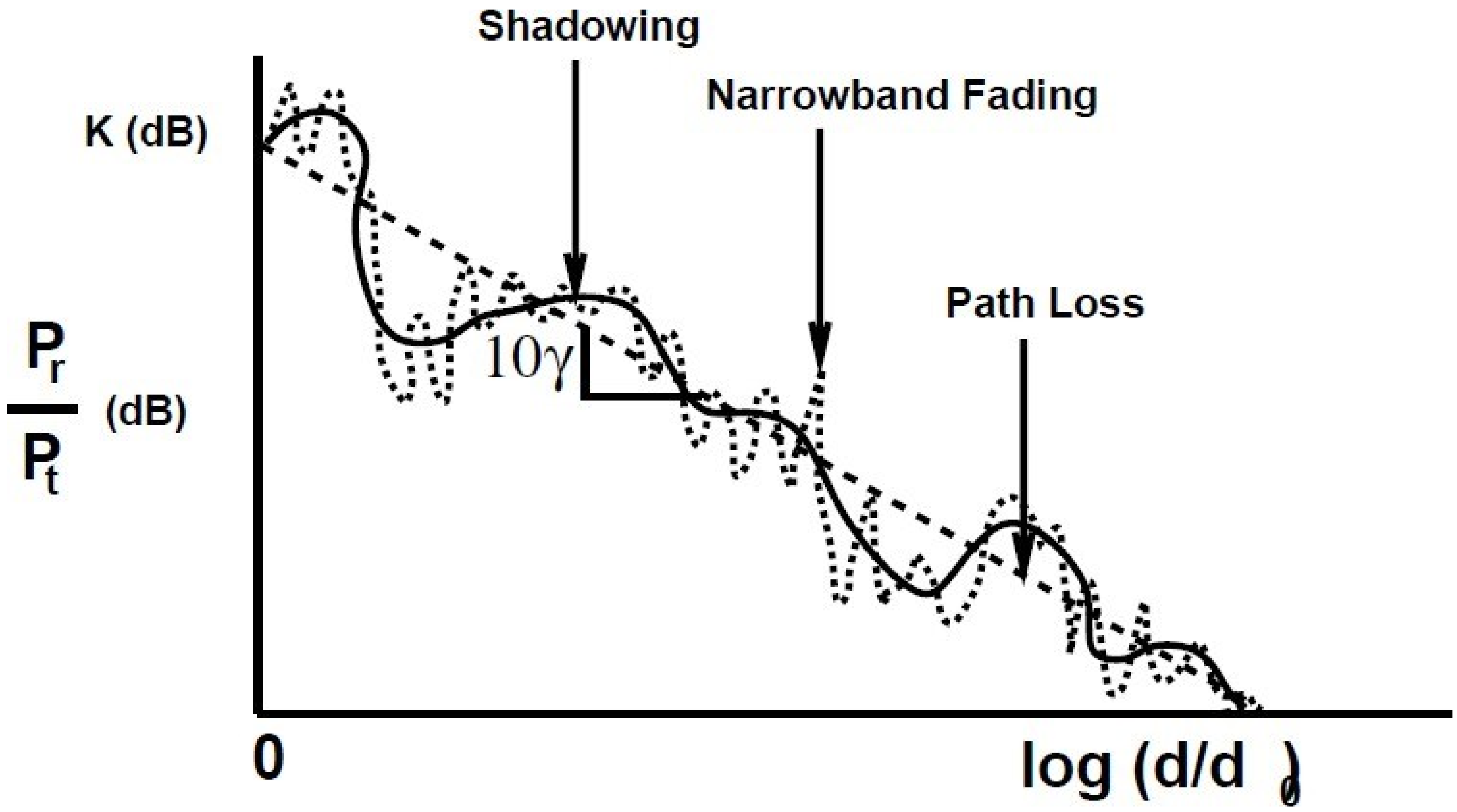
$$T_m = \max_n |\tau_n - \tau_0|, \quad T_m >> B^{-1}$$

- Multipath components
  - » may arrive at the receiver within the time period of the next symbol
  - » causing Inter-Symbol Interference (ISI).



- Techniques used to mitigate ISI
  - » multicarrier modulation
  - » spread spectrum

Multipath + Shadowing + Path Loss



Bit Rate of a Wireless Channel

- Assuming **A**dditive **W**hite **G**aussian **N**oise (AWGN)
  - » Given by Shannon´s law

$$C = B\ log_2(1+\gamma)\ \text{(bit/s)}$$

$$\gamma = P_r/(N_0 B)$$

N_0 – Noise power spectral density

- Capacity in a fading channel (shadowing + multipath)

  ➔ usually smaller than the capacity of an AWGN channel

Digital Modulation/Demodulation

- Modulation: maps information bits into an analogue signal (carrier)
- Demodulation: determines the bit sequence based on received signal

- Two categories of digital modulation
  - **Amplitude modulation - $\alpha(t)$ / Phase modulation - $\theta(t)$**
  - Frequency modulation - $f(t)$

- Modulated signal $s(t)$ $s(t) = \Re\{u(t)e^{j(2\pi f_c t)}\}$

$$s(t) = \alpha(t)\cos[2\pi(f_c + f(t))t + \theta(t) + \phi_0] = \alpha(t)\cos(2\pi f_c t + \phi(t) + \phi_0)$$

$$s(t) = \alpha(t)\cos\phi(t)\cos(2\pi f_c t) - \alpha(t)\sin\phi(t)\sin(2\pi f_c t) = \boxed{s_I(t)\cos(2\pi f_c t) - s_Q(t)\sin(2\pi f_c t)}$$

$$u(t) = s_I(t) + j s_Q(t)$$

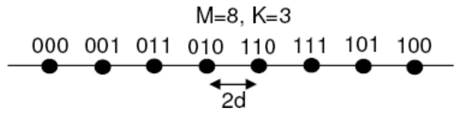
- Signal trasmited over time symbol ***i*** → ***$s_i(t)$***

Amplitude and Phase Modulation

- $K = log_2 M$ bits sent over a time symbol interval
- Amplitude/phase modulation can be:
  - » Pulse Amplitude Modulation (MPAM)

    information coded in amplitude

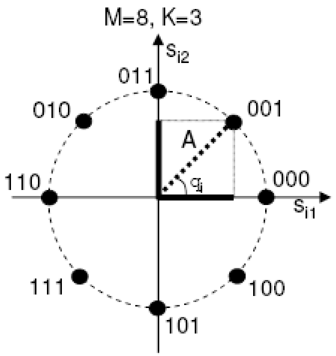
    $$\text{MPAM - } s_i(t) = Re\left\{A_i \; g(t)e^{j2\pi f_c t}\right\}$$



  - » Phase Shift Keying (MPSK)

    information coded in phase

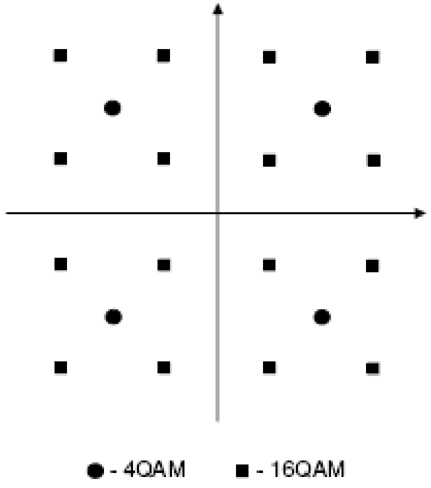
    $$\text{MPSK - } s_i(t) = Re\left\{A \; g(t)e^{j\theta_i}e^{j2\pi f_c t}\right\}$$



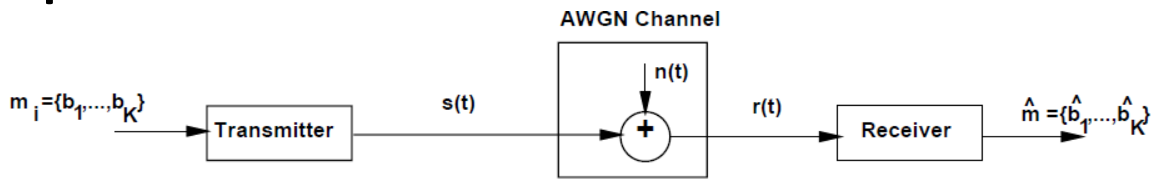
  - » Quadrature Amplitude Modulation (MQAM)

    information coded both in amplitude and phase

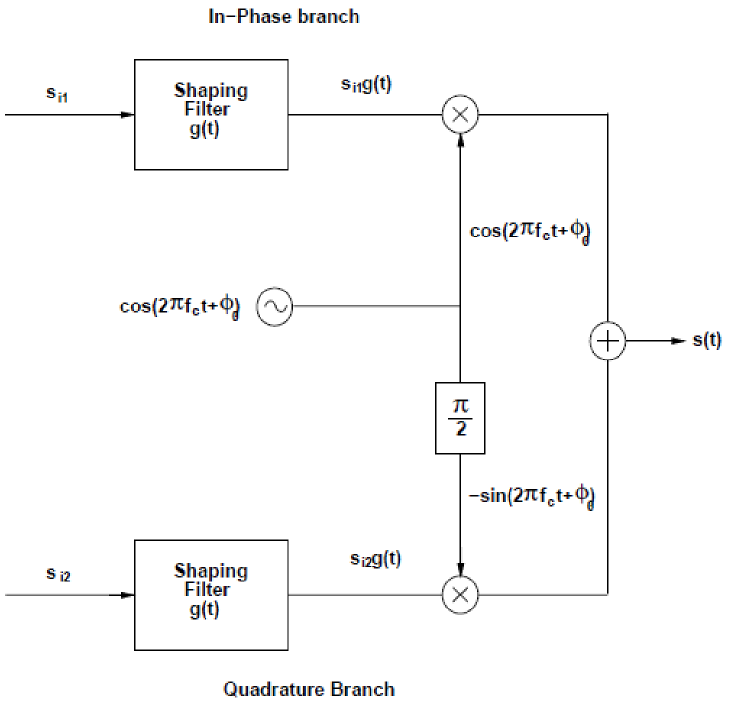
    $$\text{MQAM - } s_i(t) = Re\left\{A_i \; e^{j\theta_i}g(t)e^{j2\pi f_c t}\right\}$$



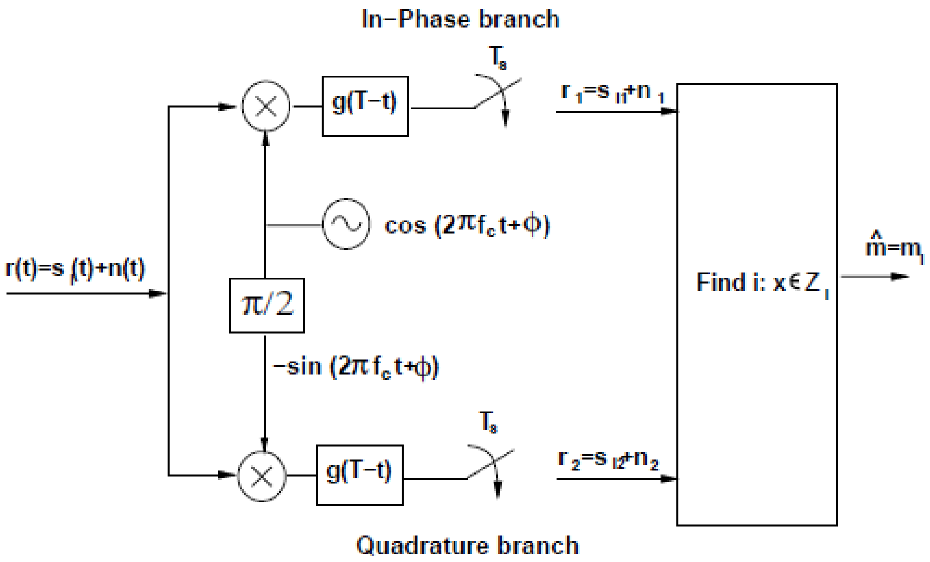
Amplitude/Phase Modulator/Demodulator



Communication System Model (no path loss)



Amplitude/Phase Modulator



Coherent Amplitude/Phase Demodulator

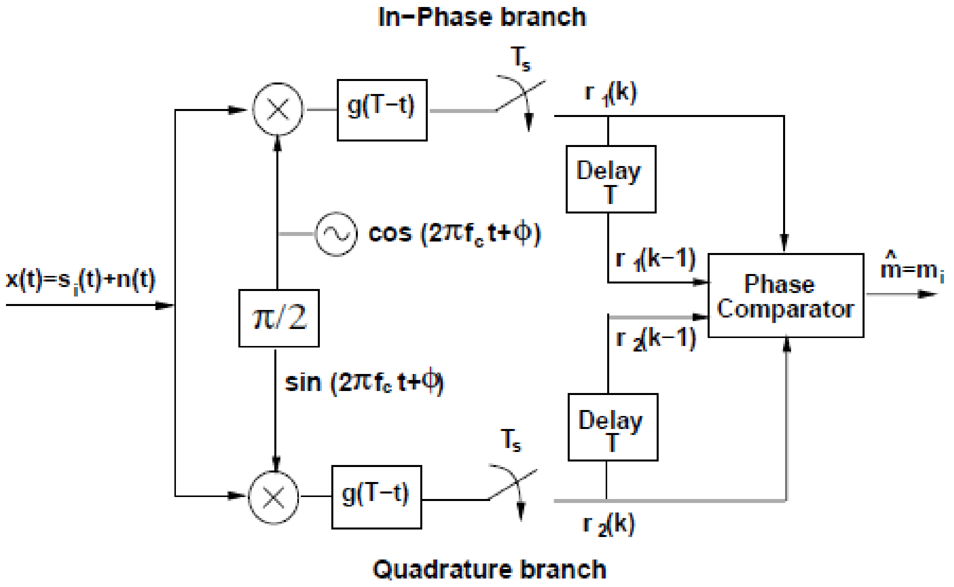
Differential Modulation

- Bits associated to a symbol

  depend on the bits transmitted over a previous symbol

- Differential BPSK (DPSK)
  - » 0 → no change phase
  - » 1 → change phase by ν

- Diferential 4PSK (DQPSK)
  - » 00 → change phase by 0
  - » 01 → change phase by 2
  - » 10 → change phase by -2
  - » 11 → change phase by ν

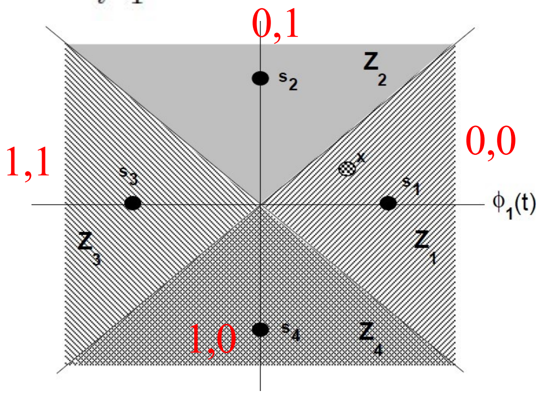


Differential PSK Demodulator

Estimating BER –Nearest Neighbor Approximation

P_s – probability of a symbol being received in error

$$P_s = \sum_{i=1}^{M} p(\mathbf{r} \notin Z_i | m_i \text{ sent}) p(m_i \text{ sent}) \longrightarrow P_s \approx M_{d_{min}} Q\left(\frac{d_{min}}{\sqrt{2N_0}}\right)$$



d_{min} – minimum distance between constellation points

M_{dmin} – number of constellation points at distance d_{min}

$$Q(z) = \frac{1}{2}\text{erfc}\left(\frac{z}{\sqrt{2}}\right) \leq \frac{1}{z\sqrt{2\pi}} e^{-z^2/2},$$

$$P_b = BER \approx \frac{P_s}{\log_2 M}$$

A symbol error associated with an adjacent decision region corresponds to only one bit error

Example

$s_1 = (A, 0)$, $s_2 = (0, A)$, $s_3 = (-A, 0)$ and $s_4 = (0, -A)$

Assume $A/\sqrt{N_0} = 4$.

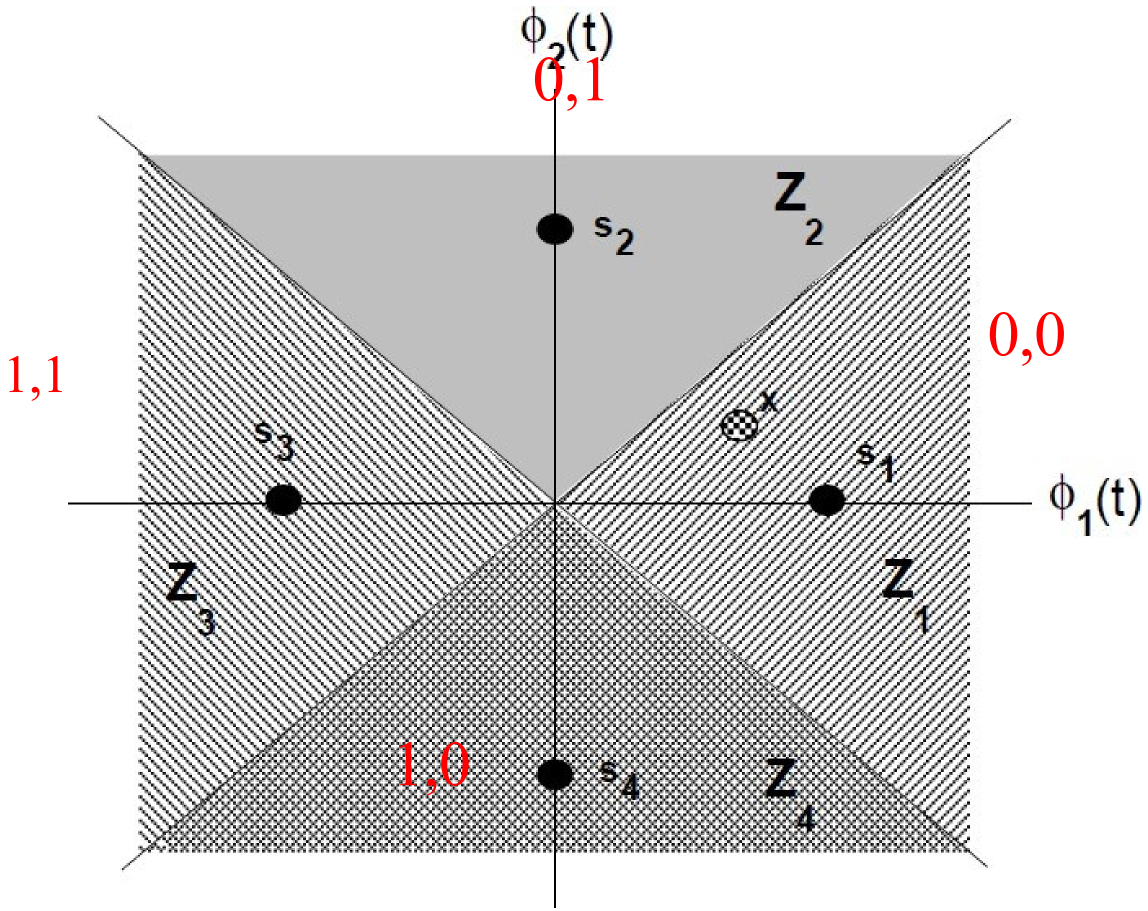
$d_{min} = d_{12} = d_{23} = d_{34} = d_{14} = \sqrt{A^2 + A^2} = \sqrt{2A^2}$.

$M_{dmin} = 2$

$$P_s \approx 2Q(4) = 3.1671 * 10^{-5} \longrightarrow BER \approx \frac{P_s}{\log_2 M} = \frac{3.17 * 10^{-5}}{2} = 1.58 * 10^{-5}$$

How does P_s depend on the *SNR*?

$$P_s \approx M_{d_{min}} Q\left(\frac{d_{min}}{\sqrt{2N_0}}\right)$$

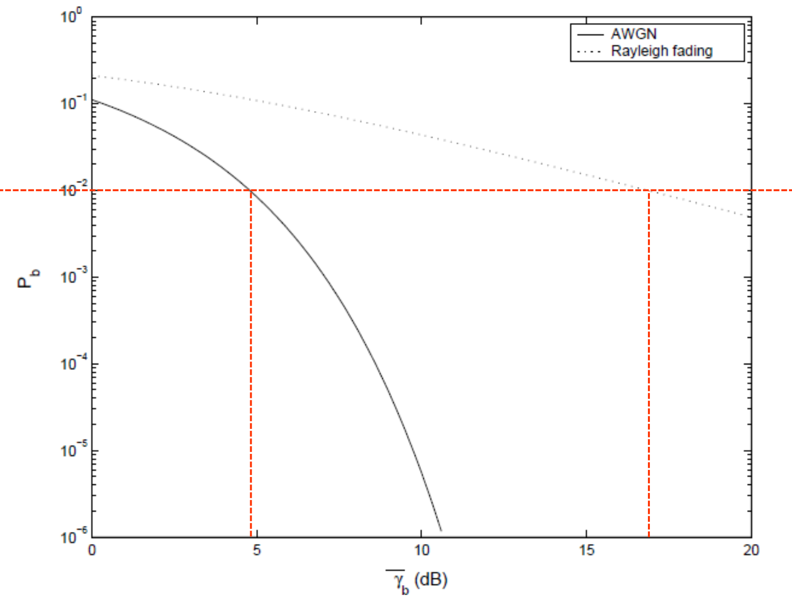


Digital Modulation – BER and SNR

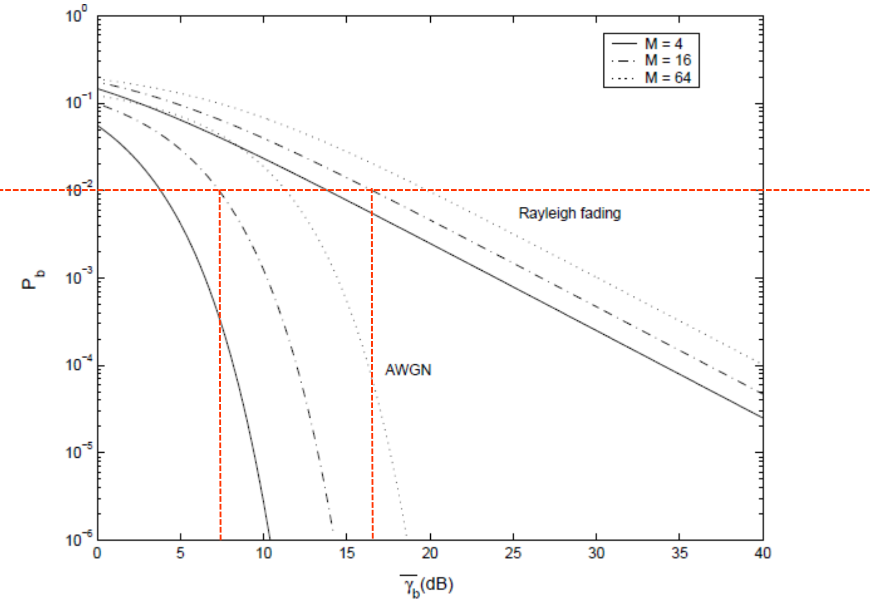
$$SNR = \frac{P_r}{N_0 B} = \frac{E_s}{N_0 B T_s} = \frac{E_b}{N_0 B T_b}, \quad T_s \approx \frac{1}{B},$$

$$\psi_s = \frac{E_s}{N_0}, \quad \psi_b = \frac{E_b}{N_0}$$

Modulation	$P_s(\gamma_s)$	$P_b(\gamma_b)$
BFSK:		$P_b = Q\left(\sqrt{\gamma_b}\right)$
BPSK:		$P_b = Q\left(\sqrt{2\gamma_b}\right)$
QPSK,4QAM:	$P_s \approx 2\,Q\left(\sqrt{\gamma_s}\right)$	$P_b \approx Q\left(\sqrt{2\gamma_b}\right)$
MPAM:	$P_s \approx \frac{2(M-1)}{M} Q\left(\sqrt{\frac{6\overline{\gamma}_s}{M^2-1}}\right)$	$P_b \approx \frac{2(M-1)}{M\log_2 M} Q\left(\sqrt{\frac{6\overline{\gamma}_b \log_2 M}{(M^2-1)}}\right)$
MPSK:	$P_s \approx 2Q\left(\sqrt{2\gamma_s}\sin(\pi/M)\right)$	$P_b \approx \frac{2}{\log_2 M} Q\left(\sqrt{2\gamma_b \log_2 M}\sin(\pi/M)\right)$
Rectangular MQAM:	$P_s \approx \frac{4(\sqrt{M}-1)}{\sqrt{M}} Q\left(\sqrt{\frac{3\overline{\gamma}_s}{M-1}}\right)$	$P_b \approx \frac{4(\sqrt{M}-1)}{\sqrt{M}\log_2 M} Q\left(\sqrt{\frac{3\overline{\gamma}_b \log_2 M}{(M-1)}}\right)$
Nonrectangular MQAM:	$P_s \approx 4Q\left(\sqrt{\frac{3\overline{\gamma}_s}{M-1}}\right)$	$P_b \approx \frac{4}{\log_2 M} Q\left(\sqrt{\frac{3\overline{\gamma}_b \log_2 M}{(M-1)}}\right)$



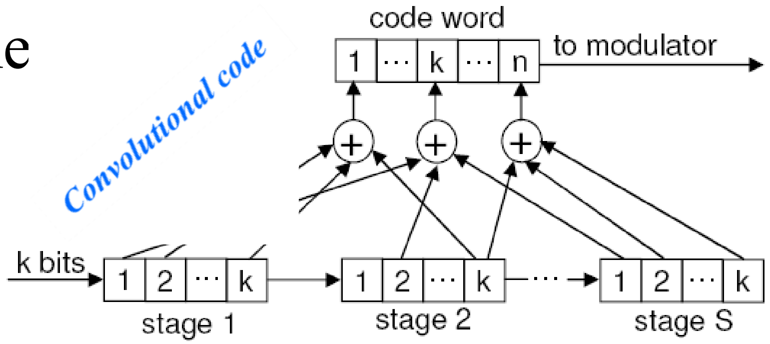
Average P_b for BPSK in Rayleigh Fading and AWGN.



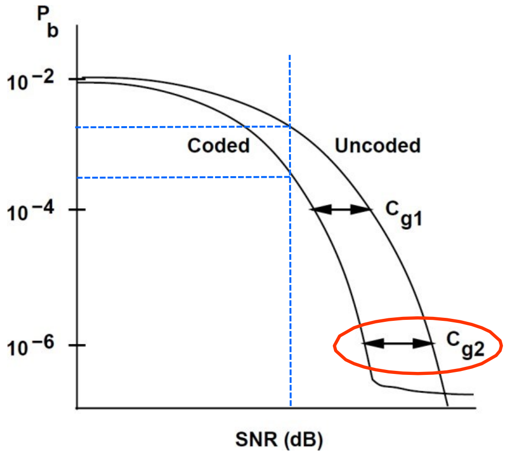
Average P_b for MQAM in Rayleigh Fading and AWGN.

Coding

- Coding enables bit errors to be eithe
  detected or corrected by receiver



- Coding gain, ***C_g***
  the amount of SNR that can be reduced for a given P_b



- Coding rate, ***k/n***
  » Code generates ***n*** coded bits for every ***k*** uncoded bits
  » If channel+modulation enable the transmission of *R bit/s*
  » Information rate = *R * k/n bit/s*

Coding in Wireless Channels

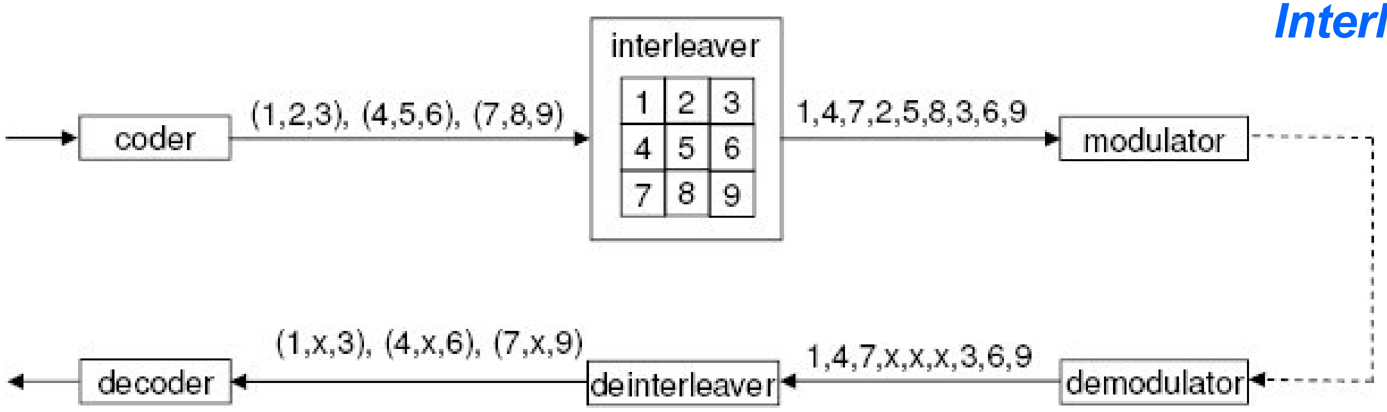
- Codes designed for AWGN channels
  - do not work well on fading channels
  - cannot correct the long error bursts that may occur in fading

Rayleigh

$$p_{Z^2}(x) = \frac{1}{P_r} e^{-x/P_r}$$

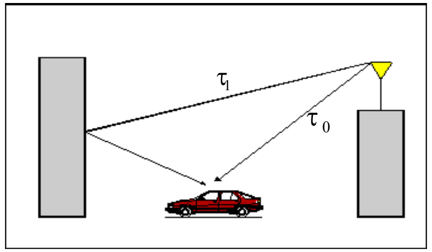
- Codes for fading channels are usually
  - based on an AWGN channel code
  - combined with interleaving
  - objective → spread error bursts over multiple codewords

Interleaving

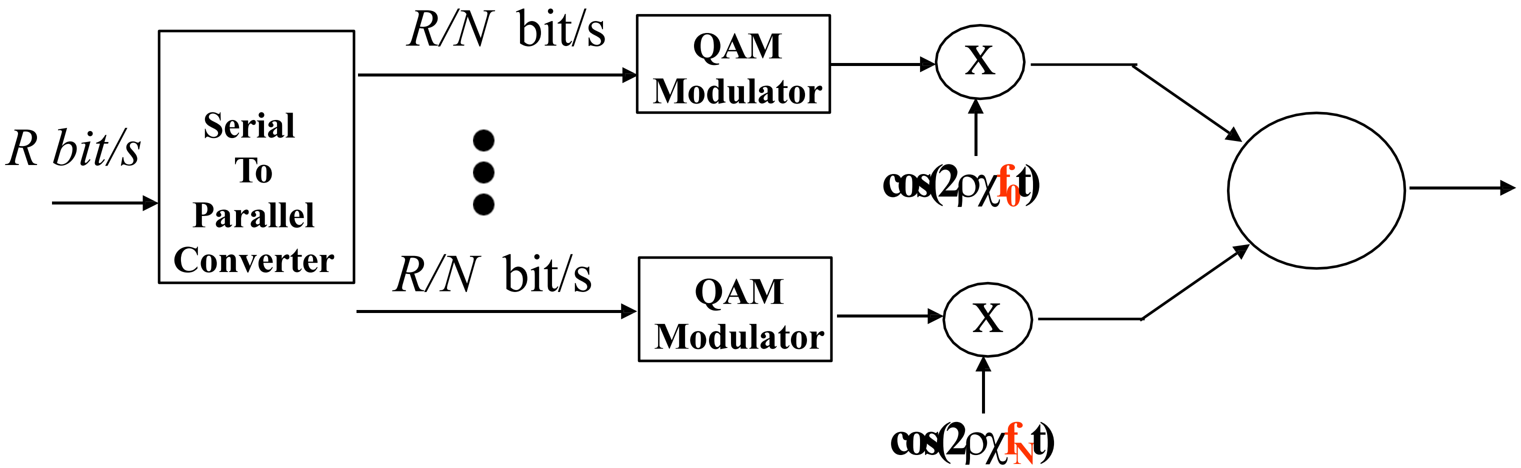


Multicarrier Modulation

- Divides a bitstream into ***N*** low rate substreams
- Sends substreams simultaneously over narrowband subchannels
- Subchannel
  - » has bandwidth $B_N = B/N$
  - » provides a data rate $R_N \approx R/N$
  - » For N large, $B_N = B/N << 1/T_m$
    - ➔ flat fading (narrowband like effects) on each sub-channel, no ISI

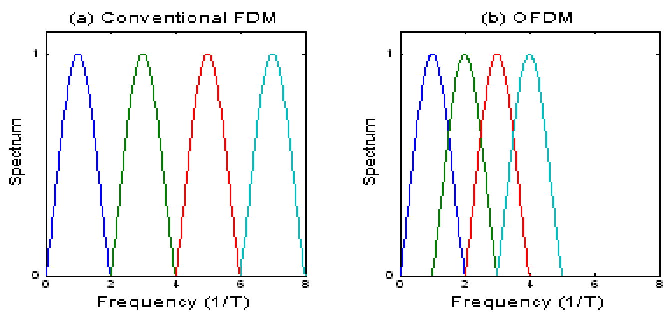


$$T_m = max_n|\tau_n - \tau_0|$$



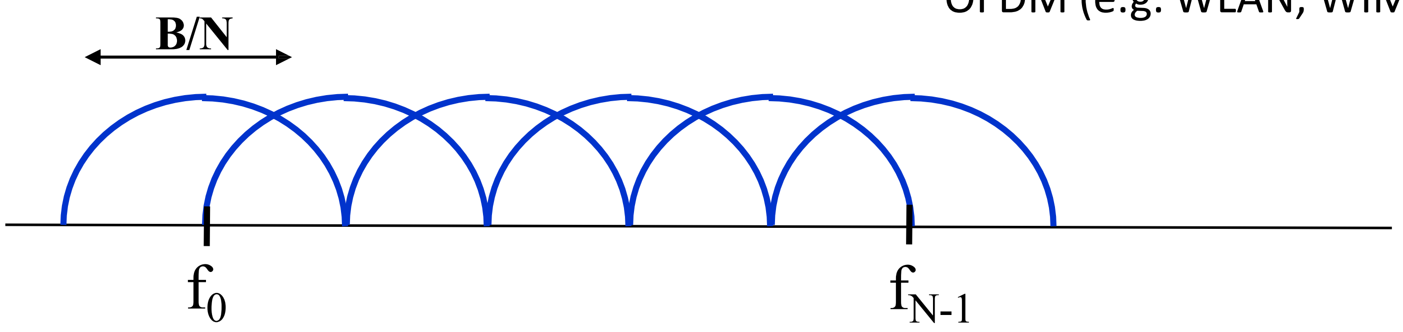
Overlapping Substreams

- Separate subchannels could be used, but
  - » required passband bandwidth is $N*B_N = B$



- OFDM uses overlaps substreams
  - » Substream separation is B/N
  - » Total required bandwidth is $B/2$, for $T_N=1/B_N$

Most of the recent wireless communications tecnologies are adopting OFDM (e.g. WLAN, WIMAX, LTE).



OFDM uses Discrete Fourier Transforms

- Discrete Fourier transforms given by

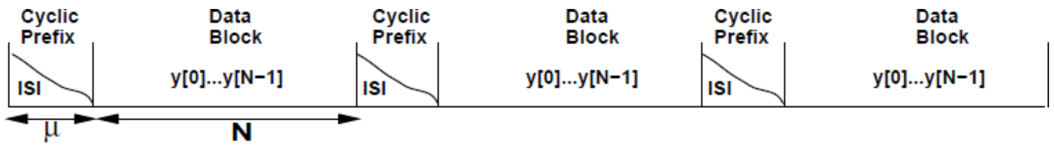
$$\mathrm{DFT}\{x[n]\} = X[i] \triangleq \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x[n] e^{-j\frac{2\pi n i}{N}}, \;\; 0 \le i \le N-1$$

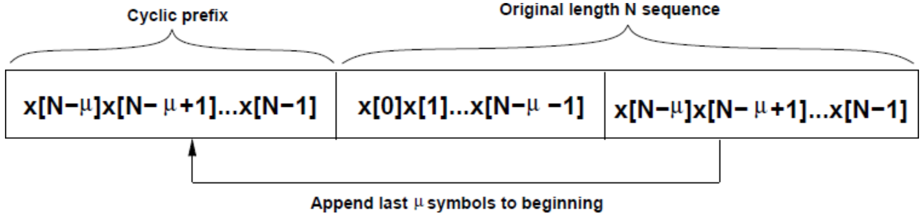
$$\mathrm{IDFT}\{X[i]\} = x[n] \triangleq \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i] e^{j\frac{2\pi n i}{N}}, 0 \le n \le N-1$$

- Circular convolution $\otimes$

$$\mathrm{DFT}\{y[n] = x[n] \otimes h[n]\} = X[i]H[i], \; 0 \le i \le N-1.$$

$$x[n] \otimes h[n] = \tilde{x}[n] * h[n] = y[n]$$

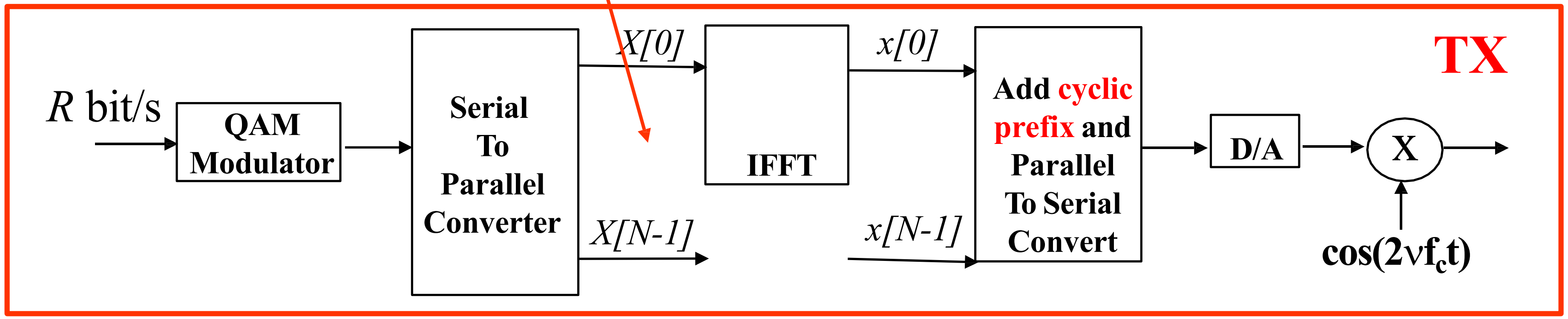




FFT Implementation of OFDM - TX

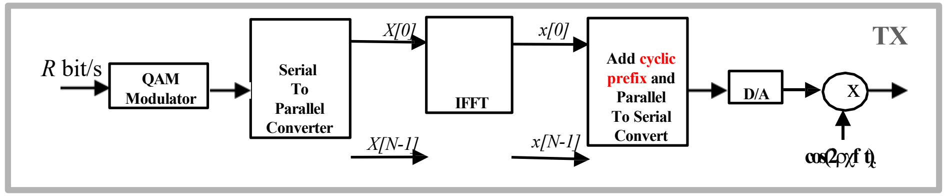
- Use IFFT at TX to modulate symbols on each subcarrier
- Cyclic prefix makes circular channel convolution
  - ➔ no interference between FFT blocks in RX processing

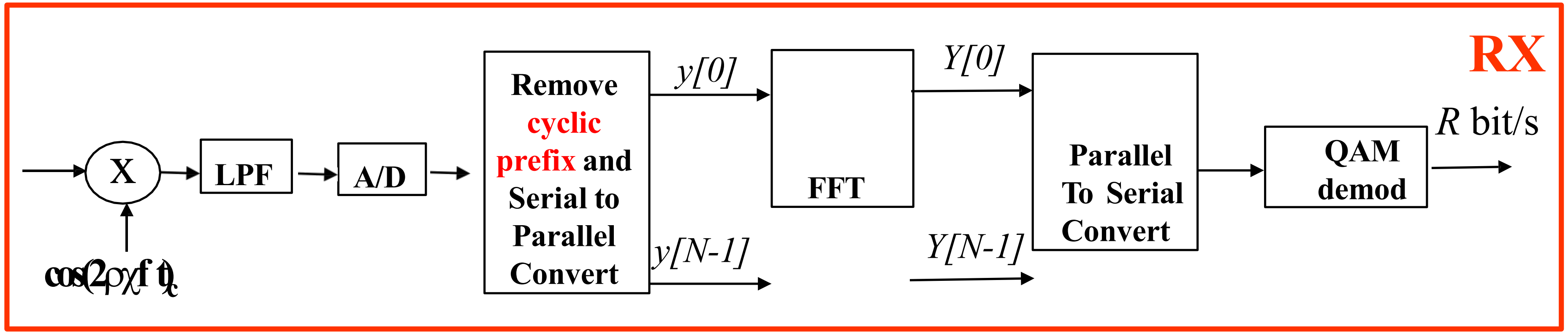
$$x[n] = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X[i] e^{j2\pi ni/N}, \quad 0 \le n \le N-1.$$



FFT Implementation of OFDM - RX

Reverse structure at RX





Spread Spectrum

Goals

- hide the information signal below the noise floor
- mitigate inter-symbol interferences
- combine multipath components

Techniques

- multiply the information signal by a spreading code