EE303: Communication Systems

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An Overview of Fundamentals: Wireless Channels

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Wireless - Very Large Distances

- The **1st wireless system** was designed by **Guglielmo Marconi** (1901) and used to transmit a wireless message **across the Atlantic Ocean** .

- Marconi was awarded the Nobel Price in Physics (1909) in recognition of his contribution to Wireless Telegraphy

- Wireless Systems have **evolved** over the years
  - to the latest developments in **Multiple-Input Multiple-Output wireless systems** and technologies and
  - to the **interconnection** of wireless devices **into a single all-IP wireless platform** .
- Due to their flexibility and comfort, today wireless systems are used to cover even **very small distances** (short range wireless links)

Wireless - Short Range and Low-Power Wireless Links

1	RF-power	several μW up to 100 mW
2	Range	several cm upto several hundred meters
3	Operation	both indoor and outdoor
		battery-operated Tx/Rx
		e.g. Body Comms, M2M ,wireless IoT
4	antennas	build-in (omnidirectional)

- For instance: "Bluetooth" which is for short-range applications of high-rate data communications for distances of several meters (developed by the Bluetooth consortium of telecommunication and PC technology leaders for eliminating wiring between computers and peripherals, as well as wireless internet access through cellular phones).
- other applications: Security Systems, Emergency Medical Alarms,Computer Accessories (e.g. mouse, keyboard), RFID (Radio Frequency Identification), WLAN (Wireless Local Area Networks),Wireless microphones/headphones/speakers; Keyless Entry, Wireless bar code readers.

Tx - Wireless Channel - Rx

- A wireless system can be partitioned into 3 main parts:
  1. **Tx** (a "**source** " that sends/transmits some information using wave propagation)
  2. **Wireless Channel** (the **physical propagation paths**)
  3. **Rx** (a "**sink** " that receives the transmitted waves)

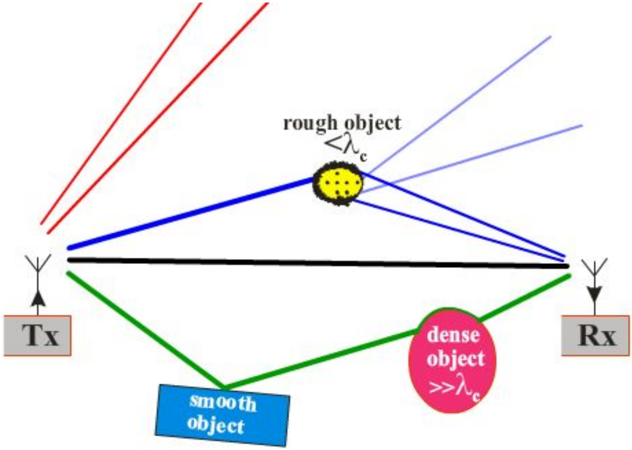
  and the objective in general is
  - to increase the **communication speed** (which is known as channel capacity)
    without sacrificing the **quality of service** (for a given energy + bandwidth)

Wireless Channels

Wireless Channels are much more **difficult** and **hostile** than wired channels.

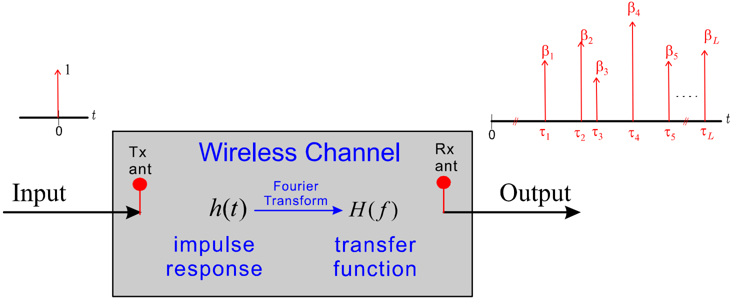
1. **noise** (thermal, sky, etc..)
2. **unintentional interference** from other Tx (multiple access interference)
3. **intentional (hostile)** interference (from Jammers)
4. **multipaths**
   - reflections
   - diffraction
   - refraction
   - scattering

Multipaths

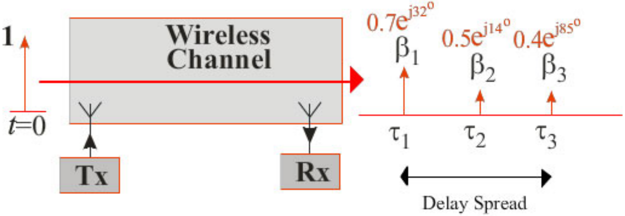

rough object
<λ_c
Tx
Rx
dense
object
>>λ_c
smooth
object

Wireless Channel: Basics (cont.)

Because of multipath reflections (echoes), the channel impulse response of a wireless channel looks likes a series of pulses.



Wireless Channels: Basics (cont.)

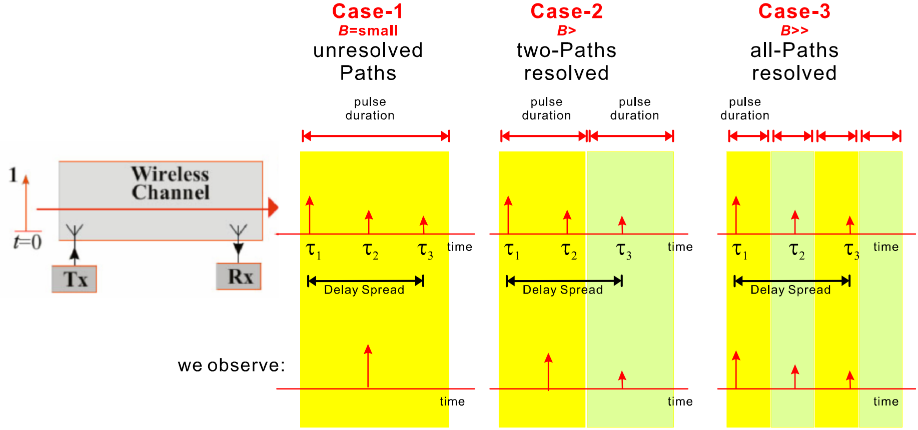


- Note: every path is represented by a **complex number** β

Resolving Multipaths

- The delay spread is **a measure** of **the multipath richness** of a wireless channel.
  - In general, it can be interpreted as the difference between the time of arrival of the earliest significant multipath component and the time of arrival of the latest significant multipath components.
- In **modern wireless systems** the aim is to **resolve** multipaths, to **estimate** them and finally to **utilise** them.

Resolving Multipaths (cont.)



- Pulse duration $= \dfrac{1}{\text{Bandwidth } (B)}$
- Pulse duration $= \downarrow\downarrow\downarrow \implies$ Bandwidth $(B) = \uparrow\uparrow\uparrow \implies$ WB/UWB

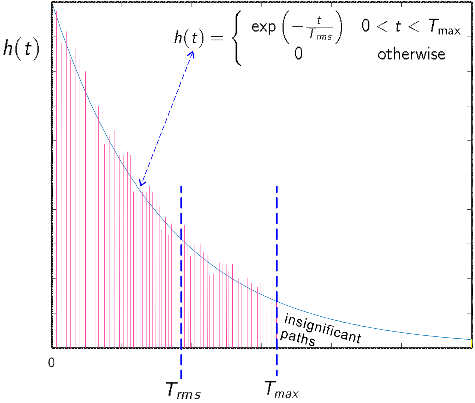
Resolving Multipaths (cont.)

- To find the number of resolvable paths: we compare **delay spread** with the **pulse duration** T_c.
  - If **pulse duration** $<$ **delay spread** $\Rightarrow$ the channel is defined as **FREQUENCY SELECTIVE CHANNEL** and

$$\text{number of resolvable paths} = \left\lfloor \frac{\text{delay spread}}{\text{pulse duration}} \right\rfloor + 1$$

Resolving Multipaths (cont.)

- In practice (indoors) the number of pulses that can be distinguished is very large



- Delay spread can be quantified through different metrics:
  - The maximum delay spread T_{max} is the total time interval during which reflections with significant energy arrive.
  - The r.m.s. delay spread T_{rms} is the standard deviation value of the delay of reflections, weighted proportional to the energy in the reflected waves.
  - The mean delay spread T_{mean}

ITU-R P.1238-1, "Propag. Data & Prediction Methods for the Planning of Indoor .... in the Frequ Range 900 MHz to 100 GHz" 1999.

Multipaths

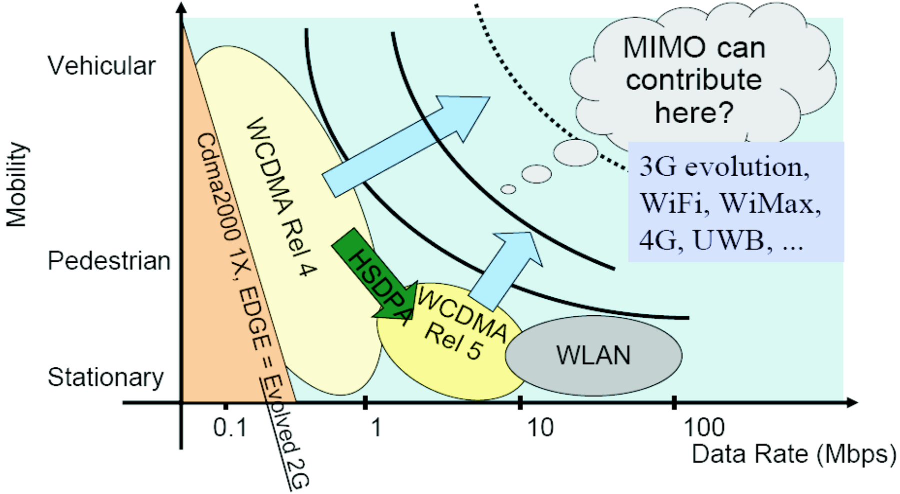
- Before, multipaths = **"unwanted" propagation effect** (known as "self interference") $\Rightarrow$ Aim: to remove multipaths

- In **modern wireless systems** the aim is to **resolve** them and to **utilise** them - using the concept of "**multipath diversity**"
  - this is **extra energy** which increases the **received desired energy** and thus **improves the performance of the system**

Wireless Systems Classification

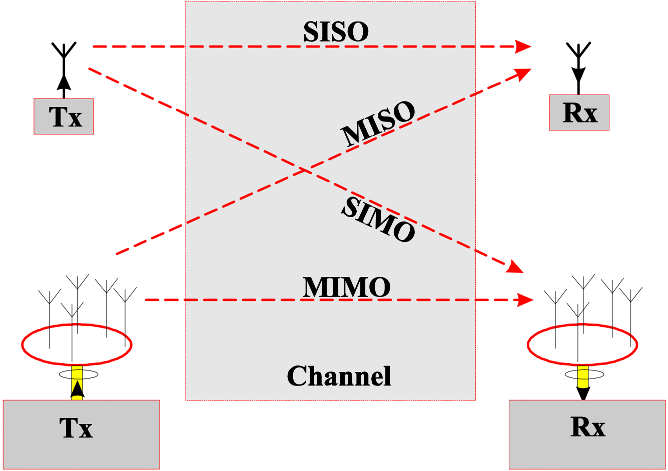
- There are many classifications. For instance:
  1. according to the **bandwidth/carrier**: **narrowband** or **wideband**
  2. according to the **spreading capabilities**: **conventional** or **spread spectrum**
  3. according to the **number of carriers**: **single carrier** or **multicarrier**
  4. according to the **"generation"**: 1G, 2G, **3G** , **3G+**
  5. according to the **"access"**: **TDMA,FDMA** , **CDMA** ,
- The **overall aims:**
  - **speed =** $\uparrow$,
  - **but maintaining reliability** (quality of service) & **spectral efficiency** (EUE,BUE)
- The current speed is expected to increase by the utilisation of the new technology of multiple antennas (MIMO) and this gives rise to **a new classification which super-sets** all the above.

Some Current Wireless Data Rates



New Wireless Systems Classification

- This **new** classification is according to the **number of antennas** used in both Tx and RX



- **My Terminology**

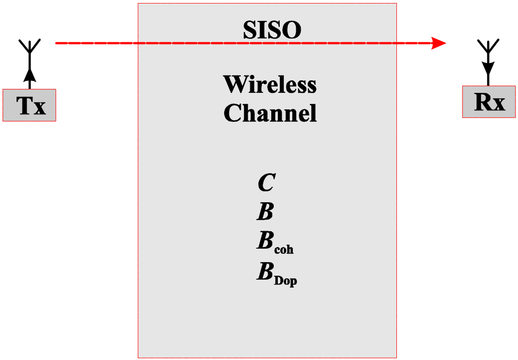
Terminology-1 (More Representative)		
1	SISO:	Scalar-Input-Scalar-Output Channel
2	SIVO:	Scalar-Input-Vector-Output Channel
3	VISO:	Vector-Input-Scalar-Output Channel
4	VIVO:	Vector-Input-Vector-Output Channel

- **Alternative Terminology**

Terminology-2 (Initial)		
1	SESE	Single-Element (SE) Tx to Single-Element (SE) Rx
2	SEME	Single-Element (SE) Tx to Multiple-Element (ME) Rx
3	MESE	Multiple-Element (ME) Tx to Single-Element (SE) Rx
4	MEME	Multiple-Element (ME) Tx to Multiple-Element (ME) Rx

Terminology-3 (More Popular)		
1	SISO:	Single-Input-Single-Output
2	SIMO:	Single-Input-Multiple-Output
3	MISO:	Multiple-Input-Single-Output
4	MIMO:	Multiple-Input-Multiple-Output

Wireless SISO Channels



Important Wireless Channel Parameters

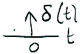
- C = Channel Capacity (inf. bits/sec)
- B = Tx-signal/channel Bandwidth (Hz)
  B_{coh} = Coherence Bandwidth of the Channel(Hz)
  ▶typical examples of coherence
  bandwidth: $B_{coh} = \begin{cases} 3 \text{ MHz outdoor wireless channel} \\ 100 \text{ MHz indoor wireless channels} \end{cases}$
  B_{Dop} = Doppler Spread of the Channel (Hz)
- T_{cs} = Duration of a channel symbol (sec)
  T_{spread} = multipath spread or delay spread (sec)
  T_{coh} = Coherence time (sec)

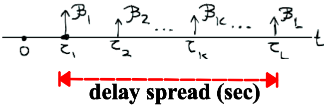
$$B = \frac{1}{T_{cs}} \tag{1}$$

$$B_{coh} = \frac{1}{T_{spread}} \tag{2}$$

$$B_{Dop} = \frac{1}{T_{coh}} \tag{3}$$

Multipaths

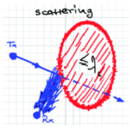
- if I/p is 

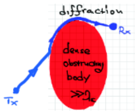
then o/p = 

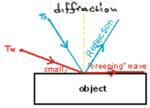
$= h(t)$

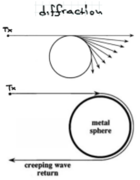
- multipaths: arise from
  - reflection
  - scattering
  - refraction, or
  - diffraction

  of the radiated energy off objects that lie in the propagation path



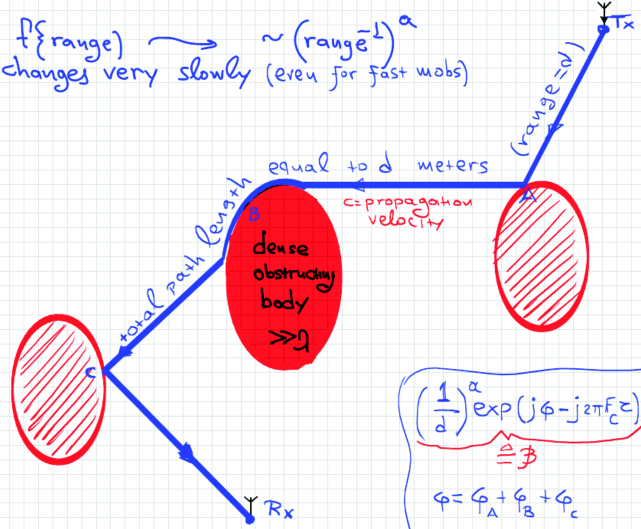






Propagation Loss

* $f\{\text{range}\} \longrightarrow \sim (\text{range}^{-1})^{\alpha}$
* changes very slowly (even for fast mobs)

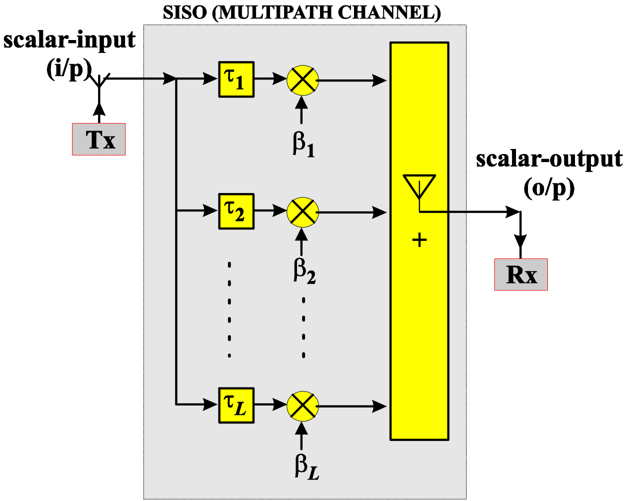


$$\underbrace{\left(\frac{1}{d}\right)^{\alpha} \exp(j\phi - j2\pi F_c\tau)}_{\triangleq \beta}\, \delta(t-\tau)$$

$$\phi = \phi_A + \phi_B + \phi_C$$

$$\tau = \frac{d}{c}$$

- In a wireless system the received signal is the summation of a number of paths (ignoring noise).

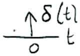
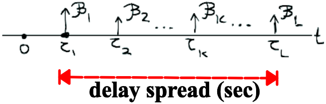


- Impulse response (baseband):

$$h(t) = \sum_{\ell=1}^{L} \underbrace{\left(\frac{1}{d_\ell}\right)^{\mathbf{a}} \exp(j\varphi_\ell - j2\pi F_\mathbf{c} \overbrace{\tau_\ell}^{\frac{d_\ell}{c}})}_{\beta_\ell} \delta(t-\tau_\ell) \tag{4}$$

$$= \sum_{\ell=1}^{L} \beta_\ell \delta(t-\tau_\ell) \tag{5}$$

or, equivalently,

if I/p is  then o/p =  $= h(t)$

Fading

Fading $\triangleq$ fluctuation in received signal levels

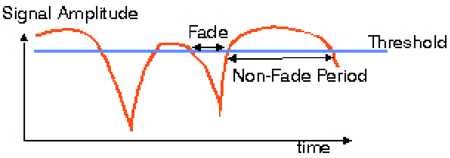
involves 2 multiplicative components

fast fading or short-term fading or multipath fading or Rayleigh fading

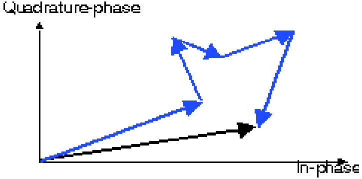
results from multipath scattering in the vicinity of the mobile

slow fading or long-term fading or shadowing

results from objects blocking the propagation path of the signal



- Sample of a "fading" signal envelope: amplitude in dB versus time or location of the antenna. Wave interference of multiple reflected waves, each with a different amplitude and phase, causes fluctuations of the received signal amplitude.
- Changing the antenna location or the carrier frequency also changes the signal amplitude.

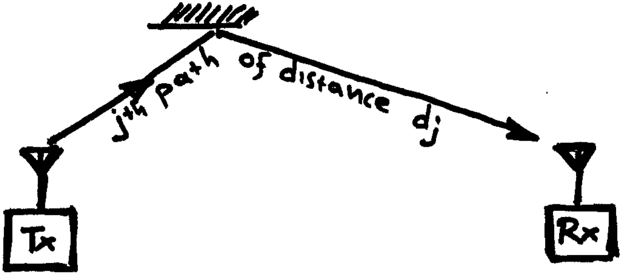


This is known as fading

Delay Spread

- This is the time it takes for light to travel a distance equal to the longest path minus the shortest path
  i.e.

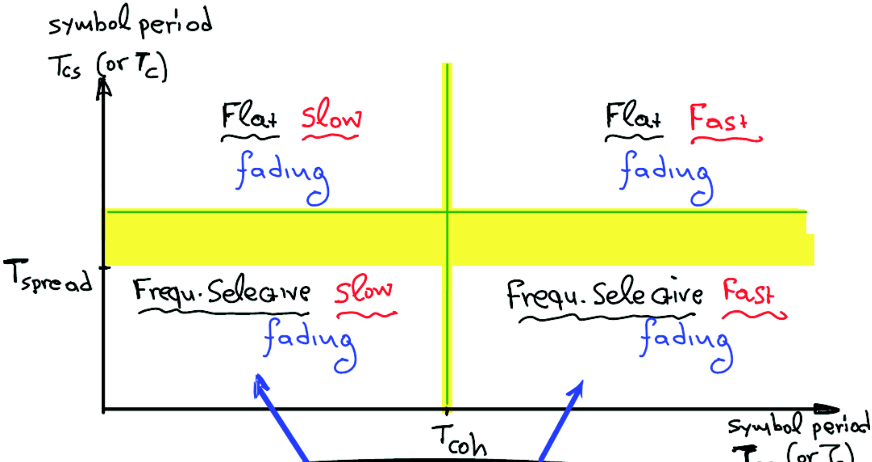
$$T_{\text{spread}} \equiv \frac{\max_{\forall j}\{d_j\} - \min_{\forall j}\{d_j\}}{c} \tag{6}$$



- **typical examples of delay spread:**
  - fraction of μs$\leq T_{\text{spread}} \leq$many μs

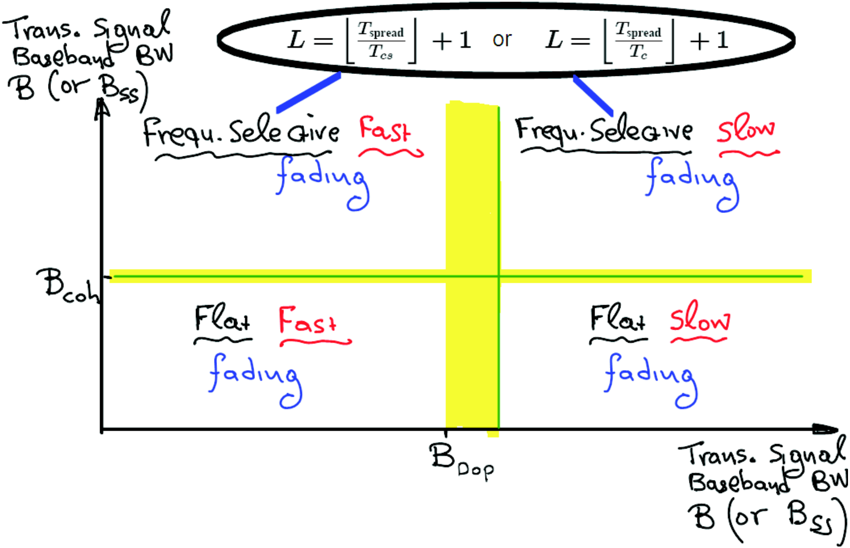
Classification of Wireless Channels

- By comparing T_{cs} (or T_c) with T_{spread} and/or T_{coh}



$$L = \left\lfloor \frac{T_{\text{spread}}}{T_{cs}} \right\rfloor + 1 \quad \text{or} \quad L = \left\lfloor \frac{T_{\text{spread}}}{T_c} \right\rfloor + 1$$

- By comparing B (or B_{ss}) with B_{coh} and/or B_{Dop}



- Some Comments on **Multipath Fading in a Conventional System**
  - In a conventional mobile cellular system (TDM/FDM) the destructive interference is known as **multipath or Rayleigh fading**.
  - This occurs **more frequently** when the mobile **is moving**.
  - This fading is **detrimental** to the system performance.
  - Thus, in a conventional system $\mathbf{T}_{\text{spread}}$ is compared to $\mathbf{T}_{\mathbf{cs}}$

$$\underline{\text{IF}} \left\{ \begin{array}{c} T_{\text{spread}} > T_{cs} \\ (\text{i.e.} B_{\text{coh}} < B) \end{array} \right\} \text{then paths can be separated}$$

$$\underline{\text{ELSE}} \text{ signals are distorted} \Longrightarrow \text{FLAT FADING}$$

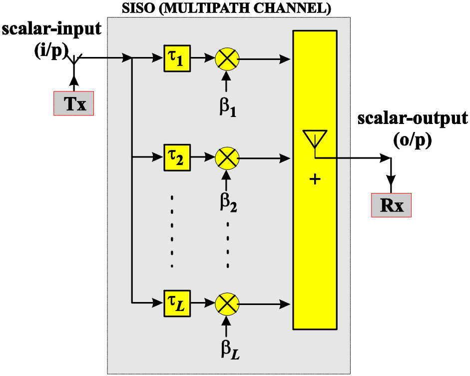
  - Number of **resolvable paths** in a conventional system:

$$L = \left\lfloor \frac{T_{\text{spread}}}{T_{cs}} \right\rfloor + 1 \tag{7}$$

- Some Comments **Multipath Fading in Spread Spectrum Systems:**
  - Multipath fading exists in Spread Spectrum (or CDMA) Systems as well but it is **significantly lower**
  - Number of **resolvable paths** in a SSS or CDMA:

$$L = \left\lfloor \frac{T_{\text{spread}}}{T_c} \right\rfloor + 1 \tag{8}$$

- Remember - Frequency Selective Channels:

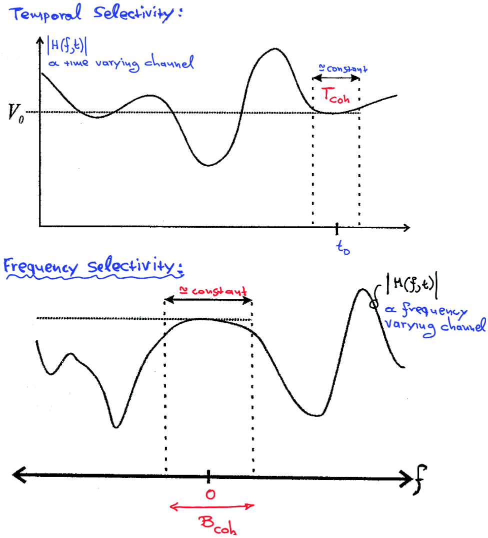


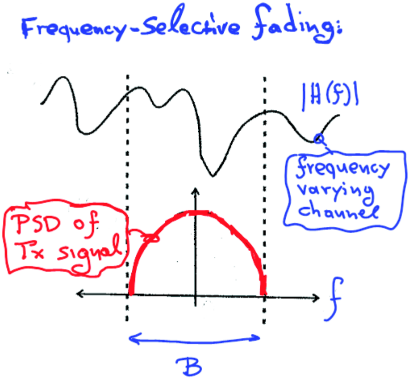
$$\Rightarrow h(t) = \sum_{\ell=1}^{L} \beta_\ell \delta(t - \tau_\ell) \tag{9}$$

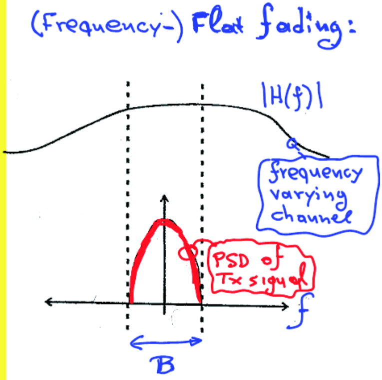
Channel Selectivity and Channel Coherence

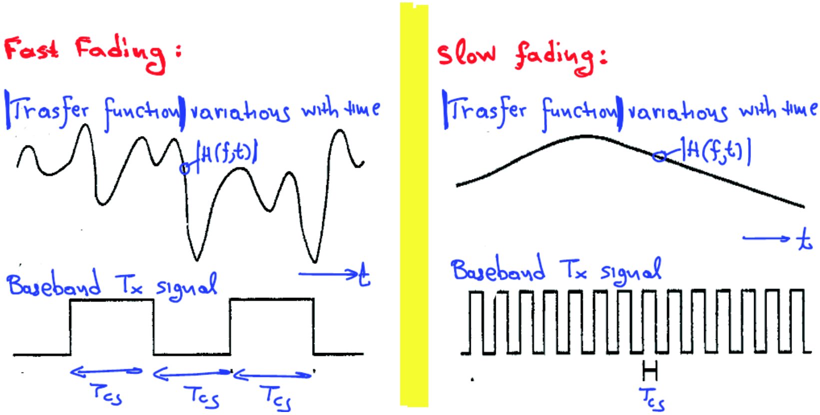
- Channel *Selectivity*: A channel has selectivity if **it varies** as a function of either time, frequency, or space
- Channel Coherence: (opposite of Channel Selectivity)
  - A channel has coherence if **it does not vary** as a function of either time, frequency, or space over a specified 'window' of interest.
  - This is the **most important** concept in describing wireless channels
  - coherence: $\begin{cases} \textit{temporal} \text{ coherence} & \text{-coherence time } T_{\text{coh}} \\ \textit{frequency} \text{ coherence} & \text{-coherence bandwidth } B_{\text{coh}} \\ \textit{spatial} \text{ coherence} & \text{-coherence distance } D_{\text{coh}} \end{cases}$

Examples: Temporal and Frequency Selectivity

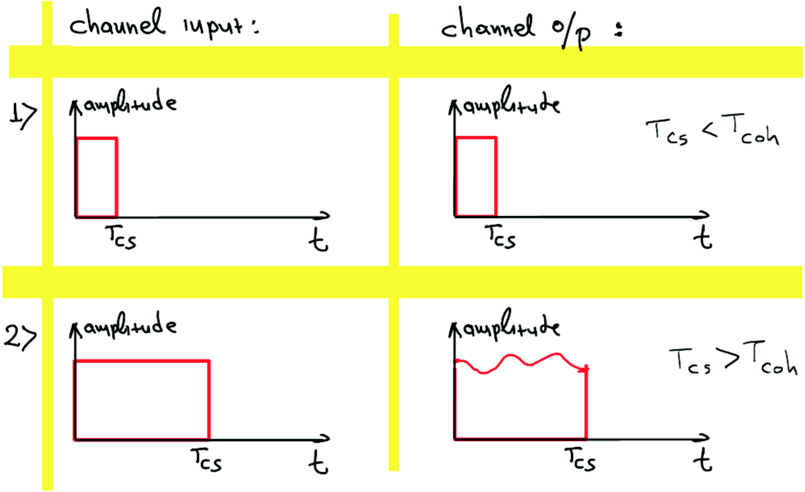



Frequency-Selective fading:
|H(f)|
frequency varying channel
PSD of Tx signal
f
B

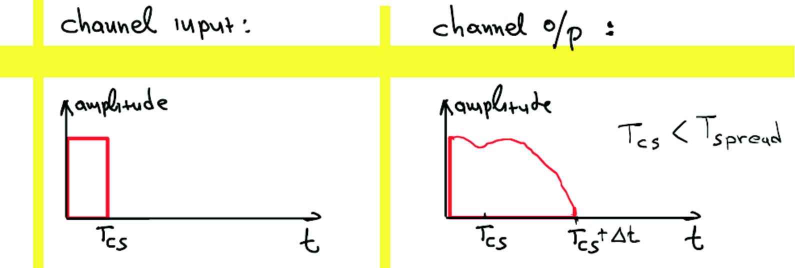

(Frequency-) Flat fading:
|H(f)|
frequency varying channel
PSD of Tx signal
f
B


Fast Fading:
|Trasfer function| variations with time
|H(f,t)|
t
Baseband Tx signal
Tcs
Tcs
Tcs
slow fading:
|Trasfer function| variations with time
|H(f,t)|
t
Baseband Tx signal
Tcs

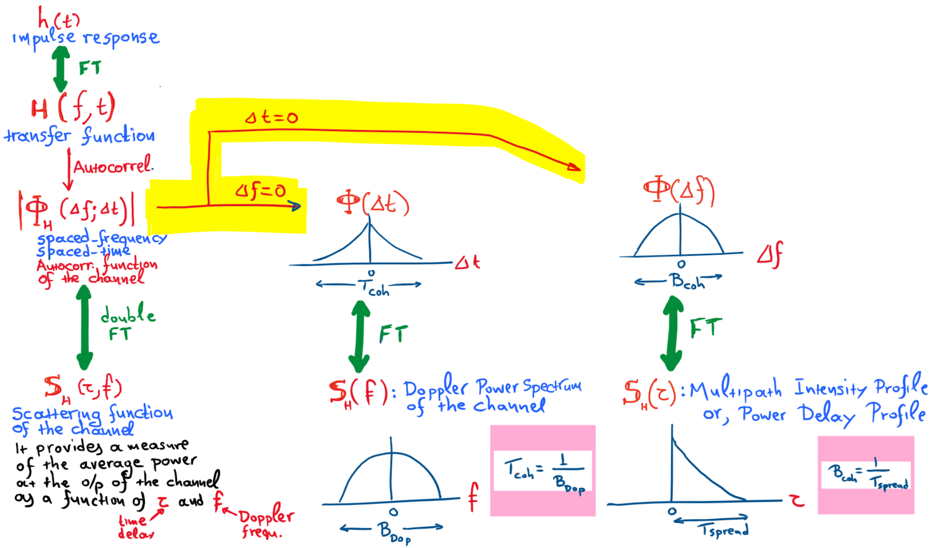
- **Example of effect** of transmitting a rect pulse over a **Time Selective** Fading Channel



- Example of effect of transmitting a rect pulse over a **Frequency Selective** Fading Channel



Wireless Channel Analysis



Some Brief Notes on the Estimation of Delay Spread

There are many ways to estimate the delay spread. For instance:

1. using the FFT of the input signal and then forming the autocorrelation function in the frequency domain (Δf). This will provide the coherence bandwidth. The inverse of the coherence bandwidth is the delay spread.
2. Using the scattering function of the wireless channel's transfer function.
3. Using the **Power Delay Profile** , $S_H(\tau)$: The power delay profile (PDP) gives the intensity of a signal received through a multipath channel as a function of time delay.
    - The abscissa is in units of time and the ordinate is usually in decibels. It is easily measured empirically and can be used to extract certain channel parameters such as the delay spread.
    - The equations for estimating the delay spread are:

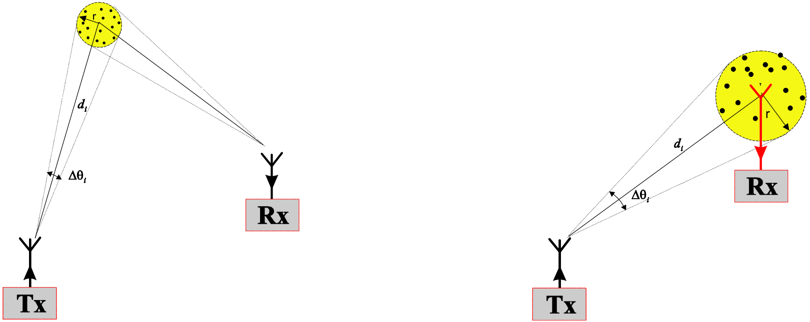
Equattion of the Delay Spread

$$T_{mean} \triangleq \frac{\int_0^{T_{\max}} \tau S_H(\tau) d\tau}{\int\limits_0^{T_{\max}} S_H(\tau) d\tau} \tag{10}$$

$$T_{rms} \triangleq \sqrt{\frac{\int_0^{T_{\max}} (\tau - T_{mean})^2 S_H(\tau) d\tau}{\int\limits_0^{T_{\max}} S_H(\tau) d\tau}} \tag{11}$$

Scatterers

- The figures below show a scatterer-cloud (the l-th scatterer) in two typical scenarios.



$$\ell\text{-th scatterer} = \sum_{k=1}^{L_{scat}} \beta_{\ell k} \delta(t - \tau_{\ell k}). \tag{12}$$

- L_{scat} = the number of paths related to this scatterer

- If the paths cannot be resolved, that is if

$$\tau_{\ell 1} \simeq \tau_{\ell 2} \simeq .. \simeq \tau_{\ell L_{scat}} \triangleq \tau_\ell \tag{13}$$

then

$$\begin{aligned}
\ell\text{-th scatterer} &= \sum_{k=1}^{L_{scat}} \beta_{\ell k}\delta(t - \tau_{\ell k}) \\
&= \sum_{k=1}^{L_{scat}} \beta_{\ell k}\delta(t - \tau_{\ell}) \\
&= \underbrace{\left(\sum_{k=1}^{L_{scat}} \beta_{\ell k}\right)}_{\beta_\ell}\delta(t - \tau_{\ell}) \\
&= \beta_\ell \delta(t - \tau_\ell) \qquad (14)
\end{aligned}$$

- In this case $\beta_\ell = \left(\sum_{k=1}^{L_{scat}} \beta_{\ell k}\right)$ is a random variable and, therefore, should be described by a probability density function (pdf).

Log-distance Path Loss Model

$$\text{Path-Loss(PL)} = \underbrace{10\log_{10}\frac{\overset{Watt}{\downarrow}}{\overset{}{P_{Tx}}}\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\!\frac{P_{Tx}}{1mW}}_{Tx \text{ power in dBm}} - \underbrace{10\log_{10}\frac{P_{Rx}}{1mW}}_{Rx \text{ power in dBm}} \text{ (dB)} \quad (15)$$

$$= \text{PL}_0 + 10\log_{10}\left(\frac{d}{d_0}\right)^a + \text{PL}_{Gaussian} \text{ (dB)} \quad (16)$$

where

$$\begin{aligned} \text{PL}_0 &= \text{the path loss at the reference distance } d_0 = 1km/1mile \\ d &= \text{path length} \\ a &= \text{path loss exponent} \\ \text{PL}_{Gaussian} &= N(0,\sigma^2). \end{aligned}$$

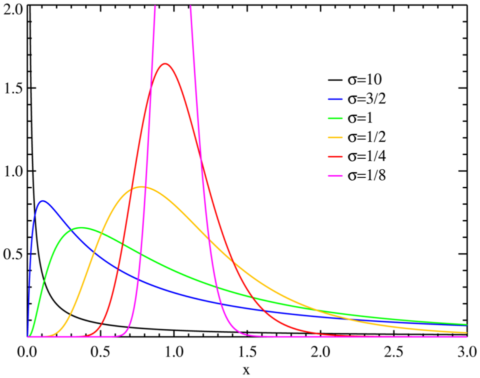
Notes on $\text{PL}_{Gaussian} = N(0, \sigma^2)$

- no-fading $\Rightarrow \sigma = 0$
- *shadow fading* or *slow fading* $\Rightarrow \sigma > 0$ in dB $\Rightarrow P_{Rx}$=random (log-normal distribution) in Watt.
- *fast fading caused by multipath propagation*, the corresponding path gain $|\beta_\ell|$ (i.e. $|\beta_\ell|^2$ in Watts) may be modelled as a random variable with *Rayleigh distribution* or *Ricean distribution*.

Log-Normal Distribution

- a log-normal distribution = a continuous probability distribution of a random variable x

$$\mathrm{pdf}_{\mathrm{x}}(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left\{ \frac{(\ln x - \mu)^2}{2\sigma^2} \right\} \tag{17}$$



- a log-normal random variable = takes only +ve real values.
- If x=Normal-distribution $\Rightarrow y = \exp(x)$ = log-normal distribution
- if y= log-normal- distribution$\Rightarrow x = \ln(y)$= normal distribution.
- A variable might be modeled as log-normal if it can be thought of as the multiplicative product of many independent random variables each of which is positive.
- In wireless communication:

$$\begin{gathered}\textit{shadow fading} \text{ or } \textit{slow fading} \\ \Downarrow \\ \mathrm{PL}_{Gaussian} = N(0, \sigma^2) \text{ with } \sigma > 0 \text{ in dB} \\ \Downarrow \\ P_{Rx} = \text{random (log-normal distribution) in Watt.}\end{gathered}$$

Fast fading (multipath propagation)

- There are two main cases
  - **CASE-1** :

$$\begin{array}{ll} \textbf{if} & \nexists \text{ a direct path} \\ \textbf{then} & \left\{ \begin{array}{l} \text{pdf of } |\beta_\ell| = \text{Rayleigh distribution} \\ \text{pdf of } \measuredangle\beta_\ell = \text{uniform distribution} \end{array} \right| \text{(urban areas \& large cells)} \end{array}$$

  - **CASE-2** :

$$\begin{array}{ll} \textbf{if} & \exists \text{ a direct path} \\ \textbf{then} & \left\{ \begin{array}{l} \text{pdf of } |\beta_\ell| = \text{Ricean distribution} \\ \text{pdf of } \measuredangle\beta_\ell = \text{uniform distribution} \end{array} \right| \begin{array}{l} \text{(small cells \&} \\ \text{satellite mobile systems)} \end{array} \end{array}$$

- A better pdf which has more degrees of freedom is the NAKAGAMI distribution. This enables a better fit to experimental measurements in urban channels.

Fast fading (multipath propagation)

Nakagami Distribution

Nakagami distribution: 6-7-97

$$\mathrm{pdf}_x(x) = \frac{2 m^m x^{2m-1}}{\underbrace{\Gamma\{m\}}_{\text{gamma function}}\sigma^2} \exp\left(-\frac{m x^2}{\sigma^2}\right)$$

$$\boxed{\sigma^2 = \mathcal{E}\{x^2\}}$$

$$\boxed{m = \frac{\sigma^2}{\mathcal{E}\{(x^2-\sigma^2)^2\}}}$$

Nakagami
- $=$ → Rayleigh $(m=1)$ if scattering process generates diffuse wave field
- $\simeq$ → Rice $(m>1)$ if $\exists$ direct path

iff $K = \dfrac{\sqrt{m^2-m}}{m-\sqrt{m^2-m}}$ $\quad m \geq 1$

with $K = \dfrac{\mu^2}{\sigma^2}$

$$\mathrm{pdf}_x(x) = \frac{2x}{\sigma^2} \exp\left(-\frac{x^2+\mu^2}{\sigma^2}\right) \underbrace{J_0\left\{\frac{2\mu x}{\sigma^2}\right\}}_{\text{modified Bessel function of order '0'}}$$

$x > 0$

power of direct path (μ^2)

Clusters

- The generation of clusters in a typical urban area is described as follows:
  - Many buildings in a typical urban area generally surround a mobile.
  - Electromagnetic waves from an MS (Mobile-Station) do not propagate in random directions, but along the streets.
  - These waves propagate to a BS (Base-Station) while being reflected or scattered at many points along the street.
  - Not all reflected or scattered waves propagate to a BS, but some waves bolstered by certain conditions will propagate to a BS because many buildings obstruct the waves.
  - Each group of selected waves is recognised as a cluster.

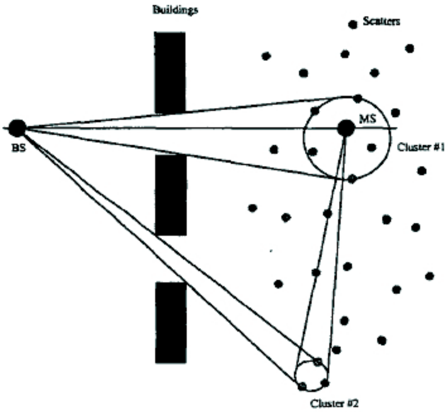
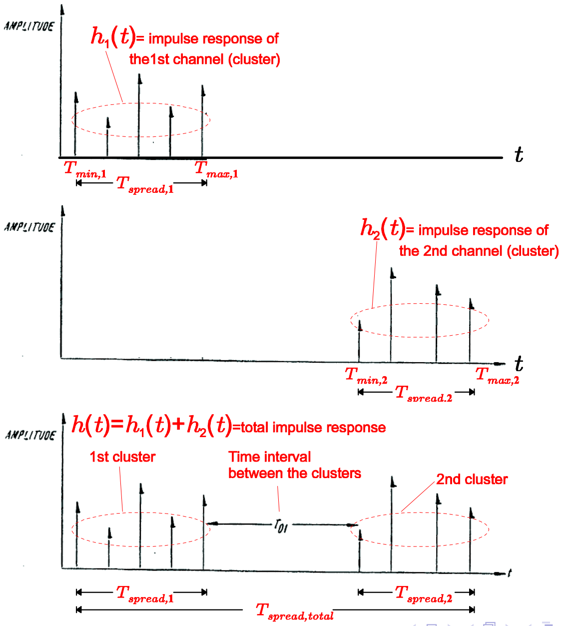


Fig. 1. Generation of clusters.

- The above will give an impulse response similar to the following


AMPLITUDE
$h_1(t)$= impulse response of the1st channel (cluster)
t
$T_{min,1}$
$T_{max,1}$
$T_{spread,1}$
AMPLITUDE
$h_2(t)$= impulse response of the 2nd channel (cluster)
t
$T_{min,2}$
$T_{max,2}$
$T_{spread,2}$
AMPLITUDE
$h(t)=h_1(t)+h_2(t)$=total impulse response
1st cluster
Time interval between the clusters
2nd cluster
T_{01}
t
$T_{spread,1}$
$T_{spread,2}$
$T_{spread,total}$

- Note that
  - if $T_{spread,1} < T_{cs}$ then the 1st cluster involves a number of unresolvable paths and becomes one ray/path by itself.
  - A similar comment can be made for the 2nd cluster.
  - if both clusters involve a number of unresolvable paths then the two clusters are seen as two resolvable paths.

Modelling of the Received Scalar-Signal x(t)

- Consider a single Tx transmitting a baseband signal $m(t)$ via an L-path SISO channel. Based on Equation 9, the received signal $x(t)$ can be modelled as follows:

$$\begin{aligned} x(t) &= h(t) * m(t) + \mathrm{n}(t) = \left(\sum_{\ell=1}^{L} \beta_\ell . \delta(t - \tau_\ell) \right) * m(t) + \mathrm{n}(t) \\ \Rightarrow x(t) &= \sum_{\ell=1}^{L} \beta_\ell . m(t - \tau_\ell) + \mathrm{n}(t) \qquad (18) \end{aligned}$$

- Next consider M transmitters operating at the same time, on the same frequency band each one with its own SISO channel.
- In this case we have added the subscript i to refer to the i-th Tx.
- The received signal $x(t)$ can be modelled as follows:

$$x(t) = \sum_{i=1}^{M} \sum_{\ell=1}^{L} \beta_{i\ell} . m_i(t - \tau_{i\ell}) + \mathrm{n}(t) \qquad (19)$$