EE303: Communication Systems

Professor A. Manikas
Chair of Communications and Array Processing

Imperial College London

An Overview of Fundamentals: Wireless Channels
Table of Contents

1 Introduction - Basics
   • Wireless Channels
   • Multipaths
   • Resolving Multipaths
   • Wireless Systems Classification

2 Wireless SISO Channels
   • Important Wireless Channel Parameters
   • Multipaths
   • Propagation Loss
   • Fading
   • Delay Spread, $T_{\text{spread}}$
   • Classification of Wireless Channels
   • Channel Selectivity and Channel Coherence
   • Examples: Temporal and Frequency Selectivity
   • Wireless Channel Analysis
   • Some Brief Notes on the Estimation of Delay Spread
   • Scatterers
   • Fading and Path Gain/Loss
     • Log-distance Path-Loss Model
     • Log-Normal Distribution
     • Rayleigh, Ricean and Uniform Distributions
     • Nakagami Distribution
   • Clusters
   • Modelling of the Received Scalar-Signal $x(t)$
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)
Introduction - Basics

Wireless - Short Range and Low-Power Wireless Links

<table>
<thead>
<tr>
<th></th>
<th>RF-power</th>
<th>several $\mu$W up to 100 mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Range</td>
<td>several cm up to several hundred meters</td>
</tr>
<tr>
<td>3</td>
<td>Operation</td>
<td>both indoor and outdoor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>battery-operated Tx/Rx</td>
</tr>
<tr>
<td></td>
<td></td>
<td>e.g. Body Comms, M2M, wireless IoT</td>
</tr>
<tr>
<td>4</td>
<td>antennas</td>
<td>build-in (omnidirectional)</td>
</tr>
</tbody>
</table>

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
Because of multipath reflections (echoes), the channel impulse response of a wireless channel looks like a series of pulses.
Wireless Channels: Basics (cont.)

- Note: every path is represented by a complex number $\beta$
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.)

**Case-1**  
\( B = \text{small} \)  
unresolved Paths

**Case-2**  
\( B > \)  
two-Paths resolved

**Case-3**  
\( B >> \)  
all-Paths resolved

we observe:

- Pulse duration = \( \frac{1}{\text{Bandwidth} \ (B)} \)
- Pulse duration = \( \downarrow \downarrow \downarrow \) \( \Rightarrow \) Bandwidth \( (B) = \uparrow \uparrow \uparrow \) \( \Rightarrow \) 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 $< \text{delay spread} \Rightarrow$ 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.

\[ h(t) = \begin{cases} 
\exp \left( -\frac{t}{T_{rms}} \right) & 0 < t < T_{max} \\
0 & \text{otherwise} \end{cases} \]

- 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 \( T_{mean} \)

Multipaths

- Before, multipaths = "unwanted" propagation effect (known as "self interference") ⇒ 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

- Vehicular
- Pedestrian
- Stationary

Data Rate (Mbps)

- WCDMA Rel 4
- HSDPA
- WCDMA Rel 5
- WLAN

MIMO can contribute here?

- 3G evolution
- WiFi, WiMax
- 4G, UWB

Prof. A. Manikas (Imperial College)
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)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SISO:</td>
<td>Scalar-Input-Scalar-Output Channel</td>
</tr>
<tr>
<td>2</td>
<td>SIVO:</td>
<td>Scalar-Input-Vector-Output Channel</td>
</tr>
<tr>
<td>3</td>
<td>VISO:</td>
<td>Vector-Input-Scalar-Output Channel</td>
</tr>
<tr>
<td>4</td>
<td>VIVO:</td>
<td>Vector-Input-Vector-Output Channel</td>
</tr>
</tbody>
</table>

### Alternative Terminology

**Terminology-2** (Initial)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SESE</td>
<td>Single-Element (SE) Tx to Single-Element (SE) Rx</td>
</tr>
<tr>
<td>2</td>
<td>SEME</td>
<td>Single-Element (SE) Tx to Multiple-Element (ME) Rx</td>
</tr>
<tr>
<td>3</td>
<td>MESE</td>
<td>Multiple-Element (ME) Tx to Single-Element (SE) Rx</td>
</tr>
<tr>
<td>4</td>
<td>MEME</td>
<td>Multiple-Element (ME) Tx to Multiple-Element (ME) Rx</td>
</tr>
</tbody>
</table>

**Terminology-3** (More Popular)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SISO:</td>
<td>Single-Input-Single-Output</td>
</tr>
<tr>
<td>2</td>
<td>SIMO:</td>
<td>Single-Input-Multiple-Output</td>
</tr>
<tr>
<td>3</td>
<td>MISO:</td>
<td>Multiple-Input-Single-Output</td>
</tr>
<tr>
<td>4</td>
<td>MIMO:</td>
<td>Multiple-Input-Multiple-Output</td>
</tr>
</tbody>
</table>
Wireless SISO Channels

SISO

Wireless Channel

Tx

B

B_{coh}

B_{Dop}

Rx
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)

\[
B = \frac{1}{T_{cs}} \quad (1)
\]

\[
B_{coh} = \frac{1}{T_{spread}} \quad (2)
\]

\[
B_{Dop} = \frac{1}{T_{coh}} \quad (3)
\]
Multipaths

- If $x(t)$ is $\delta(t)$, then $h(t)$ is the delay spread (sec)

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

of the radiated energy off objects that lie in the propagation path.
Propagation Loss

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

\[ (\frac{1}{d})^\alpha \exp(j\phi - j2\pi f_c t) \delta(t - \tau) \]

\[ \phi = \phi_A + \phi_B + \phi_c \]
\[ \tau = \frac{d}{c} \]
In a wireless system the received signal is the summation of a number of paths (ignoring noise).
• Impulse response (baseband):

\[
h(t) = \sum_{\ell=1}^{L} \left( \frac{1}{d_{\ell}} \right)^{a} \exp(j\varphi_{\ell} - j2\pi F_{c} \frac{d_{\ell}}{c} \tau_{\ell}) \delta(t - \tau_{\ell})\]

(4)

or, equivalently,

\[
h(t) = \sum_{\ell=1}^{L} \beta_{\ell} \delta(t - \tau_{\ell})
\]

(5)

or, equivalently,

If \( I/\rho \) is \( \delta(t) \) then \( O/\rho = \sum_{\ell=1}^{L} \delta(t - \tau_{\ell}) \) = \( h(t) \)
Fading

Fading $\triangleq$ fluctuation in received signal level

- **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 fading**
- 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.
  \[ T_{\text{spread}} \equiv \frac{\max\{d_j\} - \min\{d_j\}}{c} \]  
  (6)

- **typical examples of delay spread:**
  - fraction of \( \mu s \leq T_{\text{spread}} \leq \text{many} \ \mu s \)
Classification of Wireless Channels

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

\[ L = \left\lceil \frac{T_{\text{spread}}}{T_{cs}} \right\rceil + 1 \quad \text{or} \quad L = \left\lceil \frac{T_{\text{spread}}}{T_c} \right\rceil + 1 \]
By comparing $B$ (or $B_{ss}$) with $B_{coh}$ and/or $B_{Dop}$,

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

Trans. Signal Baseband BW $B$ (or $B_{ss}$)

- Frequency Selective
- Fast fading

Frequ. Selective

- Slow fading

Flat $B_{coh}$

- Fast fading

Flat $B_{Dop}$

- Slow fading

Trans. Signal Baseband BW $B$ (or $B_{ss}$)
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 $T_{\text{spread}}$ is compared to $T_{cs}$

  \[
  \begin{align*}
  \text{IF} \quad & \left\{ \begin{array}{l}
  T_{\text{spread}} > T_{cs} \\
  \text{(i.e. } B_{\text{coh}} < B) \end{array} \right. \\
  \Rightarrow & \text{ then paths can be separated} \\
  \text{ELSE} & \text{ signals are distorted} \quad \Rightarrow \quad \text{FLAT FADING}
  \end{align*}
  \]

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

  \[
  L = \left\lfloor \frac{T_{\text{spread}}}{T_{cs}} \right\rfloor + 1 \quad (7)
  \]
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:

\[ L = \left\lfloor \frac{T_{\text{spread}}}{T_c} \right\rfloor + 1 \]  

(8)
- Remember - Frequency Selective Channels:

\[ h(t) = \sum_{\ell=1}^{L} \beta_{\ell} \delta(t - \tau_{\ell}) \]  

(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:
    - **temporal coherence** - coherence time $T_{coh}$
    - **frequency coherence** - coherence bandwidth $B_{coh}$
    - **spatial coherence** - coherence distance $D_{coh}$
Examples: Temporal and Frequency Selectivity

**Temporal Selectivity:**

\[ |H(f,t)| \]

\( \alpha \) time varying channel

\( V_0 \)

\( t_D \)

\( T_{coh} \)

**Frequency Selectivity:**

\[ |H(f,t)| \]

\( \alpha \) frequency varying channel

\( f \)

\( B_{coh} \)
Frequency-Selective fading:

- **PSD of Tx signal**
- **Frequency varying channel**

(Frequency-) Flat fading:

- **PSD of Tx signal**
- **Frequency varying channel**
Wireless SISO Channels

Examples: Temporal and Frequency Selectivity

Fast Fading:
- Transfer function variations with time $H(\omega, t)$
- Baseband Tx signal

Slow Fading:
- Transfer function variations with time $H(\omega, t)$
- Baseband Tx signal
**Example of effect** of transmitting a rect pulse over a **Time Selective** Fading Channel

1. **channel input:**
   - Amplitude
   - \( T_{cs} \) \( t \)

2. **channel o/p:**
   - Amplitude
   - \( T_{cs} \) \( t \)

   - \( T_{cs} < T_{coh} \)

3. **channel o/p:**
   - Amplitude
   - \( T_{cs} \) \( t \)

   - \( T_{cs} > T_{coh} \)
Example of effect of transmitting a rect pulse over a **Frequency Selective** Fading Channel

- **Channel Input:**
  - Amplitude
  - $T_{cs}$
  - $t$

- **Channel Output:**
  - Amplitude
  - $T_{cs}$
  - $T_{cs} + \Delta t$
  - $t$

$T_{cs} < T_{spread}$
Wireless Channel Analysis

- Impulse response $h(t)$
- Transfer function $H(f, t)$
- Auto-correlation function $\Phi_H(\Delta t)$
- Frequency spaced-time spaced function $\Phi_H(\Delta f, \Delta t)$
- Scattering function of the channel $S_H(\tau, f)$

$\Phi(H)$

- $\Phi(\Delta t)$
- $\Phi(\Delta f)$
- Doppler power spectrum $S_H(f)$ of the channel
- Multipath intensity profile $S_H(\tau)$ or power delay profile

- $T_{coh} = \frac{1}{B_{Dop}}$
- $B_{coh} = \frac{1}{T_{spread}}$
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 \((\Delta f)\). 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:
Equation of the Delay Spread

\[
T_{\text{mean}} \triangleq \frac{\int_0^{T_{\text{max}}} \tau S_H(\tau) d\tau}{\int_0^{T_{\text{max}}} S_H(\tau) d\tau} \tag{10}
\]

\[
T_{\text{rms}} \triangleq \sqrt{\frac{\int_0^{T_{\text{max}}} (\tau - T_{\text{mean}})^2 S_H(\tau) d\tau}{\int_0^{T_{\text{max}}} S_H(\tau) d\tau}} \tag{11}
\]
Scatterers

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

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

- \( L_{\text{scat}} \) = the number of paths related to this scatterer
If the paths cannot be resolved, that is if

\[ \tau_{\ell_1} \sim \tau_{\ell_2} \sim \ldots \sim \tau_{\ell L_{\text{scat}}}, \]

then

\[
\ell\text{-th scatterer} = L_{\text{scat}} \sum_{k=1}^{L_{\text{scat}}} \beta_{\ell k} \delta(t - \tau_{\ell k})
\]

\[
= \sum_{k=1}^{L_{\text{scat}}} \beta_{\ell k} \delta(t - \tau_{\ell})
\]

\[
= \left( \sum_{k=1}^{L_{\text{scat}}} \beta_{\ell k} \right) \delta(t - \tau_{\ell})
\]

\[
= \beta_{\ell} \delta(t - \tau_{\ell})
\]

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

\[
\text{Path-Loss}(PL) = 10 \log_{10} \left( \frac{P_{Tx}}{1\text{mW}} \right) - 10 \log_{10} \left( \frac{P_{Rx}}{1\text{mW}} \right) \quad (\text{dB}) \quad (15)
\]

\[
= PL_0 + 10 \log_{10} \left( \frac{d}{d_0} \right)^a + \text{PL}_{\text{Gaussian}} \quad (\text{dB}) \quad (16)
\]

where

\[
PL_0 = \text{the path loss at the reference distance } d_0 = 1\text{km/1mile}
\]

\[
d = \text{path length}
\]

\[
a = \text{path loss exponent}
\]

\[
\text{PL}_{\text{Gaussian}} = \mathcal{N}(0, \sigma^2).
\]
Notes on PL_{Gaussian} = N(0, \sigma^2)

- no-fading \Rightarrow \sigma = 0

- *shadow fading* or *slow fading* \Rightarrow \sigma > 0 \text{ in dB} \Rightarrow P_{Rx} = \text{random (log-normal distribution) in Watt.}

- *fast fading caused by multipath propagation*, the corresponding path gain \mid \beta_\ell \mid (i.e. \mid \beta_\ell \mid^2 \text{ 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 $x$

$$pdf_x(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left\{ \frac{(\ln x - \mu)^2}{2\sigma^2} \right\}$$ (17)
• a log-normal random variable = takes only +ve real values.

• If $x$=Normal-distribution $\Rightarrow y = \exp(x) = \text{log-normal distribution}$

• if $y= \text{log-normal- distribution} \Rightarrow x = \ln(y)= \text{normal distribution}$.

• 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:

  $\text{shadow fading or slow fading}$

  $\downarrow$

  $\text{PL}_{\text{Gaussian}} = N(0, \sigma^2)$ with $\sigma > 0$ in dB

  $\downarrow$

  $P_{Rx} = \text{random (log-normal distribution)}$ in Watt.
Fast fading (multipath propagation)

- There are two main cases
  - **CASE-1**: if \( \exists \) a direct path then
    \[
    \begin{align*}
    &\text{pdf of } |\beta_\ell| = \text{Rayleigh distribution} \\
    &\text{pdf of } \angle \beta_\ell = \text{uniform distribution}
    \end{align*}
    \]
    (urban areas & large cells)
  
  - **CASE-2**: if \( \exists \) a direct path then
    \[
    \begin{align*}
    &\text{pdf of } |\beta_\ell| = \text{Ricean distribution} \\
    &\text{pdf of } \angle \beta_\ell = \text{uniform distribution}
    \end{align*}
    \]
    (small cells & satellite mobile systems)

- 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

\[ p_{\text{Nakagami}}(x) = \frac{2^m x^{2m-1}}{\Gamma(m) \sigma^2} \exp\left(-\frac{x^2}{\sigma^2}\right) \]

\[ m = \frac{\sigma^2}{\text{Var}(x)} \]

\[ \sigma^2 = \text{Var}(x) \]

Rayleigh \ (m=1) if scattering process generates diffuse wave field

Nakagami

Rice \ (m>1) if \exists direct path

\[ k = \frac{\mu^2}{\sigma^2} \]

\[ x > 0 \]

\[ p_{\text{Rice}}(x) = \frac{2x}{\sigma^2} \exp\left(-\frac{x^2+\mu^2}{\sigma^2}\right) J_0\left(\frac{2\mu x}{\sigma^2}\right) \]

modified Bessel function of order 0
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.
The above will give an impulse response similar to the following.
Wireless SISO Channels

Clusters

$h_1(t) = \text{impulse response of the 1st channel (cluster)}$

$h_2(t) = \text{impulse response of the 2nd channel (cluster)}$

$h(t) = h_1(t) + h_2(t) = \text{total impulse response}$

1st cluster

Time interval between the clusters

2nd cluster

$T_{\text{spread,1}}$ to $T_{\text{spread,2}}$

$T_{\text{spread,1}}$ to $T_{\text{spread,2}}$

$T_{\text{spread, total}}$

$T_{\text{min,1}}$, $T_{\text{spread,1}}$, $T_{\text{max,1}}$

$T_{\text{min,2}}$, $T_{\text{spread,2}}$, $T_{\text{max,2}}$
Note that

- if \( T_{\text{spread},1} < T_{cs} \) 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:

$$x(t) = h(t) * m(t) + n(t) = \left( \sum_{\ell=1}^{L} \beta_\ell \delta(t - \tau_\ell) \right) * m(t) + n(t)$$

$$\Rightarrow x(t) = \sum_{\ell=1}^{L} \beta_\ell \cdot m(t - \tau_\ell) + n(t) \quad (18)$$

- 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:

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