Department of Computer Engineering & Informatics

Signal Processing and Communications Lab

Wireless and Mobile Communications

Mobile Communication Channel Characteristics

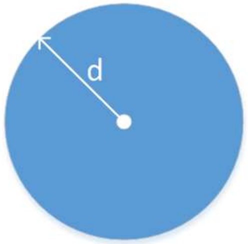
Presentation outline

- Wireless Channel basics
- Propagation mechanisms
- Large scale fading
- Small scale fading
- Model of the channel
- Large scale fading metrics
- Advanced (and recently emerged) issues
  - mmWave Com
  - Visible Light Com
  - Underwater Com

The Wireless Channel: Introduction (1/4)

- The wireless channel is the physical transmission medium through which information is transmitted from a transmitter to a receiver.
    - Air, free space, water …
- The transmitter and receiver use antennas to send and receive electromagnetic waves, respectively.

- Different antenna types (directionality, gain).



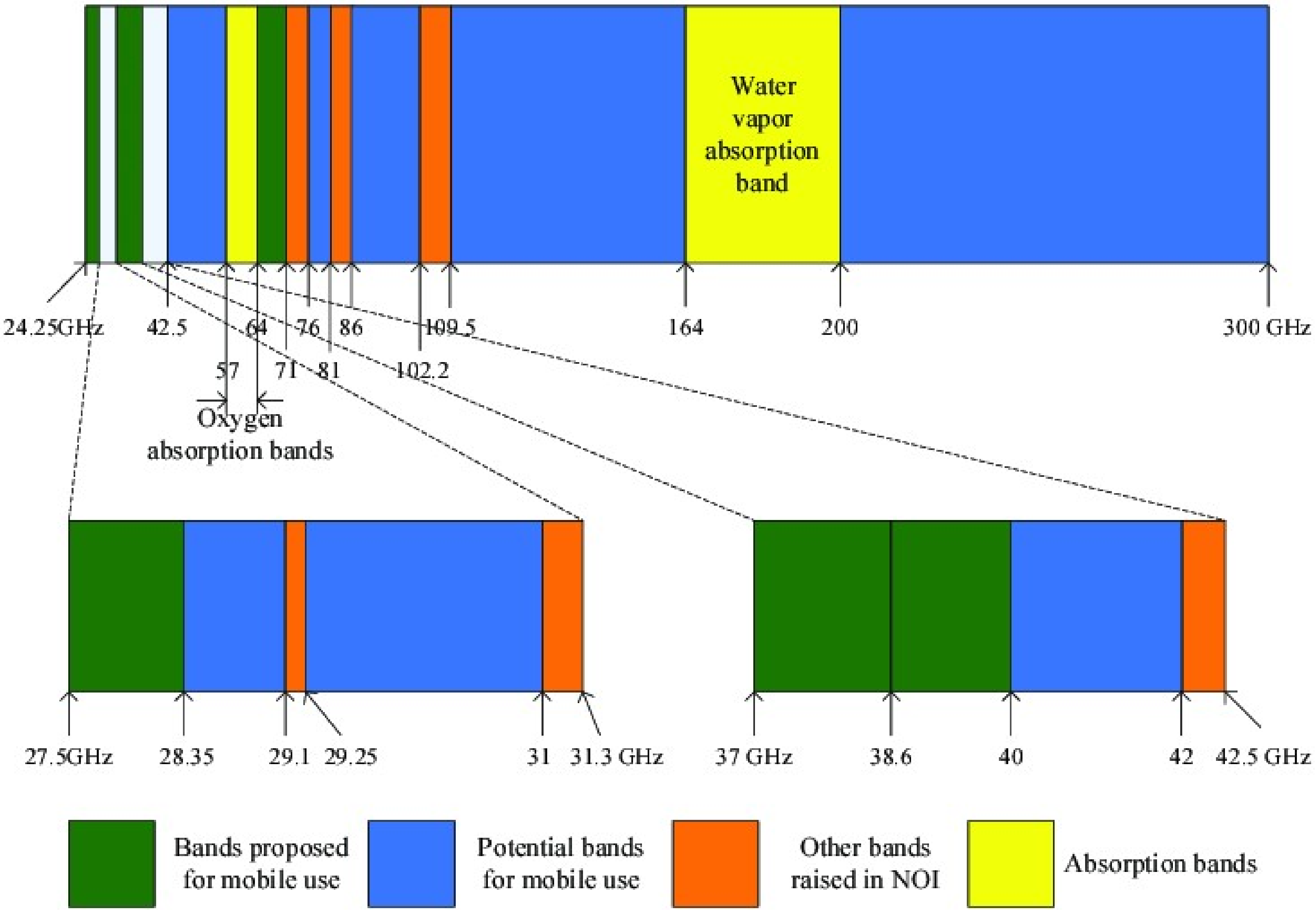
The Wireless Channel: Introduction (2/4)

- A signal transmitted through any channel undergoes various degradations, due to:
  - Power fading, noise, inter-symbol interference (ISI).
- A signal transmitted over a wireless channel is subject to additional degradations, due to:
  - Multipath phenomenon,
  - Temporal variability of the channel (why?),
  - Interferences (self, other users, etc)
- Power attenuation can be useful in some cases
- Multipath phenomenon can be properly exploited !

The Wireless Channel: Introduction (3/4)

- Among the most important characteristics of a wireless channel is the corresponding electromagnetic spectrum (frequency bands)
- International Telecommunication Union
  - World Radiocommunication Conference
  - Electronic Communications Committee
  - European Conference of Postal and Telecommunications Administrations
- National Telecommunication and Post Commission

The Wireless Channel: Introduction (4/4)



Parametric model of multipath channel

The wireless (and mobile) channel can be considered as a Linear Time Variant system with impulse response $h(\tau;t)$

The wireless (and mobile) channel can also be described in terms of the parameters of the various paths, as follows:

- Parametric form of the impulse response:

$$h(\tau;t) = \sum_{k=1:L} a_k(t)\delta(t - t_k(t))$$

- Received signal:

$$r(t) = s(t) * h(\tau;t) + n(t)$$

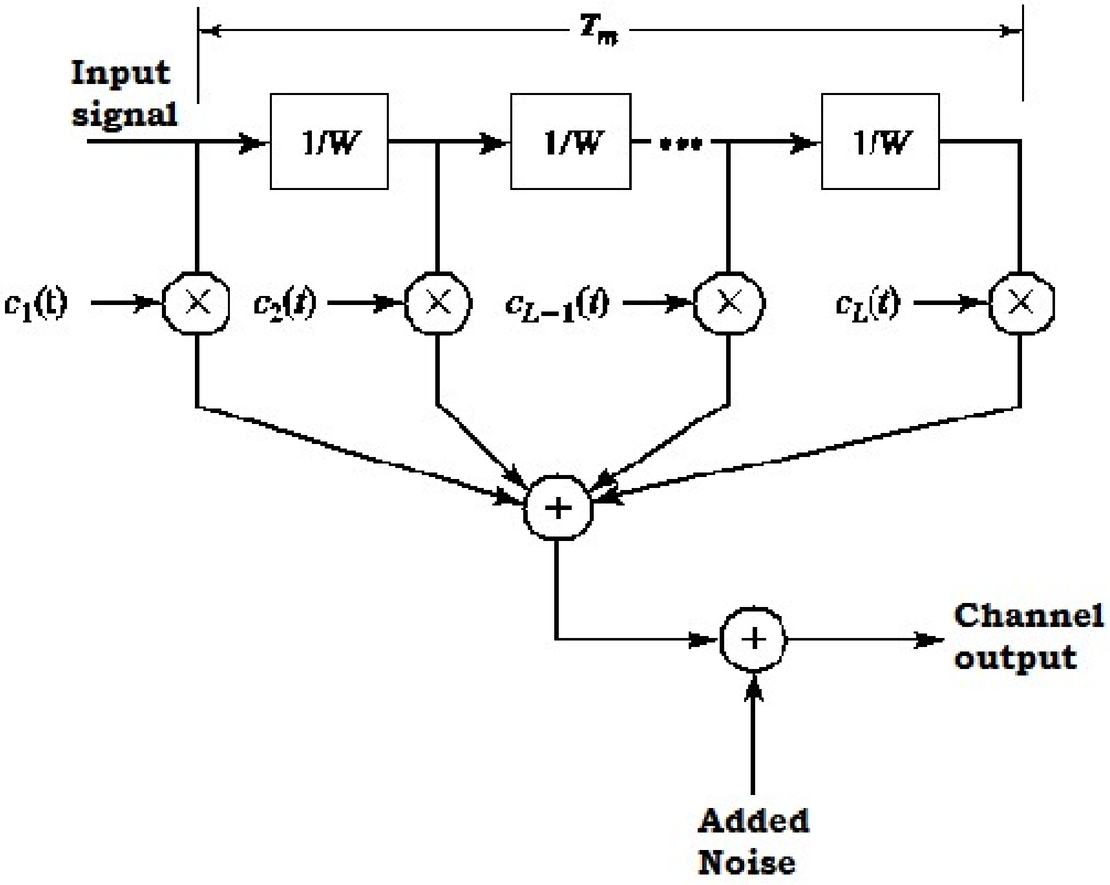
- Therefore:

$$r(t) = \sum_{k=1:L} a_k(t)\, s(t - t_k(t)) + n(t)$$

Discrete LTV* multipath channel (OXI)

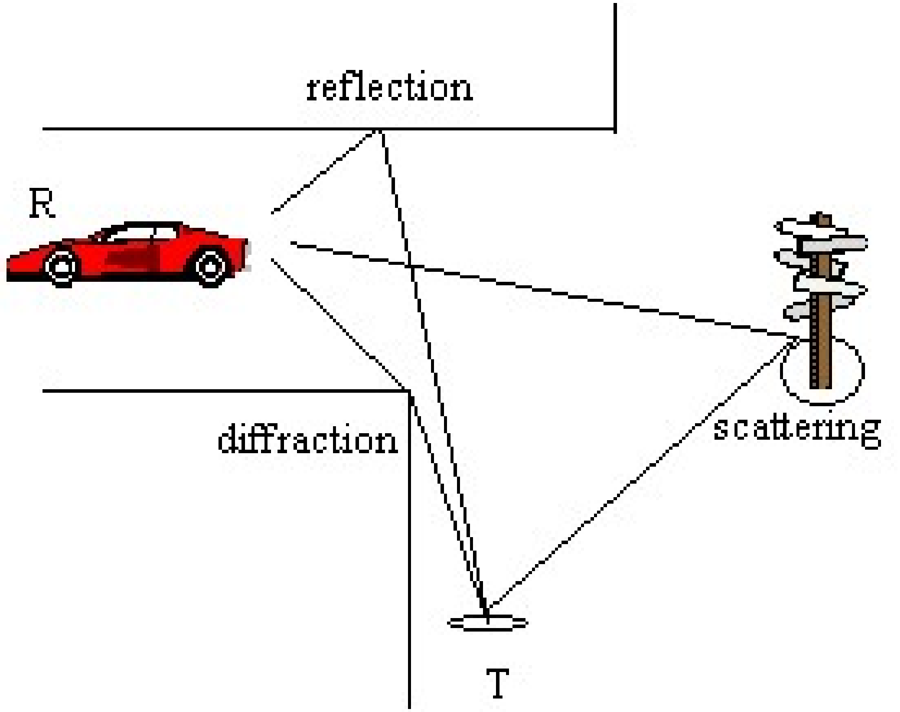
It can also be described as a linear time variant (LTV) FIR system.

The filter coefficients are time – varying.



- Assumption: the channel frequency response is defined in [-W/2 , W/2]

Propagation mechanisms (1/4)



- reflection
- diffraction
- scattering

Propagation mechanisms (2/4)

- Reflection mechanism
    - Incidence of the wave on objects larger than λ
    - Partial reflection on surface boundary areas with different dielectric constants
    - Phase change due to materials with different magnetic permeability.
    - Added delay relative to the direct path
- Terrestrial reflection (two-ray geometric model):

    Useful in large-scale parameter estimates

Propagation mechanisms (3/4)

- Diffraction mechanism
  - The waves are incident on objects with edges (of the order of λ) located between the transmitter and the receiver.
  - According to the *Huygens'* principle, every point on the spherical front of the wave can be regarded as secondary sources of wavelets.
  - The wave bends and propagates even in the "shadow" areas of the object.
  - At high frequencies, the phenomenon is becoming dependent on: geometry and morphology of the object, amplitude and phase of the incident wave, type of polarization.

Propagation mechanisms (4/4)

- Scattering
  - The waves are incident on objects (or surfaces with protrusions) with dimensions less than λ.
  - The number of objects and/or protrusions per unit volume must be large enough.
  - The waves is reflected to different directions.
- For the surface to be considered uneven, it must hold

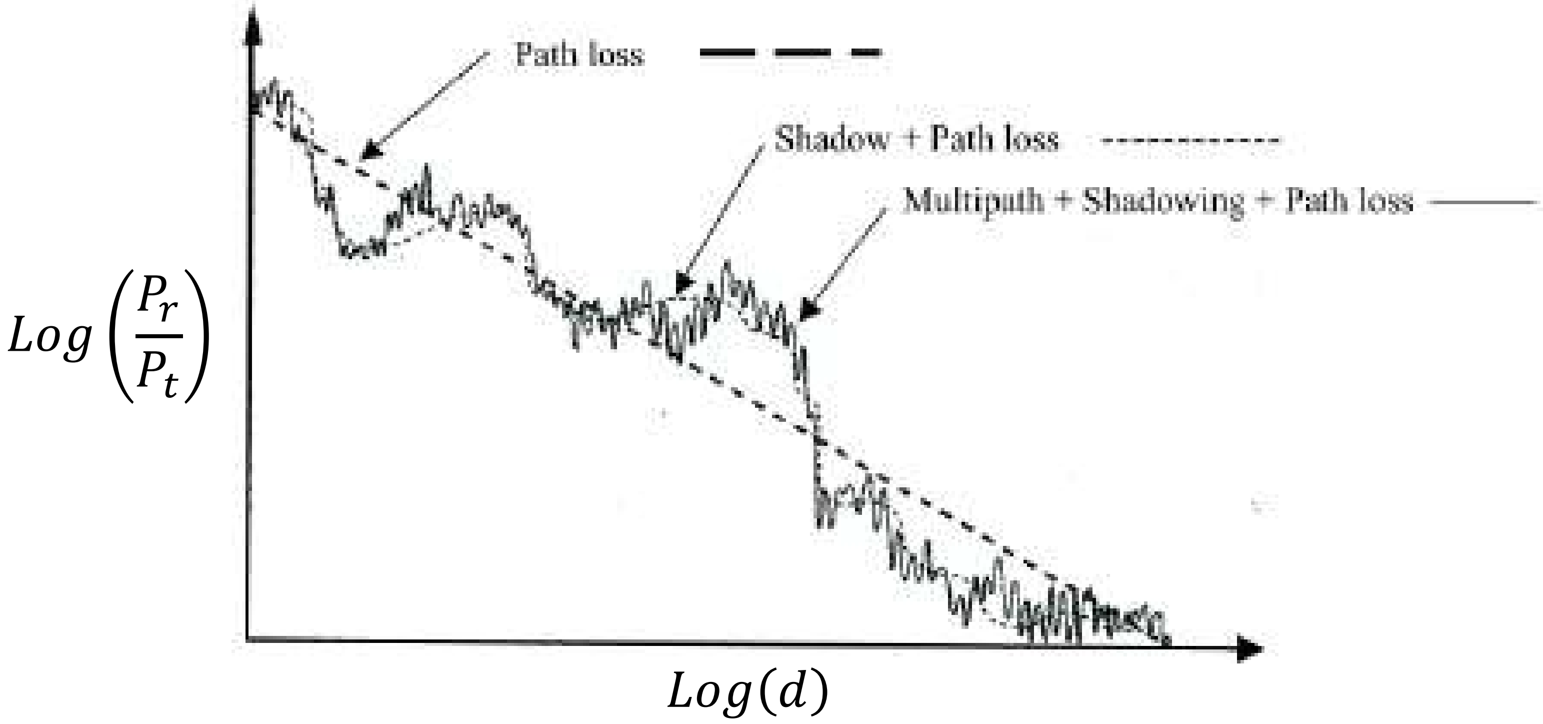
$$\left(\frac{\min(h)}{\max(h)}\right) > h_c$$

where, $h_c=\lambda/(8\sin\theta_i)$ the critical protrusion height and θ_i the angle of incidence.

The nature of fading

- Fading describes the effect of the wireless channel on the power of the transmitted signal, when the receiver is located at distance *d*

- There is large- and small-scale fading.



Large scale fading (1/5)

- As the mobile moves away from the B.S. (10m, 1000m) the local average value of the received signal power decreases (path loss)
- The phenomenon of fading is also affected by the terrain: hills, vegetation, buildings, etc. (shadowing)

P_t	Transmitter power
$P_r(d)$	Local average value of received power at distance d
$PL(d) = \frac{P_t}{P_r(d)}$	Path loss
$PL(d) = 10\log_{10}\frac{P_t}{P_r(d)}[dB]$	Path loss in dB

- This phenomenon can be mitigated by increasing the transmitter power (also, if possible, better transmitter and receiver positions could be selected)

Large scale fading (2/5)

In order to predict the average received power at some point in the cell and to determine key quantities (such as: transmission power, coverage areas, power consumption from the mobile terminal) we need to model the so-called large-scale phenomena

Friis free space equation:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

- G_t: Transmitter’s antenna gain
- G_r: Receiver's antenna gain
- λ: Wavelength
- L: Factor for other losses (transmition lines, antennas, filters, etc.)

Assumptions:

- d >> λ (far field)
- Free space
- TX and RX antennas have the same polarization

Antenna gain: The ratio of the radiation intensity in a given direction to the radiation intensity that would be produced if the power accepted by the antenna were isotropically radiated.

Large scale fading (3/5)

Ideal propagation model:

$$P_r(d) = P_r(d_0)\frac{d_0^2}{d^2}$$

Power received with respect to power at some reference distance d_0

Reverse n-power propagation model (average value when the assumptions of the ideal model do not hold true):

$$\overline{PL}(d) = \overline{PL}(d_0)\frac{d^n}{d_0^n}$$

PL: path loss, $\overline{PL}$: measured PL
($n = 3$ in urban areas)

$$\overline{PL}(d) = \overline{PL}(d_0) + 10n\log_{10}\frac{d^n}{d_0^n}\ [dB]$$

Log-distance PL model

$$\overline{PL}(d) = \overline{PL}(d) + X_\sigma\ [\text{dB}]$$

X_σ: Gaussian distribution with zero mean and standard deviation 6-8 dB.

Large scale fading (4/5) (OXI)

- In addition to the previous statistical model, experimental models have been developed that focus on specific transmission conditions (in terms of frequencies, antenna heights, urban or non-urban environment, etc.).
- The Okumura model is used in urban areas and has been developed for frequencies from 150MHz to ~2GHz, for distances 1Km-100Km and for antenna heights at base stations from 30m to 1000m.

$$PL_{50} = PL_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA}$$

PL_{50} : median (50%) value of propagation loss
(median value of the dynamic range of L)
PL_F : free space propagation loss
A_{mu} : median attenuation relative to free space, read from Okumura curves
$G(h_{te})$: BS antenna height gain factor
$G(h_{re})$: MS antenna height gain factor
G_{AREA} : Gain due to the type of environment (correction factor)

Large scale fading (5/5) (OXI)

- The extended Hata model (COST-231) is also used in urban areas and has been developed for frequencies from 1500MHz to 2000MHz, for distances of 1m-20m, for antenna heights at base stations from 30m to 200m and receiver antenna height from 1m to 10m.

$$PL(d)[dB] = 46.36 + 33.9\log(f_c) - 13.82\log(h_t) - a(h_t) \\ +(44.9 - 6.55\log(h_t))\log(d) + C_M$$

$PL(d)$ = Path loss in urban areas.
h_t, h_r = Heights of BS and MS antennas.
f_c = Frequency of transmitted carrier.
C_M = Correction factor (3 dB for metropolitan centers, else 0 dB).
$\alpha(h_t)$ = Correction factor.

- Indoor propagation models (same or different floors, doors).
- Large scale fading is used to calculate:
  - The actual coverage area.
  - The required transmit and receive power.
  - The interference degree between adjacent cells.

Small scale fading: Multipath

- Even if the mobile device moves slightly (10cm, 20cm, 30cm) the instantaneous power value of the received signal may fluctuate dramatically (30-40dB).
  - this is mainly due to multipath and Doppler effect
- Due to multipath, the received EM field may come from constructive or annihilative (destructive) sum of many components coming from different directions with random phases but similar delays
- $r(t) = r_1(t) + r_2(t) + r_3(t)$

- It can be reduced by intelligent signal processing algorithms (not by merely increasing transmit power)

Small scale fading: Modeling the sum of many paths

- The complex sum $r(t)$ of many different reflections is Gaussian distributed.
- The amplitude is described either as

  Rayleigh Distributed (NLOS)

$$f_R(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}$$

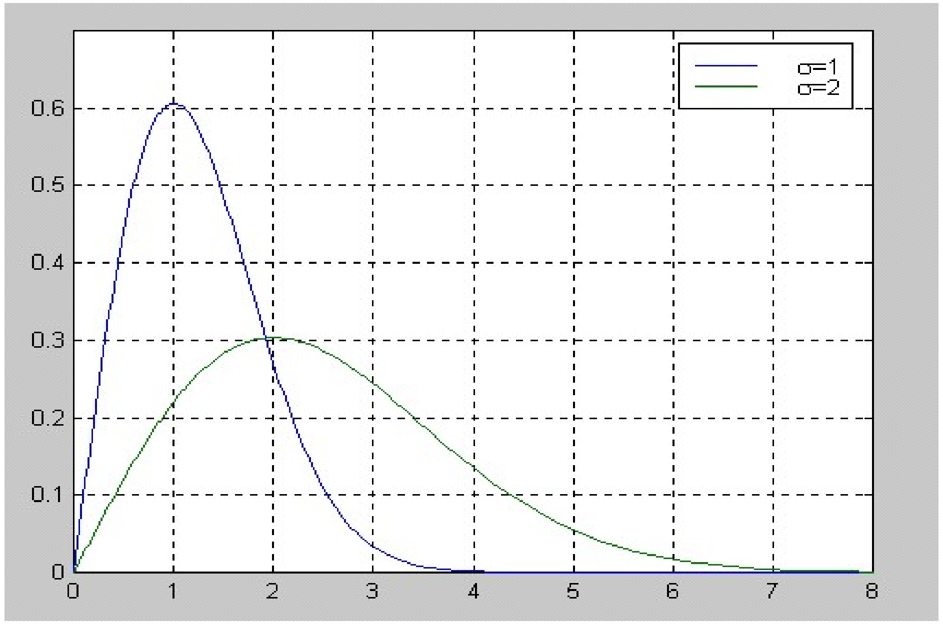
  or as Rice Distributed (LOS)

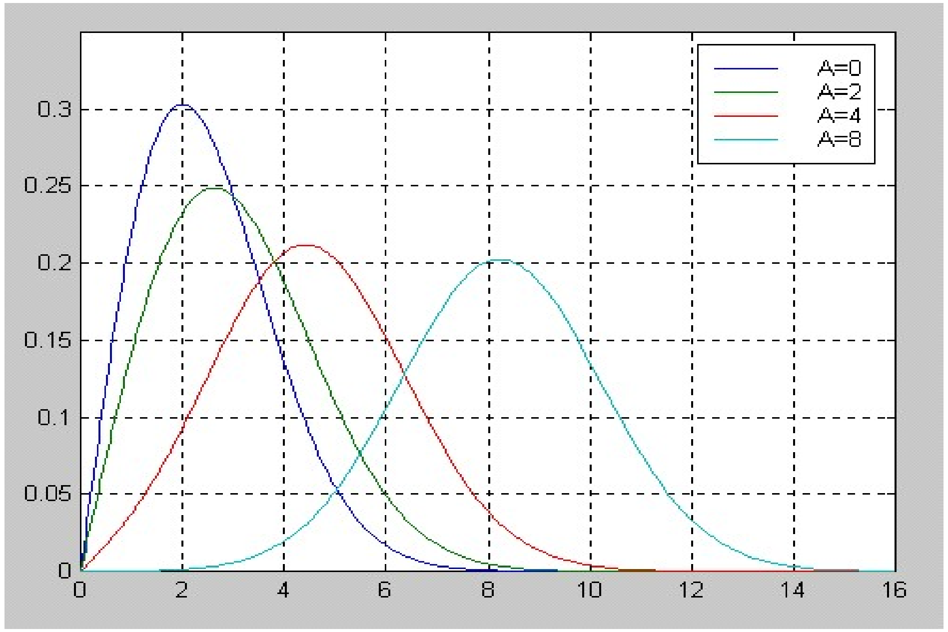
$$f_R(r) = \frac{r}{\sigma^2} e^{-\frac{r^2+A^2}{2\sigma^2}} I_0\left(\frac{Ar}{\sigma^2}\right)$$

  A: maximum amplitude of the main component

  I_o(.) : Bessel function of the first kind and zero-order

- Phase: uniform r.d. in [0, 2π)

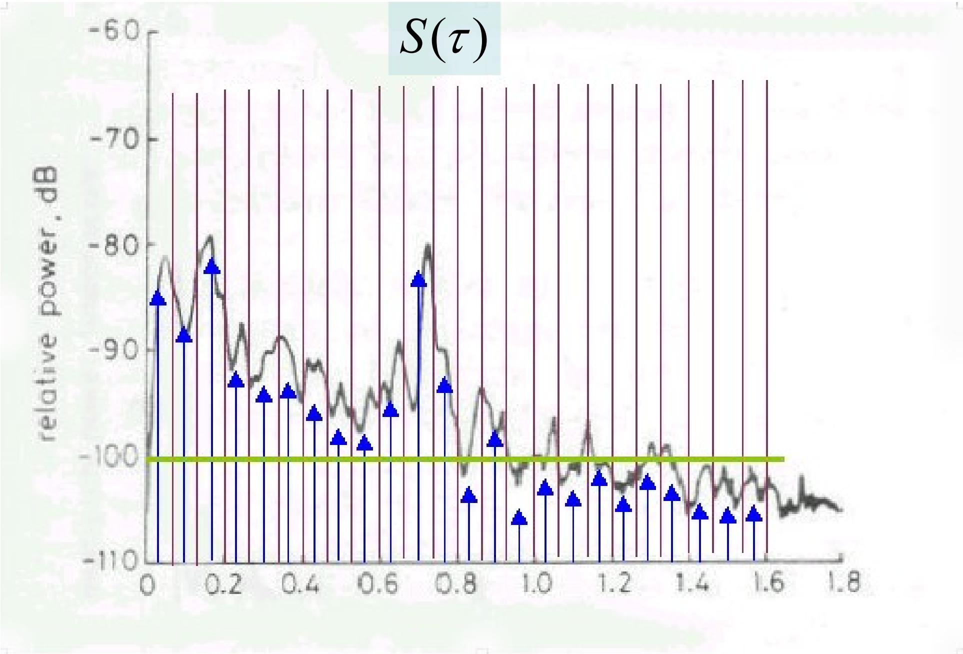




Small scale fading: Power – Delay profile

- In most cases, the first group of components that arrives at the receiver corresponds to the LOS path (if any) and they are Rayleigh distributed

- Power-Delay profile: The received power is plotted with respect to the delay of each group.
  - A very narrow pulse is used for the calculation.



- Maximum delay T_m, is an important parameter (as we will see later in more detail)

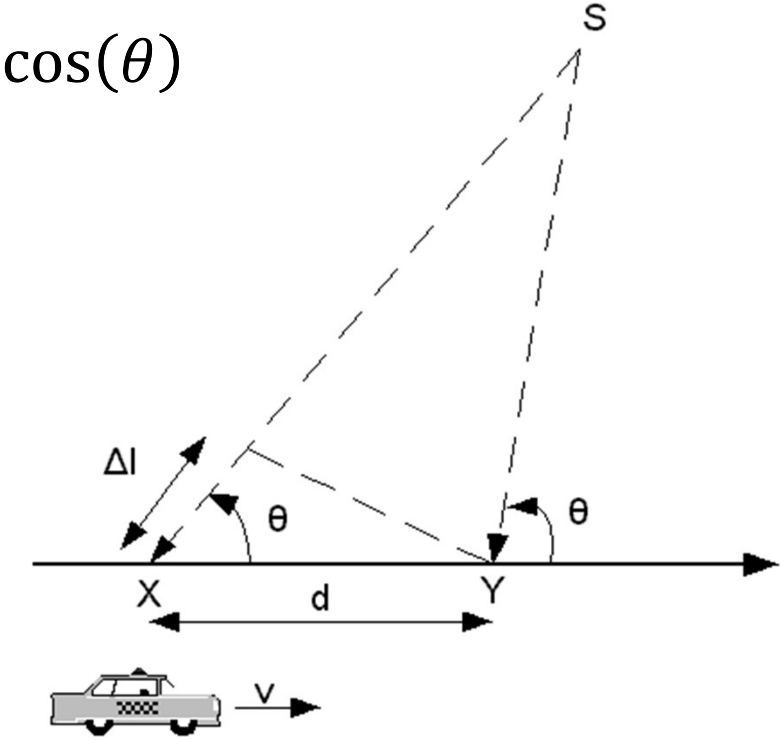
- What happens in case $T_m > T_s$? (where T_s is the symbol period)

Small scale fading: Doppler Effect

- ■ This effect appears in cases of relative motion between the transmitter and the receiver.
- ■ As a result, there is a shift in the nominal value of carrier frequency f_c by f_d (i.e., $f_c + f_d$).

$$f_d = \frac{v}{\lambda}\cos(\theta) = f_D\cos(\theta)$$

f_D is the maximum Doppler shift



The effect is related to the temporal variability of the channel

In addition to the transmitter and the receiver, there may exist moving reflectors at different speeds

Channel impulse response (1/3) (OXI)

- Consider the transmission of the carrier signal at f_c Hz

$$\begin{aligned}\tilde{s}(t) &= a_o(t)\cos\big(2\pi f_c t + \phi_o(t)\big)\\ &= Re\left\{a_o(t)e^{j(2\pi f_c t+\phi_o(t))}\right\}\\ &= Re\left\{s(t)e^{j2\pi f_c t}\right\},\end{aligned}$$

where, $s(t) = a_o(t)e^{j\phi_o(t)}$ is the equivalent (complex) baseband signal

- ➢We assume multipath propagation
- ➢ and horizontal motion at speed v
  - due to Doppler effect, the frequency of the *n*-th wave (received at an angle $\zeta_n(t)$) is shifted w.r.t. the nominal frequency by

$$f_n(t) = f_D cos\zeta_n(t), \text{ όπου } f_D = \frac{v}{\lambda_c}$$

Furthermore, the *n*-th wave is subject to:

- fading $\alpha_n(t)$
- delay $\tau_n(t)$
- phase change from reflections $\varphi_n(t)$

Channel impulse response (2/3) (OXI)

- The received bandwidth signal can be written as:

$$\tilde{r}(t)$$

$$= \sum_{n} a_n(t)\, a_o\big(t-\tau_n(t)\big) \cos\big(2\pi\big(f_c+f_n(t)\big)\big(t-\tau_n(t)\big)+\Phi_o\big(t-\tau_n(t)\big)+\varphi_n(t)\big)$$

$$= Re\left\{\sum_{n} a_n(t)\, a_o\big(t-\tau_n(t)\big)\, e^{j(2\pi((f_c+f_n(t))(t-\tau_n(t))+\Phi_o(t-\tau_n(t))+\varphi_n(t))}\right\}$$

$$= Re\left\{\sum_{n} a_n(t)\, s\big(t-\tau_n(t)\big)\, e^{j(-2\pi((f_c+f_n(t))\tau_n(t)+\varphi_n(t))}\, e^{j2\pi f_n(t)t} e^{j2\pi f_c t}\right\}$$

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

Where, $r(t)=\sum_n a_n(t)s\big(t-\tau_n(t)\big)e^{-j\theta_n(t)}$ the equivalent baseband signal,
$\theta_n(t)=2\pi\big[\big(f_c+f_n(t)\big)\tau_n(t)-f_n(t)t\big]-\phi_n(t)$.

- The impulse response of the baseband model

$$h(\tau,t)=\sum_{n} a_n(t)e^{-j\theta_n(t)}\delta\big(\tau-\tau_n(t)\big)$$

- In general (complex) amplitudes change faster than time delays

Channel impulse response (3/3) (OXI)

$$h(\tau,t)=\sum_{n} a_n(t)\, e^{-j\theta_n(t)}\, \delta\big(\tau-\tau_n(t)\big)$$

$$r(t)=\sum_{i=0}^{N-1} \beta_i\, h_i(t) s\big(t-\tau_i'(t)\big)$$

- The received signal consists of N different component groups
- $h_i(t)$ describes the small scale fading that each group has experienced, and it is usually described as Gaussian (with Rayleigh or Rician amplitude and uniform phase in [0 2π))
- In case of relative motion, all the above are being affected by Doppler (i.e. frequency shift by f_D)
- Finally, β_i are derived from the channel power profile for each different component group delay.

Small scale fading (cont.) (OXI)

- **Multipath** results in **frequency selective fading** which, in turn, causes intersymbol interference.
- If the channel is time invariant, then

$$h(\tau) = \sum_n a_n e^{-j\theta_n} \delta(\tau - \tau_n), \qquad \theta_n = 2\pi f_c \tau_n - \phi_n$$

- In frequency domain, the channel can be described as

$$H(f) = \sum_n \alpha_n e^{-j\theta_n} e^{-j2\pi f \tau_n}$$

- Single tone signals passing through the channel are subject to different “treatment” (in terms of attenuation and/or phase shift) depending on their frequency
- If there is only one path (e.g., flat fading), then

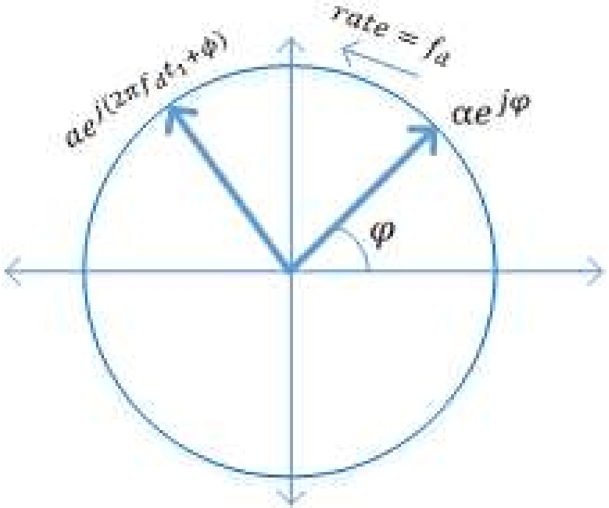
$h(\tau) = ae^{-j\theta}\delta(\tau)$ ή $H(f) = ae^{-j\theta}$.

Small scale fading (cont.) (OXI)

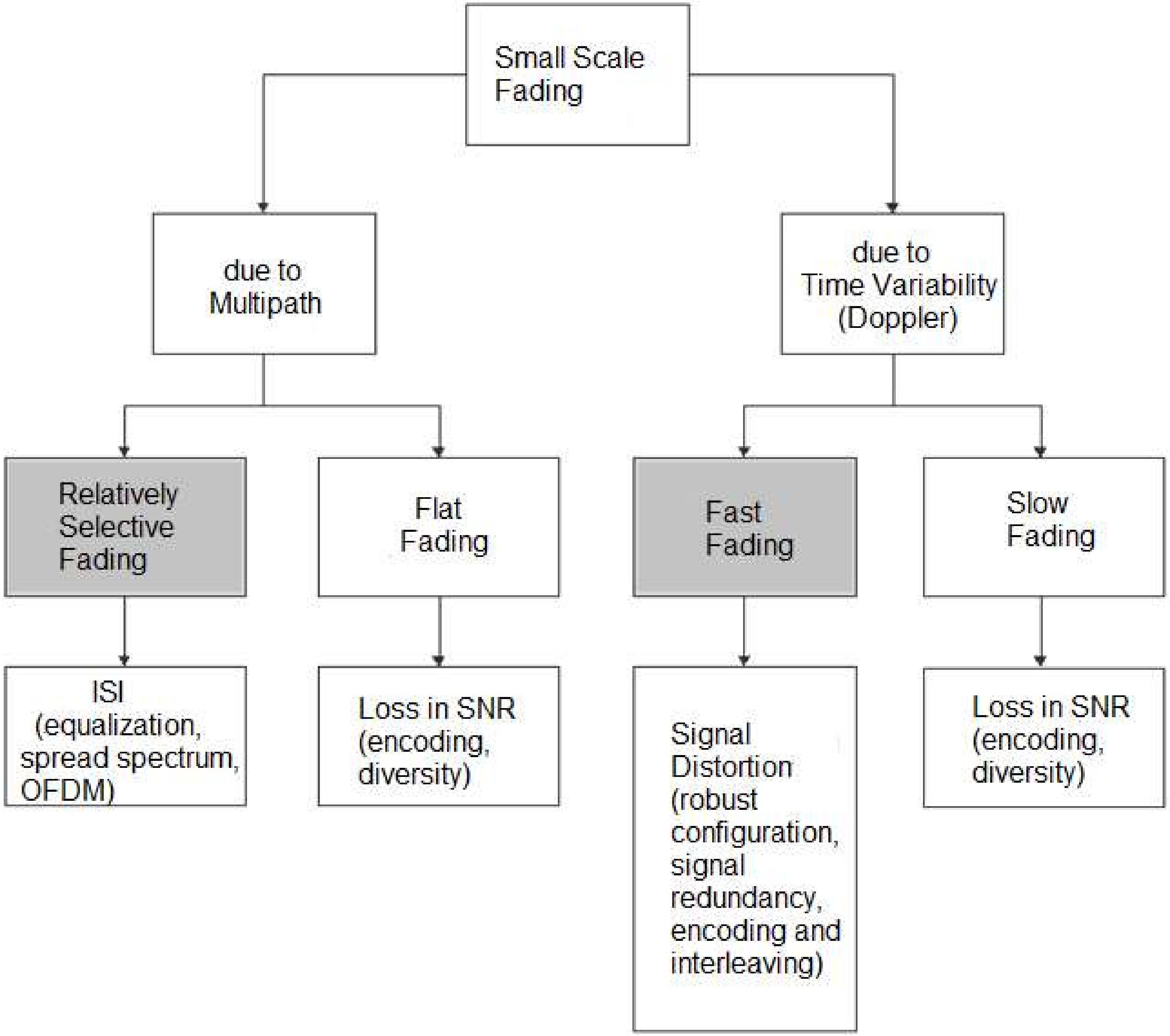
- When **Doppler effect** is present (due to relative movement between transmitter and receiver), **time selective fading** is observed.
- If there is only one direct path, then

$$h(t) = a(t)e^{-j\theta(t)}\delta(\tau), \qquad \theta(t) = -2\pi f_d(t)t - \phi(t)$$

- The channel is time variant at a rate which depends on the introduced Doppler Spread.
  - If $\alpha(t) = a$, $\varphi(t) = \varphi$, $\zeta(t) = \zeta$. Then, $h(t) = ae^{j(2\pi f_d t+\phi)}$



Types of small scale fading



Small Scale Fading

due to Multipath

due to Time Variability (Doppler)

Relatively Selective Fading

Flat Fading

Fast Fading

Slow Fading

ISI (equalization, spread spectrum, OFDM)

Loss in SNR (encoding, diversity)

Signal Distortion (robust configuration, signal redundancy, encoding and interleaving)

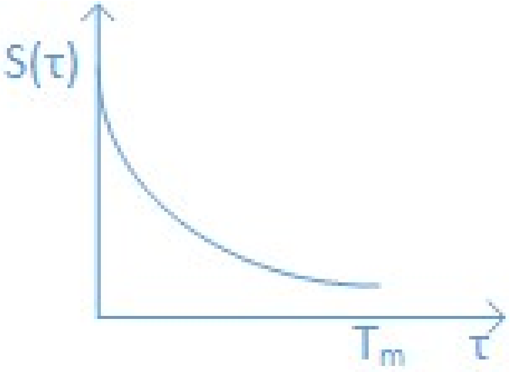
Loss in SNR (encoding, diversity)

Important parameters of multipath channels (1/3)

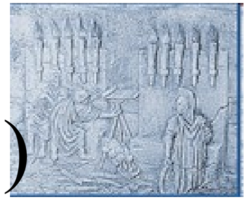
- The parameters that quantify the effect of multipath are related to the power-delay profile $S(\tau)$ $(S(\tau) = E\{h^*(\tau,t)h(\tau,t)\})$
- Time dispersion and coherence bandwidth
- Maximum excess delay:

$$T_m = \tau_N - \tau_0$$

  - T_m depends on the interval in which $S(\tau) \neq 0$ (considering a relative threshold).
  - Do two channels with the same T_m have the same effect on the transmitted signal?



Important parameters of multipath channels (2/3)



- **Mean delay**:

$$\bar{\tau} = \frac{\sum_i S(\tau_i)\tau_i}{\sum_i S(\tau_i)}$$

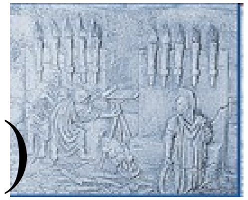
- **RMS delay spread**:

$$\sigma_\tau = \sqrt{\overline{\tau^2} - \bar{\tau}^2},$$

where, $\overline{\tau^2} = \frac{\sum_i S(\tau_i)\tau_i^2}{\sum_i S(\tau_i)}$.

- When $T_s \gg \sigma_\tau$, where T_s the symbol period, then the multipath phenomenon does not introduce Intersymbol Interference (ISI)
  - Rule of thumb : $T_s > 10\sigma_\tau$

Important parameters of multipath channels (3/3)



- Let $H(f,t)$ be the Fourier transform of the channel $h(\tau,t)$.
- Multipath can also be described by the function

$R(\Delta f) = E\{H^*(f,t)H(f+\Delta f,t)\}$.

  - It can be proved that $R(\Delta f)$=Fourier($S(\tau)$).

- Coherence bandwidth: $B_c \simeq \frac{1}{T_m}$.
  - Determines the range of frequencies at which the channel passes all spectral components with approximately equal gain and linear phase.
  - Since T_m is not always representative, empirical formulas have been defined, such as $B_c = \frac{1}{50\sigma_\tau}$
- If $W \ll B_c$, where W is the bandwidth of the signal, then the intersymbol interference can be considered negligible.

Time variant multipath channels

- Let $H(f,t)$ be the Fourier transform of channel the $h(\tau,t)$.
- To quantify the time variability of the channel, the autocorrelation function is calculated:

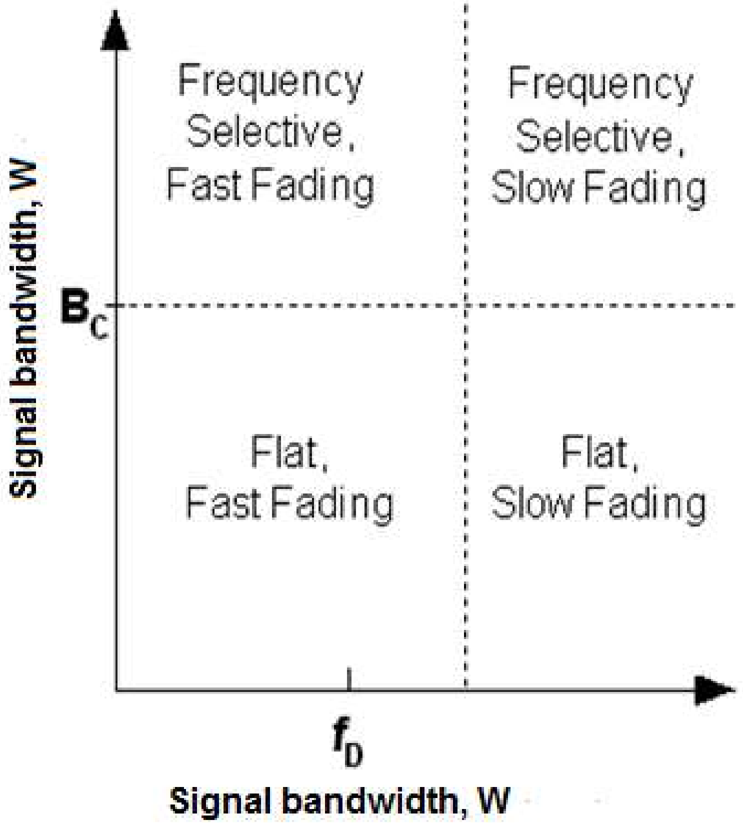
$$R(\Delta t) = E\{H^*(f,t)H(f,t+\Delta t)\}$$

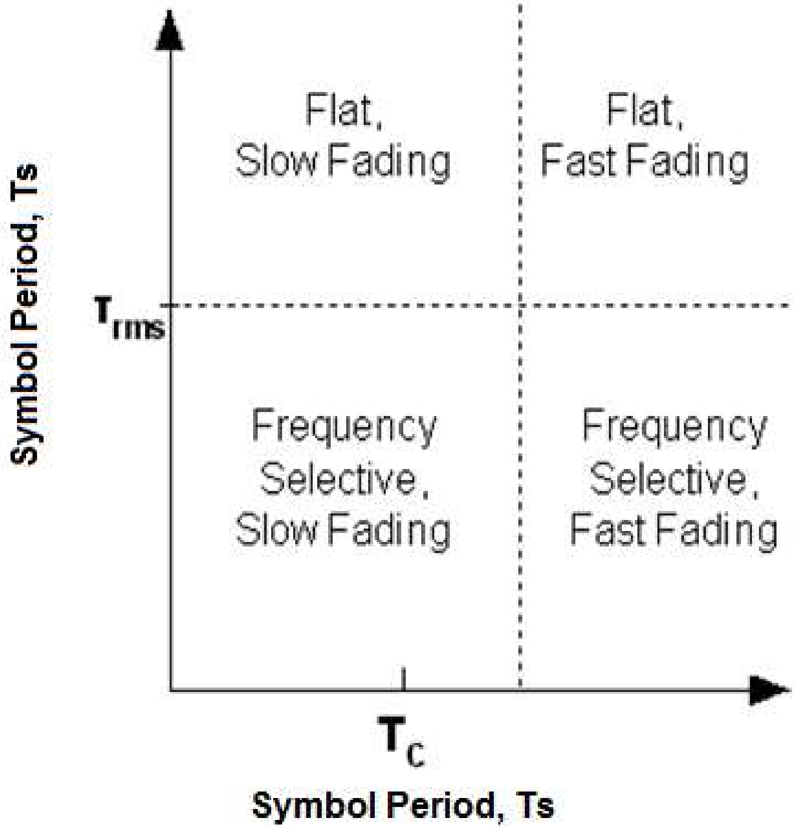
- The Doppler Power Range is defined as:

$$S(f_d) = \text{Fourier}(R(\Delta t))$$

- The **Doppler spread B_d** refers to the Doppler frequency range for which $S(f_d) \neq 0$ and is set *to* $\boldsymbol{B_d = f_D}$
- **Coherence time** T_c is the measure of the expected time at which the channel response remains approximately the same (i.e., with no significant changes)
- The coherence time $T_c \simeq 1/f_D$. An empirical rule is $T_c = 0{,}423/f_D$.
- *If* $T_s \ll T_c$ or $W \gg B_d$, then the channel changes slowly over time.

Fading type and the involved parameters





Usually: $B_c \leq W$ and $W >> B_d$

Practical examples

Example 1: What types of fading are expected?

- Let $v = 100 km/h$, $f_c = 1800\ MHz$, $\sigma_\tau = 1{,}5\ \mu s$ and $W = 200\ KHz$.
- The wavelength is: $\lambda = 17$ cm.
- The Doppler spread is: B_d=163 Hz.
- The bandwidth is: $B_c = \frac{1}{50 * \sigma_\tau} = 13{,}33$ KHz.
- Therefore, $W \gg B_d$ and $W > B_c$

So, the channel can be considered frequency selective and slow fading (equalizer is needed to eliminate ISI)

Example 2: Equalizer not required

$$T_s > 10\sigma_\tau$$

- 2 Mbits/s => T_{bit}=500 ns.
- 1 symbol=4 bits => T_s=2000ns => $\sigma_\tau < 200\ ns$.

Special topics

- The millimeter frequency range.
- Visible range wireless telecommunications.
- Underwater wireless telecommunications.
- Wireless channel models examples.

The millimeter-wave frequency range (1/2)

- The millimeter spectrum refers to the frequency range from 30 GHz to 300 GHz
  - What is the corresponding range of wavelengths?
- The main motivations for using this specific range
  - Underused bands and availability of high bandwidth channels (e.g., 5 GHz)
  - The short wavelength allows the construction of very small antenna arrays that could be used even in mobile devices
- Some examples of frequency assignments in Europe:
  - 57-66 GHz: ISM, Non-specific Short-Range devices
  - 30-31, 66-74, 252-265: Mobile Satellite.
  - 76-81: Radar systems in cars.
  - 76-77,5: Railway applications.
- Disadvantages: high absorption, implementation difficulties

The millimeter-wave frequency range(2/2)

- Some characteristics of a wireless channel in the millimeter frequency range (relative to currently used microwave channels).
- Large path loss according to the Friis equation:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

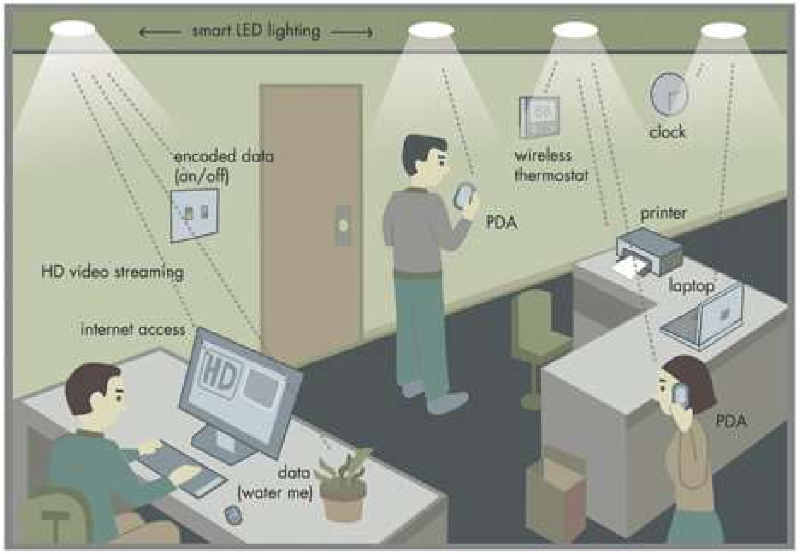
- Large time variation.

Maximum Doppler shift: $f_D = \frac{v}{\lambda}$

- Intermittent transmissions since the diffraction mechanism to avoid obstacles is limited.
    - Even a passing person can create a problem.

- On the other hand, the advantages of mmWave (e.g., huge bandwidth, use of massive antennas, etc.) may over-compensate the above problems.

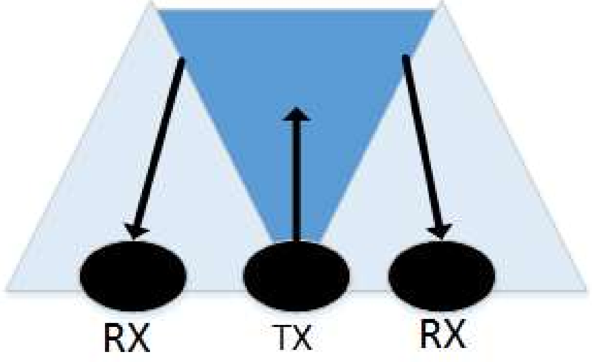
Visible light wireless communications



- Visible light wireless communications use frequencies in the range 400THz-850THz (780-375nm).
- The transmitter modulates the light emitted by an array of LEDs and the receiver uses a photosensor to receive the signal.
- VLC mechanisms
  - Direct LOS link
  - NLOS link (e.g. via reflections)
  - The so-called Diffuse Link (the space is “filled up” with reflections).
    - Movement, shading, directionality of the receiver, etc.
    - The channel is often frequency selective.

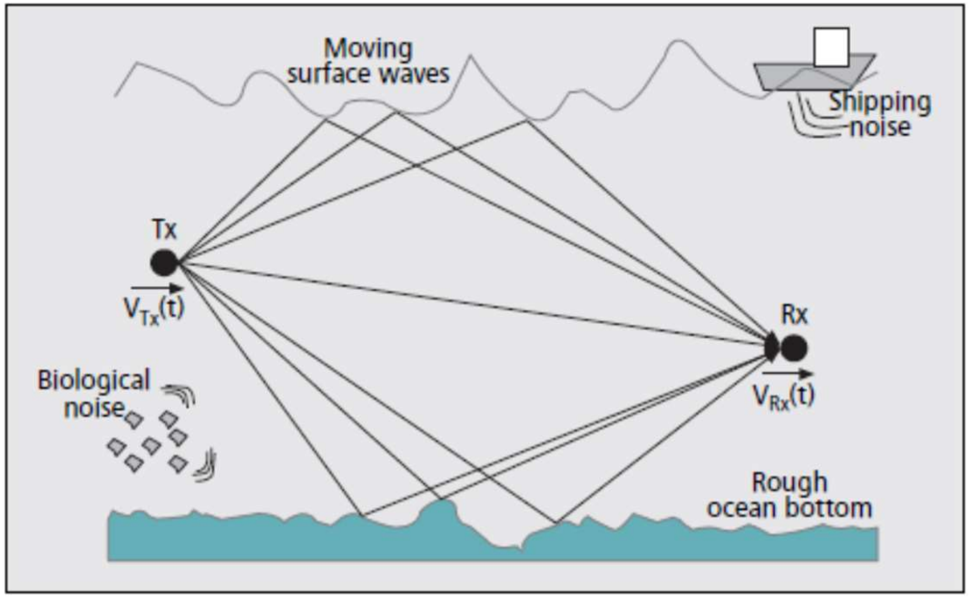
$$h(t) = \frac{H_o}{2\sigma_\tau} e^{-\frac{t}{2\sigma_\tau}}, \quad H(f) = \frac{H_o}{1+j4\pi\sigma_\tau f}$$

where, $H_o = \int_{-\infty}^{\infty} h(t)$.



Underwater wireless communications

- Underwater wireless communications use acoustic signals to send information over long distances.
- The wireless channel is particularly hostile:
  - Long excess delay with multiple paths of different lengths.
  - Temporal variability due to relative transmitter / receiver movement, marine ecosystem and waves.
  - Path loss as a function of distance and frequency.



Examples of wireless channel models (1/3) (OXI)

- **SUI Models** (Stanford University Interim)

Channel	Area	f_D	T_m	LOS
SUI-1	C	Low	Low	High
SUI-2	C	Low	Low	High
SUI-3	B	Low	Low	Low
SUI-4	B	High	Moderate	Low
SUI-5	A	Low	High	Low
SUI-6	A	High	High	Low

- Area A: Area with hills, medium to high density of trees and high loss of path.
- Area B: Area with low tree density or flat area with medium to high tree density and medium path loss.
- Area C: Flat area with low tree density and low path loss.

Examples of wireless channel models (2/3) (OXI)

- SUI-2 Model:
  - Delays per path: $0, \ 0.4, \ 1.1$ (in μs).
  - Power per path: 0, -12, -15 (in dB).
  - Doppler displacement per path: 0.2, 0.15, 0.25 (in Hz).
  - $\sigma_\tau = 0.202 \ \mu s.$
- SUI-5 Model:
  - Delays per path: $0, \ 4, \ 10$ (in μs).
  - Power per path: 0, -5, -10 (in dB).
  - Doppler displacement per path: 2, 1.5, 2.5 (in Hz).
  - $\sigma_\tau = 2.842 \ \mu s.$
- **ITU Models**
  - Models have been defined for (a) indoor communications, (b) outdoor communication, and

    (c) communication between car and base station

Examples of wireless channel models (3/3) (OXI)

- **ITU Models(continued)**
  - For each case two channel versions have been selected, one for short (Channel A) and one for long (Channel B) redundancy.
- ITU-Indoor – Channel A
  - Delays per path: $0,\ 50,\ 110, 170, 290, 310$ (in ns).
  - Power per path: 0, -3, -10, -18, -26, -32 (in dB).
  - $\sigma_\tau = 35$ ns.
- ITU-Vehicular – Channel B
  - Delays per path: $0,\ 300,\ 8900,\ \ 12900,\ \ 17100,\ \ 20000$ (in ns).
  - Power per path: -2.5, 0, -12.8, -10, -25.2, -16 (in dB).
  - $\sigma_\tau = 4000$ ns.