Why is there poor signal reception in urban clutters?
Multi-path propagation occurs as a consequence of reflections, scattering, and diffraction of the transmitted electromagnetic wave at natural and man-made objects.

Waves from different directions with varying delays, phases and attenuations, superpose and cause amplitude and phase variations in the composite received signal.
This is commonly known as **small scale fading**, and occurs over distances of a wavelength of the transmitted signal.

The Suzuki fading profile superimposes small-scale fading effects (the squiggly fluctuations in power) onto the gently rolling power envelope. [3]
SMALL SCALE FADING

CAUSES:

- Multipath propagation
- Speed of mobile terminals
- Speed of surrounding objects
- Transmission bandwidth of the signal
The figure is a representation of the constructive and destructive interference between 2 multipath components, causing attenuation and phase change in the received signal. The key role is played by the phase difference between S1 and S2. [4]
SMALL SCALE FADING-contd.

EFFECTS:

- Rapid changes in signal strength over a small travel distance or time interval
- Random frequency modulation
- Time dispersion (echoes)
In brief, for a flat fading channel, the symbol duration is greater than the time spread of propagation path delays. The following few slides illustrate the distributions of the received signal envelope under such conditions.
DISTRIBUTIONS OF RECEIVED ENVELOPE

RAYLEIGH

Let \( r(t) \) be the low-pass equivalent of the received bandpass signal. As seen in the previous lecture, this is a complex signal and can be represented as:

\[
r(t) = r_i(t) + j r_q(t)
\]

The envelope of this low pass equivalent signal is the information bearing modulating/message signal. It is given by:

\[
z(t) = \sqrt{r_i^2(t) + r_q^2(t)}
\]
Considering \( r_i(t) \) and \( r_q(t) \) to be zero-mean independent Gaussian random variables, the envelope has a Rayleigh distribution, given by

\[
f_z(x) = \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}
\]

Here the average envelope power is \( 2\sigma^2 \).

**FEATURES**

- Applicable when there is no LOS path between Tx and Rx.
DISTRIBUTIONS OF RECEIVED ENVELOPE-contd.

- $\sigma^2$ is the variance of the i/q components of $r(t)$.
- The squared envelope, $z^2(t)$, which is the power in the received message signal, is distributed exponentially.
- The plot of the PDF of a Rayleigh random variable is shown below:
RICEAN

- Now suppose that there exists an LOS path with amplitude $S$, along with the other non LOS paths.

- Let

$$K = \frac{|S|^2}{2\sigma^2}$$

be the ratio of deterministic signal power $s^2$ to the average power in the rest of the signal, $2\sigma^2$. This is the “K factor” or the Ricean factor.

- In such cases, the received envelope can be modeled as a Ricean.
FEATURES:

- The pdf of the received envelope $\alpha$ is given by

$$p_\alpha(x) = \frac{2x(K + 1)}{\Omega_p} \exp \left\{ -K - \frac{(K + 1)x^2}{\Omega_p} \right\} I_0 \left( 2x \sqrt{\frac{K(K + 1)}{\Omega_p}} \right), \quad x \geq 0$$

$\Omega_p$ is the average envelope power.

- When $K=0$, the Ricean distribution approaches a Rayleigh distribution.

- When $K=\infty$, there is no fading.
DISTRIBUTIONS OF RECEIVED ENVELOPE-contd.

- The parameters of the distribution, are \( s^2 = \frac{K \Omega_p}{1 + K} \) and \( \sigma^2 = \frac{\Omega_p}{2(1 + K)} \).

- A comparison between Rayleigh and Ricean fading distributions is given below:

![Comparison of Rayleigh and Ricean distributions](image)

[6]
The Nakagami distribution was selected to fit empirical data, and is known to provide a closer match to some experimental data than either the Rayleigh or Ricean distribution.

FEATURES:

- The Nakagami distribution describes the magnitude of the received envelope $\alpha$ by
  \[
p_\alpha(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega_p^m} \exp\left\{-\frac{mx^2}{\Omega_p}\right\} \quad m \geq \frac{1}{2}
\]
- $\Omega_p$ is again the average envelope power.
The Rice distribution can be closely approximated by the following relation between the Ricean factor $K$ and the Nakagami shape factor $m$,

$$K = \frac{\sqrt{m^2 - m}}{m - \sqrt{m^2 - m}} \quad m > 1$$

$$m = \frac{(K + 1)^2}{(2K + 1)}.$$

- When $m=1$, the distribution becomes Rayleigh.
- When $m=1/2$, it becomes a one-sided Gaussian distribution.
When $m=\infty$, it becomes an impulse, implying there is no fading.

The Nakagami distribution leads to convenient closed form expressions*.

The figure shows the Nakagami distribution for several values of $m$: 

\[
\begin{array}{c}
m = 1 \\
m = 2 \\
m = 4 \\
m = 8 \\
m = 16
\end{array}
\]
QUANTIFICATION OF SMALL SCALE FADING CHANNELS

The following slides illustrate a few parameters that help to classify and quantify small scale fading channels.
CHANNEL PARAMETERS

- Considering only Wide Sense Stationary channels, let the channel response to the impulse $\delta(t - \tau)$ be given by $c(t, \tau)$.
- The power delay profile (multipath intensity profile) is given by:

$$\Phi_c(t, \tau) = E[c(t, \tau)c^*(t, \tau)]$$

- It is the average power which is received with an excess delay that falls within $(\tau, \tau + dt)$, taken for all $\tau$. 
The delay profile characterizes the extent to which the channel fading at two frequencies is correlated.

The figure on the right shows a measured power delay profile at 1920 Mhz, with significant multipath.
The **mean delay** is defined to be the first moment of the power delay profile and is given as:

\[
\mu_\tau = \frac{\int_0^\infty \tau \phi_c(\tau) d\tau}{\int_0^\infty \phi_c(\tau) d\tau}
\]

The **RMS delay spread** is the square root of the second central moment and is defined as:

\[
\sigma_\tau = \sqrt{\frac{\int_0^\infty (\tau - \mu_\tau)^2 \phi_c(\tau) d\tau}{\int_0^\infty \phi_c(\tau) d\tau}}
\]
Coherence Bandwidth

Denoted as $B_C$, it is defined as the range of frequencies over which two frequency components have a strong potential for amplitude correlation.

If this frequency correlation function is taken to be above 0.9, then the following relation holds:

$$B_C \approx \frac{1}{50\sigma_\tau}$$
If this frequency correlation function is taken to be above 0.5, then the following relation holds:

\[ B_c \approx \frac{1}{5\sigma_\tau} \]

Delay spread and coherence bandwidth describe only the time dispersive effects of the channel.

The time varying nature of the channel is captured by coherence time and Doppler spread.
DOPPLER SPREAD

- Doppler shift is illustrated by the following diagram.

- The observer in the above figure is stationary and the vehicle is moving towards her. The wave fronts of a signal transmitted from the vehicle bunch up in front of the ambulance and spread out behind it.
DOPPLER SPREAD—contd.

- Denoted by $B_D$, the Doppler Spread is defined as the range of frequencies over which the received Doppler spectrum is non-zero.

Measured Doppler spread at 1800 MHz. Doppler spread = 60.3 Hz
DOPPLER SPREAD-contd.

- It is thus a measure of the spectral broadening caused by the time rate of change of the mobile radio channel.
- If the baseband signal’s bandwidth is greater than the Doppler spread then its effects can be neglected.
COHERENCE TIME

- It characterizes the time varying nature of the frequency dispersiveness of the channel in the time domain.
- Denoted by $T_c$, it is the time duration over which the channel impulse response is time invariant, and therefore represents the duration over which two received signals have a strong potential for amplitude correlation.
- Doppler spread and coherence time are inversely proportional to each other.
If the coherence time is the time over which the time correlation function is taken to be >0.5, then

\[ T_c \approx \frac{9}{16\pi f_m} \]

where \( f_m = \frac{v}{\lambda} \) is the maximum Doppler spread. \( v \) is the speed of the mobile and \( \lambda \) is the wavelength of operation of the mobile.
CHANNEL PARAMETERS - SIMPLIFIED

(a) Multipath intensity profile

(b) Doppler power spectrum

(c) Spaced-frequency correlation function

(d) Spaced-time correlation function
TYPES OF SMALL SCALE FADING

- Based on the channel parameters that have been defined, the channel can be classified as flat/frequency selective fading, and slow/fast fading.

FLAT FADING

- When the coherence bandwidth is greater than the symbol bandwidth of the channel, i.e., $B_s < B_C$ the channel is ‘flat’. Also, $T_s > 10\sigma_r$.

- Here, the channel fading coefficient can be modeled as having no excess delay.

- All frequencies in the transmitted signal experience the same random attenuation and phase shift.
TYPES OF SMALL SCALE FADING - contd.

- FLAT FADING CHANNEL CHARACTERISTICS

![Diagram showing signal transmission through a channel with symbols for s(t), h(t, \tau), and r(t).]
FREQUENCY SELECTIVE FADING

- When the symbol bandwidth is greater than the coherence bandwidth of the channel, i.e., $B_c < B_S$ or equivalently, the symbol duration is less than the delay spread, i.e., $T_s < 10\sigma_r$, the received signal is distorted in amplitude and phase.

- Such channels are wideband and induce intersymbol interference into the transmitted signal, because the channel varies in gain and phase across the spectrum of the transmitted signal.
TYPES OF SMALL SCALE FADING - contd.

- FREQUENCY SELECTIVE FADING

CHANNEL CHARACTERISTICS
FLAT AND FREQ. SELECTIVE CHANNELS COMPARED

(a) Typical frequency-selective fading case ($f_0 < W$)

(b) Typical flat-fading case ($f_0 > W$)

(c) Null of channel frequency-transfer function occurs at signal band center ($f_0 > W$)
SLOW FADING

- In a slow fading channel, the channel impulse response changes at a rate much slower than the transmitted signal.
- Thus the channel may be assumed to be static over one or several reciprocal symbol bandwidths.
- Therefore a signal undergoes slow fading if
  \[ T_C > T_S \quad \text{and} \quad B_S > B_D \quad . \]
TYPES OF SMALL SCALE FADING - contd.

FAST FADING

- In a fast fading channel, the channel impulse response changes rapidly within the symbol duration.
- This causes frequency dispersion due to Doppler spreading, which leads to signal distortion.
- Therefore a signal undergoes fast fading if

\[ T_c < T_s \quad \text{and} \quad B_D > B_s \]
A SIMPLE “4-in-1” GRAPH

- These 2 graphs give a concise graphical representation of the 4 types of small scale fading, based on the parameters discussed so far.
SIGNIFICANCE OF THE FADING TYPES*

- A flat fading channel implies that the rate of data transmission is smaller than the dual of the coherence time of the channel.

- High data rate transmission schemes suffer from frequency selective fading. Thus equalization schemes are necessary at the receiver to combat the ISI.

- Fast and slow fading channels, depend on the velocity of the mobile, the transmission bandwidth and the time rate of change of the channel, thus causing time selective fading.
SIGNIFICANCE OF THE FADING TYPES—contd.

- If the relative velocity between the transmitter and the receiver is high, the Doppler spread is high and if this is greater than the signal bandwidth, it results in fast fading. This situation manifests itself in a scenario with fast moving mobiles. In practice, fast fading occurs for very low data rates.

- In contrast, if the mobile is stationary/ moving very slowly such that the received Doppler spread is less than the signal bandwidth, the situation causes just slow fading.
SIGNIFICANCE OF THE FADING TYPES—contd.

- The above facts suggest that a fast frequency selective fading channel is the worst kind of channel to transmit in, since there is ISI and signal distortion within a symbol duration.
REFERENCES

REFERENCES-contd.

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