DAYANANDA SAGAR COLLEGE OF ENGINEERING

An Autonomous Institute Affiliated to Visvesvaraya Technological University, Belagavi, Approved by AICTE & ISO 9001 -2008 Certified

Shavige Malleshwara Hills, Kumaraswamy Layout, Bengaluru-560078

Accredited by National Assessment and Accreditation Council (NAAC) with 'A' Grade

DEPARTMENT OF TELECOMMUNICATION ENGINEERING

Accredited by National Board of Accreditation (NBA)

NOTES: MODULE 1

COURSE NAME: MIMO Communication

COURSE CODE: TE814

Faculty Incharge: Dr Vinod B Durdi, Dr Sayed Abdulhayan

CONTENTS:

Fading channels and diversity techniques: Wireless channels – Error/Outage probability over fading channels – Diversity techniques – Channel coding as a means of time diversity – Multiple antennas in wireless communications.

Wireless channels

There are fundamental differences between wireless channels and usual wireline channels. For example, over wireless channels, signals are received through multiple paths. Also there are significant time variations caused by the relative motion of the transmitter and the receiver as well as changes in the environment. Furthermore, different signals being transmitted over a wireless medium might interfere with each other.

Electromagnetic waves travel

Electromagnetic waves travel through three different mechanisms: reflection, refraction and scattering. When waves impinge upon a surface with surface variations significantly larger than their wavelength, part of the signal reflects as illustrated in Figure 1. This phenomenon is referred as reflection. The second mechanism, refraction, is basically the process of secondary wave production by “knife edge” as also illustrated in the figure. Finally, scattering usually arises due to surface variations of nearby objects that are smaller than the signal wavelength, e.g., due to the roughness of surfaces, due to foliage, etc. As a result of these different forms of electromagnetic wave propagation, the signals transmitted over a wireless channel are received via multiple secondary paths, in addition to the possible line of sight.

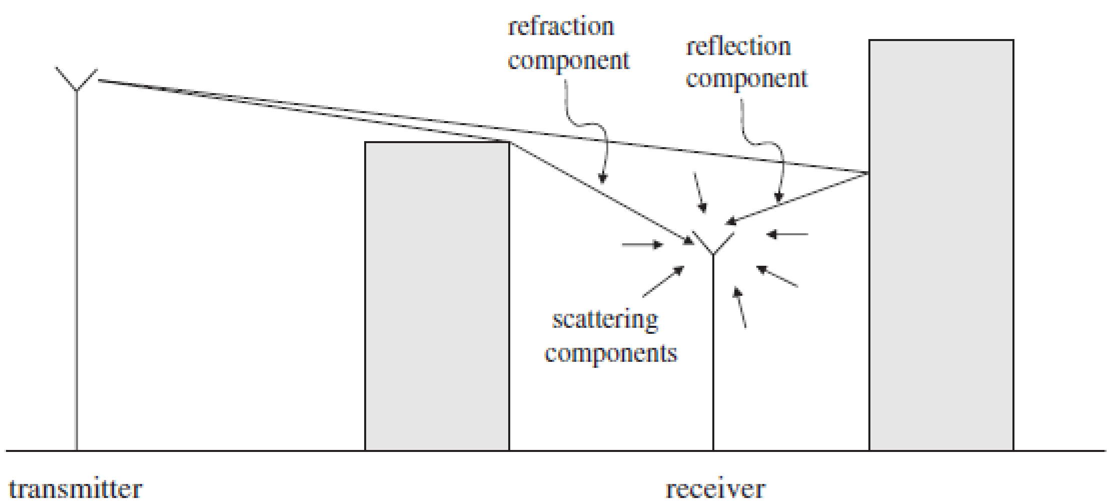


Figure 1. Illustrations of Wireless Propagation Mechanism

Different multipath propagation mechanisms, and also the fact that, depending on the materials involved and frequency of the operation, penetration of the electromagnetic waves through walls, allow reception of signals even when there is no direct line of sight between the transmitter and the receiver.

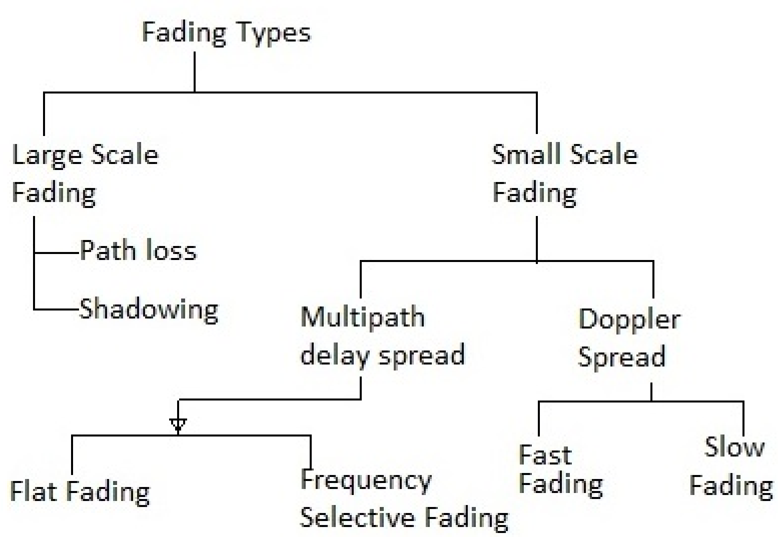
However, the effects of multipath propagation are usually deleterious. This is due to the fact that different paths have different lengths, resulting in different attenuation factors and phase differences for replicas of the transmitted signals.

How the different phase difference is there in multipath received signals.

Since frequencies employed in wireless communications are usually very high, the corresponding wavelengths are very small (compared with the differences in lengths of paths that different signal components travel). For instance, for cellular telephony, transmission bands are usually in the range of 800 MHz–2 GHz, thus wavelengths of the transmitted signals are in the range of 15–37.5 cm, whereas the path length differences can be in the order of tens of meters, or hundreds of meters. As a result, the phase differences between the different replicas of the received signal will be significant. The amplitude variations will also be significant since, for example, the components due to scattering, or due to refraction or reflection will not all have similar signal strengths.

The relative motion of the transmitter and the receiver, and the changes in the environment cause the multipath channel, through which the signals are being transmitted, to be time varying as well. This is also in sharp contrast with the wireline channels which are typically constant. For a clear understanding of wireless channels, their multipath and time variations should be characterized properly and suitable channel models should be developed.

List the classification in Channel Fading.



Considering various channel related impairments and position of transmitter/receiver following are the types of fading in wireless communication system.

➤Large Scale Fading: It includes path loss and shadowing effects.

➤Small Scale Fading: It is divided into two main categories viz. multipath delay spread and doppler spread. The multipath delay spread is further divided into flat fading and frequency selective fading. Doppler spread is divided into fast fading and slow fading.

Path Loss, Shadowing and Small-Scale Fading

The effects of multipath propagation and time variations in a wireless channel can be observed in the received signal power levels. A first order characterization of the average received signal power level is obtained by using path loss models. If we consider the average power of the received signal over a long period of time, denoted by.

$Pr=(c/d^{n)} Pt$

where c is a constant,
Pt is the transmit signal power level,
d is the separation between the transmitter and the receiver, and
n is the path loss exponent.

The path loss exponent is typically between two and six, depending on the specific environment. For instance, for free space (when only a direct line of sight exists, no scatterers), $n = 2$, whereas for an indoor transmission in an office building with multiple floors, it could be as high as six. The constant c depends on a variety of factors including transmit and receive antenna gains, and frequency of operation.

Path loss is a useful characterization of the received signal strength, but it alone does not provide a satisfactory understanding of a wireless link. Instead of averaging over a very long period of time, if we use a smaller window, say in the order of a few seconds or minutes, we will find that the average received signal strength is a random variable.

Let us denote it by Pr . We can model the received power at this scale as

$P_r \text{dBm} = .P_r \text{dBm} + X_\sigma \text{dB},$

where powers are expressed in dBm,

$X\sigma$ is a zero mean random variable.
For the common model of log-normal shadowing, $X\sigma$ is taken as a zero mean Gaussian random variable with standard deviation σ.
In other words, as a more refined characterization of the wireless link, we see that the received power level, when expressed in dBm, is given by a Gaussian random variable.

Shadowing

The shadowing standard deviation σ is heavily dependent on the environment, and could be in the range of three to 12 dBs. We further note that the shadowing component of the received signal has spatial dependence, that is, two different receiver locations separated by a few meters or even tens of meters may experience highly dependent shadow fades. We note that shadowing is also referred to as large-scale fading. The effects of the path loss and shadowing on the received signal powers are illustrated in Figure 2

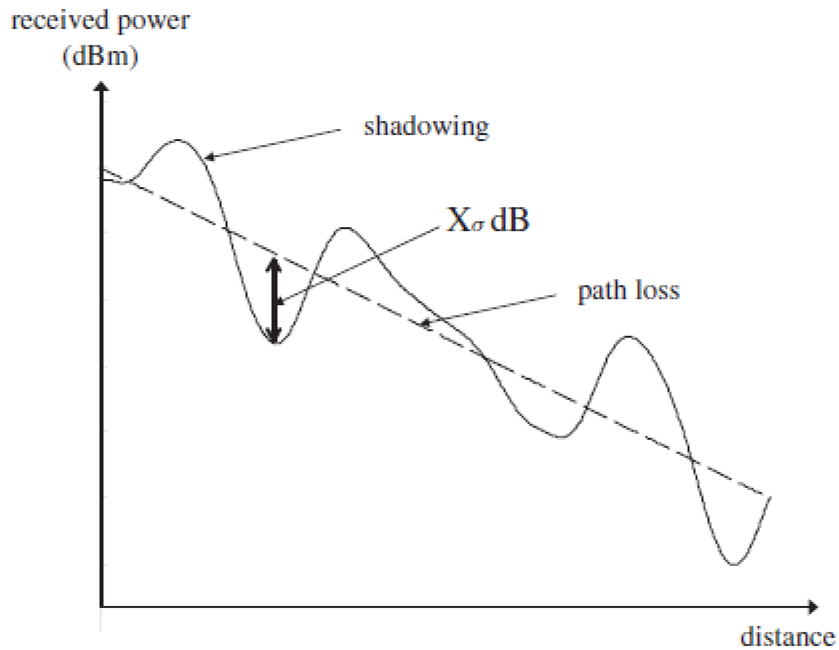


Figure 2 Effect of path loss and shadowing on the received signal power

Path loss and log-normal shadowing are average quantities. In fact, the actual received signal power in a wireless channel is a much more rapidly varying random quantity (as illustrated in Figure .3) which needs to be characterized using statistical models.

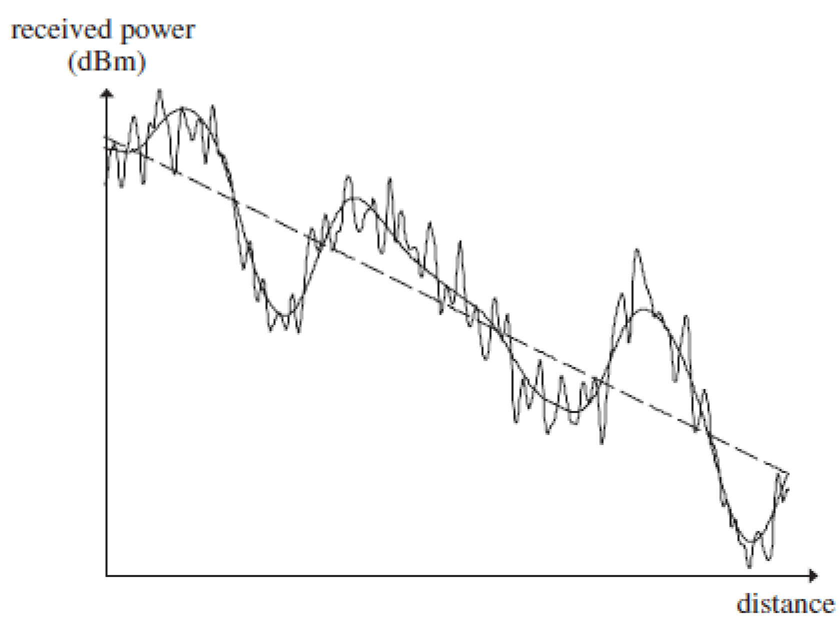


Figure 3 Received power when small-scale fading is also taken into account

Fading Channel models:

In this section, we briefly present a statistical characterization of fading channels, and describe several relevant wireless channel models. These models will be used throughout the book.

Fading channels are modeled as linear time-varying systems where the time variations are random. Since most wireless transmission systems employ bandpass transmission centered around a carrier frequency *fc*, more specifically, we model these channels as linear time-varying bandpass systems.

Let us denote the transmitted bandpass signal by *x(t)*, and its low-pass equivalent by *xl (t)*.

That is, *x(t)* = Re{*xl (t)ej2πfct* }.

If the low-pass equivalent channel impulse response is denoted by *c(τ ; t)*, the received signal in the absence of noise can be written as

$$y_l(t) = \int_{-\infty}^{\infty} c(\tau; t) x_l(t-\tau) d\tau.$$

If we define the time-varying channel transfer function as the Fourier transform of the channel impulse response with respect to the *τ* variable, we obtain

$$C(f; t) = \int_{-\infty}^{\infty} c(\tau; t) e^{-2\pi f\tau} d\tau.$$

Clearly, we can also write

$$y_l(t) = \int_{-\infty}^{\infty} C(f; t) X_l(f) e^{j2\pi ft} df.$$

where *Xl(f)* is the Fourier transform of the low-pass equivalent of the transmitted signal.

Time variations of fading channels are characterized by a correlation function (in the *t* variable), and its Fourier transforms.

Discuss the multipath spread of the channel and coherence bandwidth. How they are related with each other.

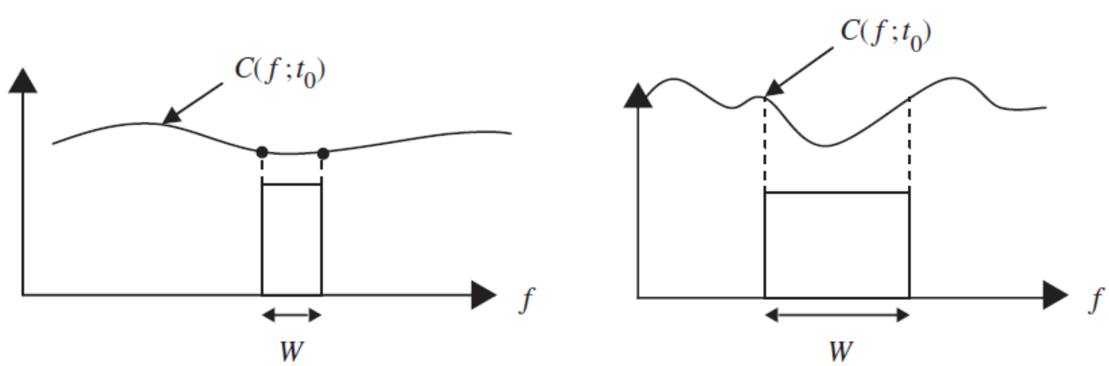
The multipath structure can be characterized in the time domain using the “multipath intensity profile” of wireless channels, which basically shows relative powers of the received signal through different delays (we note that there are multiple paths corresponding to each delay). The extent of the non-negligible values of this function is called the multipath spread of the channel, *Tm*. The multipath spread is basically the time difference between the shortest and the longest paths that the transmitted signal goes through. Typical values could be in the order of nanoseconds for indoor applications, and up to several tens of microseconds for outdoor applications (depending on the exact propagation environment).

The Fourier transform of the multipath intensity profile gives a frequency domain characterization of the wireless channel’s multipath structure. The coherence bandwidth of the channel, *BC*, is the range of non-negligible values of this Fourier transform. Roughly speaking, *BC* ~ 1 *Tm*

Two frequencies separated by less than the coherence bandwidth of the channel are affected in almost the same way by the channel. On the other hand, frequencies separated by more than the coherence bandwidth undergo different channel fades.

Frequency Flat versus Frequency Selective Fading Channels

Consider digital modulation over a wireless channel, and assume that the bandwidth of the signal used in the transmission is *W*. Let us now characterize the type of fading that will be experienced using the multipath structure of the channel. If the signal bandwidth *W* is significantly smaller than the coherence bandwidth of the channel *Bc*, clearly, all the frequency components of the transmitted signal see the same effective channel, i.e., *C(f ; t)* for the frequency range of interest will be independent of *f* . This is illustrated on the left-hand side of Figure 4. For this case, we can write



flat fading | frequency selective fading

Figure 4 Frequency flat versus frequency selective fading (in the frequency domain).

in the absence of channel noise. This expression basically means that the effect of the wireless channel is simply multiplicative if the bandwidth of the signal transmitted is significantly smaller than the coherence bandwidth of the channel, where the multiplicative term is a complex Gaussian random process. We note that the condition $W << Bc$ is equivalent to saying that the multipath spread of the channel is significantly smaller than the signal duration in time, and therefore, there is no intersymbol interference between consecutive transmitted symbols.

If the condition $W << Bc$, or equivalently, $Tm << Ts$ (where Ts is the symbol duration), is not satisfied, then different frequency components of the signal undergo different channel fades as illustrated on the right-hand side of Figure .5. In such a case, the channel is said to be frequency selective, and it exhibits intersymbol interference. We illustrate the effect of a frequency selective fading channel on the transmitted signal in the time domain in Figure 5.

Illustration of frequency selective fading in the time domain.

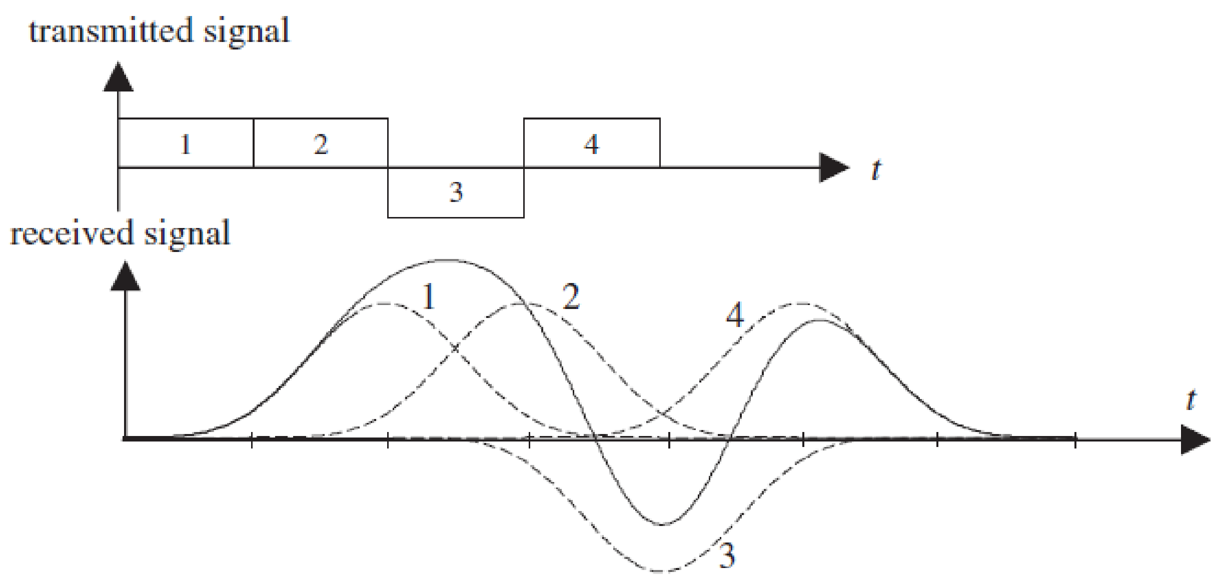


Figure 5 Illustration of frequency selective fading in the time domain.

Slow versus Fast Fading Channels:

In communications systems, a communication channel may change with time. **Coherence time** is the time duration over which the channel impulse response is considered to be not varying. Such channel variation is much more significant in wireless communications systems, due to Doppler effects.

When there is no relative motion between the transmitter and the receiver, due to multipath the receiver can receive the same signal at different times, because a one copy took a short path and arrived quickly, another took a long path (header in a different direction, bounced off a building, and reflected back toward the receiver). This is multipath.

Now add relative motion to the scenario above. Because of the different incident angle, not only will the longer path signal arrive later, but it will have a arrive with a different incident angle, and therefore (due to the Doppler Effect) it will have a different frequency. So the Doppler spread would be the difference of the two frequencies received (even though there is only a single fixed frequency being transmitted).

If you make an analogy with sound waves, it's easier to understand. For example, if you are standing on a street, and an ambulance passes with the sirens on, you'll notice the pitch rises as it comes near you and lowers when it draws apart. This happens because the source of the sound waves is moving, so the waves get to you "distorted". Broader waves means lower frequency, thus making the pitch lower. The same principle applies to electromagnetic waves.

Based on **doppler spread** there are two types of fading viz. fast fading and slow fading. These doppler spread fading types depend on mobile speed i.e. speed of receiver with respect to transmitter.

FAST FADING

The phenomenon of fast fading is represented by rapid fluctuations of signal over small areas (i.e. bandwidth). When the signals arrive from all the directions in the plane, fast fading will be observed for all directions of motion.

Fast fading occurs when channel impulse response changes very rapidly within the symbol duration.

- High doppler spread
- Symbol period > Coherence time
- Signal Variation < Channel variation

This parameters result into frequency dispersion or time selective fading due to doppler spreading. Fast fading is result of reflections of local objects and motion of objects relative to those objects.

In fast fading, receive signal is sum of numerous signals which are reflected from various surfaces. This signal is sum or difference of multiple signals which can be constructive or destructive based on relative phase shift between them. Phase relationships depend on speed of motion, frequency of transmission and relative path lengths.

Fast fading distorts the shape of the baseband pulse. This distortion is linear and creates ISI (Inter Symbol Interference). Adaptive equalization reduces ISI by removing linear distortion induced by channel.

SLOW FADING

Slow fading is result of shadowing by buildings, hills, mountains and other objects over the path.

- Low Doppler Spread
- Symbol period <<Coherence Time
- Signal Variation >> Channel Variation

Slow fading results in a loss of SNR. Error correction coding and receiver diversity techniques are used to overcome effects of slow fading.

In most wireless applications, the rate of transmission is several orders of magnitude larger than the Doppler spread of the channel. In other words, the symbol duration is significantly smaller than the coherence time of the channel, meaning that the channel remains the same over an entire symbol period. As an example, consider the case of a vehicle moving with a constant speed of 100 miles per hour, and carrier frequency 1 GHz.

In this case, the maximum Doppler shift can be calculated to be approximately 150 Hz, which is a very high value in practical scenarios.

Then the coherence time of the channel is in the order of 6.7 ms, meaning that the wireless channel will effectively remain constant over an interval of 6.7 ms.

For practical wireless applications, such a duration typically corresponds to a large number of symbols. For instance, if the symbol rate is 100 kilo symbols per second, then the channel will not change for about 670 symbols.

Time variations of wireless channels can be described using several channel models

Quasi-static fading channels: - the channel remains the same for an entire frame of data, and it changes from one frame to the next. In such a case, there is no means of "averaging" over the fading statistics by increasing the frame length, i.e., the channel is non-ergodic.

Block fading channels are used as proper models if channel fading is constant for a block of symbols, and changes from one block to another. However, the frame may consist of many differently faded blocks. Block fading models could be encountered if, for example, frequency hopping is employed and different parts of the frame are transmitted in different frequency bands.

Rayleigh, Rician and Nakagami Fading Channels

We have just argued that the effect of the wireless channel on the transmitted signals is multiplicative (for frequency flat fading channels), where the multiplicative term is a complex Gaussian random variable.

Rayleigh: If the channel gain has zero mean, then such a channel is considered as Rayleigh fading since the absolute value of the channel gain is a Rayleigh random variable.

Rician :If the channel gain has a non-zero mean, then its absolute value is Rician distributed, and the channel is said to be Rician

Nakagami: There is another popular fading channel model called Nakagami fading which has its basis on experimental observations as opposed to theoretical models used to develop Rayleigh and Rician models. For Nakagami fading,

Summary of Fading Channel Models:

Flat Fading Channels:

Mathematically, the received signal at time *k*, *y(k)*, for a flat fading channel is given by

$$y(k) = \sqrt{\rho}h(k)x(k) + n(k),$$

where *x(k)* is the *k*th transmitted symbol, *h(k)* is the fading channel coefficient corresponding to this symbol, and *n(k)* is the additive zero mean white complex Gaussian noise term. We assume that *E*[|*h(k)*|2] = 1, the average signal power is normalized to unity, and the noise term has zero mean and 1⁄2 variance per dimension. Thus, *ρ* can be interpreted as the average signal-to-noise ratio at the receiver. The distribution of the random channel gain depends on the exact channel model. For example, if the channel is Rayleigh fading, then |*h(k)*| is Rayleigh distributed, and *φ(k)* = *∠h(k)* is uniform on *(*0*,* 2*π)*.

Frequency Selective Fading Channels:

As mentioned before, a popular model for a frequency selective fading channel is the symbol spaced tapped delay line model, which basically states that the received signal at time *k* is given by

$$y(k) = \sqrt{\rho}\sum_{l=0}^{L-1} h^{(l)}(k)\ x(k-l) + n(k),$$

where *L* denotes the number of intersymbol interference (ISI) terms, and *h(l)(k)* is the complex channel coefficient for the *l*th ISI tap at time *k*. We normalize the channel coefficients such that _*L*−1 *l*=0 *E*[|*h(l)(k)*|2] = 1, the signal power and noise distribution are the same as the flat fading case, thus *ρ* refers to the signal-to-noise ratio. For Rayleigh fading channels, the channel tap coefficients are modeled as complex Gaussian random variables. The coefficients corresponding to different channel paths are usually assumed to be independent. Finally, the time correlations (with respect to *k*) depend on the rapidity of the fading.

Error/Outage Probabilities over Fading Channels

As we know from basic digital communications, error rates for digital modulation techniques such as phase shift keying (PSK), quadrature amplitude modulation (QAM) and frequency shift keying (FSK) all reduce exponentially with the signal-to-noise ratio for additive white Gaussian noise (AWGN) channels. However, for fading channels, the situation is quite different, and if not mitigated properly, the effects of channel fading are deleterious on the digital communication system performance. We illustrate this point in detail in this section.

Outage Probability for Rayleigh Fading Channels

We first consider a scenario where fading is extremely slow, and we observe only a single state of the channel over an entire frame of data, i.e., quasi-static fading. Assume that a certain frame error rate or bit error rate is tolerable for a particular application, however if the error rate goes above this level, the resulting performance is simply unacceptable.

For instance, if we consider speech transmission, frame error rates of 5% may be tolerable, but beyond this value, we cannot communicate reliably. Assuming that this specified error rate corresponds to a certain minimum acceptable signal-to-noise ratio, if the instantaneous signal-to-noise ratio over the channel is below this level, the system is in outage. This is because, for this channel model, we are unable to “average” over different fading coefficients. Therefore, the channel outage probability can be used to evaluate the system performance. Let us compute the outage probability over a flat Rayleigh fading channel for illustration.

$$P_{out} = \int_0^{\rho_{min}} \frac{1}{\rho} e^{-x/\rho} dx,$$

$$= 1 - e^{-\frac{\rho_{min}}{\rho}},$$

which can be approximated at large signal-to-noise ratios by

$$P_{out} \approx \frac{\rho_{min}}{\rho}.$$

This result clearly shows that the communication failure probability is inversely proportional to the average signal-to-noise ratio. For many applications, this is simply unacceptable, because, to make the outage probability low, excessive transmission powers will be required.

Average Error Probabilities over Rayleigh Fading Channels

Let us deviate from the slow fading channel assumption to illustrate what happens if we are able to see different states of the channel, thus we can average over the channel statistics. As an example, consider binary PSK (BPSK) transmission over frequency flat Rayleigh fading channels. Assuming that the channel phase can be estimated and tracked perfectly, it can be compensated for at the receiver, and the optimal detector becomes the same as the one for an AWGN channel.

$$
\begin{aligned}
P_b &\approx \frac{1}{4}\frac{1}{1+\rho}, \\
&\approx \frac{1}{4\rho}.
\end{aligned}
$$

This expression clearly shows that the error probability for a Rayleigh fading channel is only inversely proportional to the signal-to-noise ratio. This is in sharp contrast with error rates over AWGN channels as they decay exponentially with ρ.

For other modulation schemes, following similar steps, it can also be shown that error rates only decay inversely with the signal-to-noise ratio for Rayleigh fading channels. This is a very slow decrease, demonstrating the deleterious effects of Rayleigh fading on the system performance. Clearly, increasing the transmission power alone to reduce the error rates is not acceptable. This is because, for example, to reduce the error rates by an order of magnitude, the transmission power has to be increased by the same factor, which is very inefficient. We need ways of mitigating the adverse effects of channel fading for reliable operation of digital communication systems. Such methods are collectively known as diversity techniques,

Extension to other Fading Channels:

Due to the existence of the specular component, the outage probability expressions and average error rates for the case of Rician fading will be better than those of Rayleigh fading. Due to the existence of the specular component, the outage probability expressions and average error rates for the case of Rician fading will be better than those of Rayleigh fading. Depending on the value of the K parameter, the resulting error rates could be close to those of AWGN or Rayleigh fading channels. As an example, Figure 6 illustrates the average bit error rates for BPSK modulation for several values of the Rician factor.

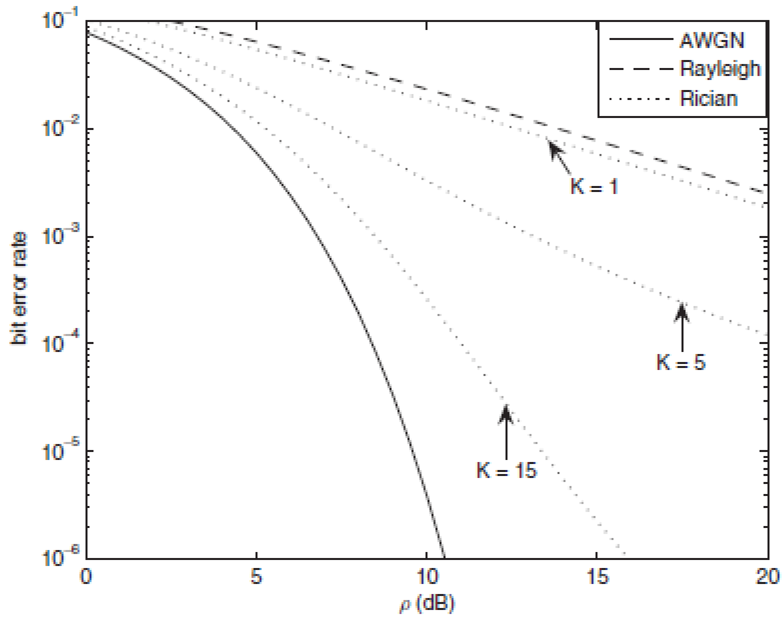


Figure 6 Error rates of BPSK modulation over Rayleigh and Rician fading channels

Performance over Frequency Selective Fading Channels:

Although the existence of ISI may seem like a degrading factor, it effectively provides frequency diversity (or, multipath diversity), that is, effectively each signal gets transmitted through several differently faded channels. Therefore, error rates may improve with frequency selectivity compared with flat fading channels. which can be approximated at large signal-to-noise ratios by

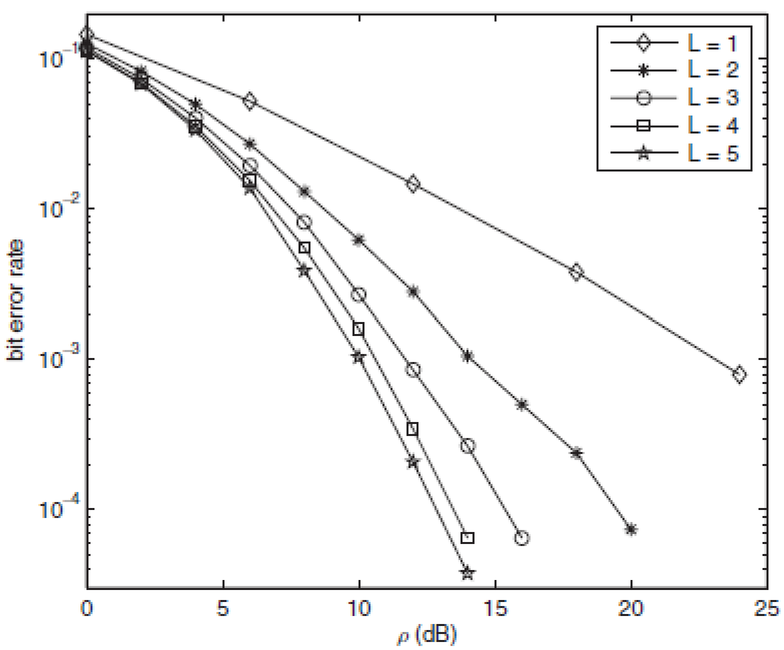


Figure 7 Error rates of BPSK modulation over several frequency selective fading

channels.

Diversity Techniques:-

There are many methods by which diversity can be achieved. Examples include time diversity, frequency diversity, space (spatial) diversity, channel coding (as an efficient means of time diversity) among others.

Time diversity can be realized by transmitting the same signal several times using different time intervals. Obviously, the separation of these time intervals has to be sufficiently large, i.e., it should be more than the coherence time of the channel, so that the fading channel coefficients change, and different channel gains are observed as illustrated in Figure 8.

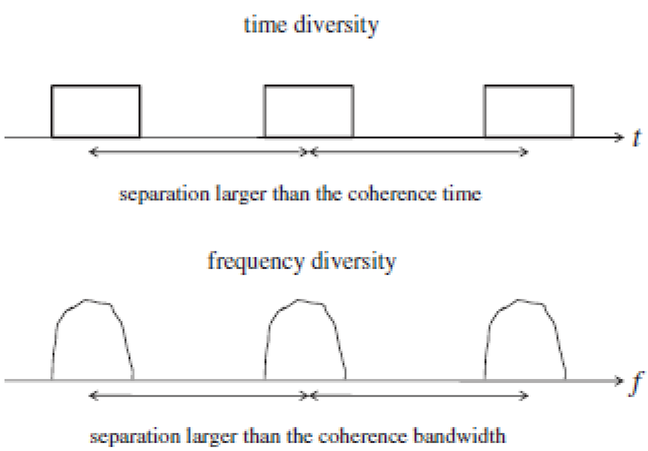


Figure 8 Illustration of time and frequency diversity techniques

Frequency diversity is obtained by transmitting different replicas of the signal over different frequency bands. To make sure that the channels seen are different (ideally, independent), separation of these frequency bands has to be more than the coherence bandwidth of the channel shown in figure 8.

"Space" can also be used as a resource that can efficiently provide diversity. Assume that the receiver is equipped with multiple antennas. Then, different replicas of the transmitted signal will be picked up by each of these antennas as illustrated in Figure 9. If the separation of the receive antennas is sufficient (as a rule of thumb, more than half a wavelength in a uniform scattering environment), then the received signals will undergo different channel fades, thereby providing "spatial" diversity.

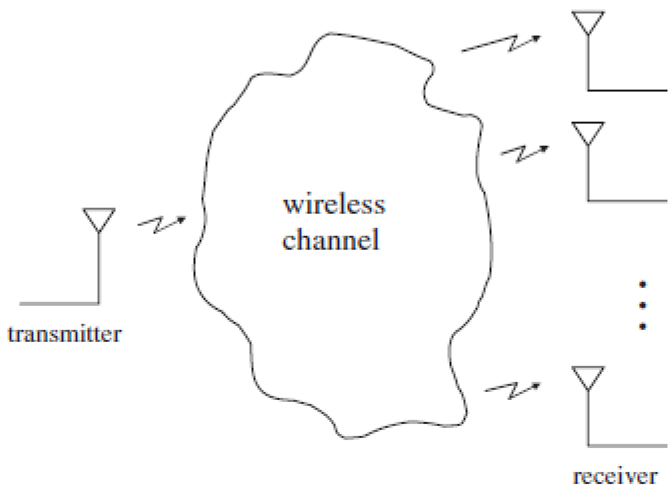


Figure 9 Spatial diversity scheme.

Polarization diversity

Here, the electric and magnetic fields of the signal carrying the information are modified and many such signals are used to send the same information. Thus orthogonal type of polarization is obtained.

Angle Diversity

Here, directional antennas are used to create independent copies of the transmitted signal over multiple paths.

Signals obtained through different diversity branches have to be combined at the receiver to detect the transmitted symbols. There are different methods to accomplish this which include selection combining, maximal ratio combining, equal-gain combining, etc. Let us describe the system set up and explain these combining schemes in a little more detail.

System Model for *L*th Order Diversity

Consider an M-ary digital modulation scheme with constellation points $x1, x2, xM$. Assume that a certain constellation point, denoted by x, is transmitted over L diversity branches. The channel gain for the lth branch is given by hl , and the received signals are corrupted by independent Gaussian noise terms, denoted by nl . Assume that the average signal energy is normalized to unity, the channel powers are normalized such that $E[|hl\ |2] = 1$, and the noise variance per complex dimension is 1/2. Also assume that the average signal-to-noise ratio per branch is ρ. This model for an L branch diversity scheme is illustrated in Figure 10.

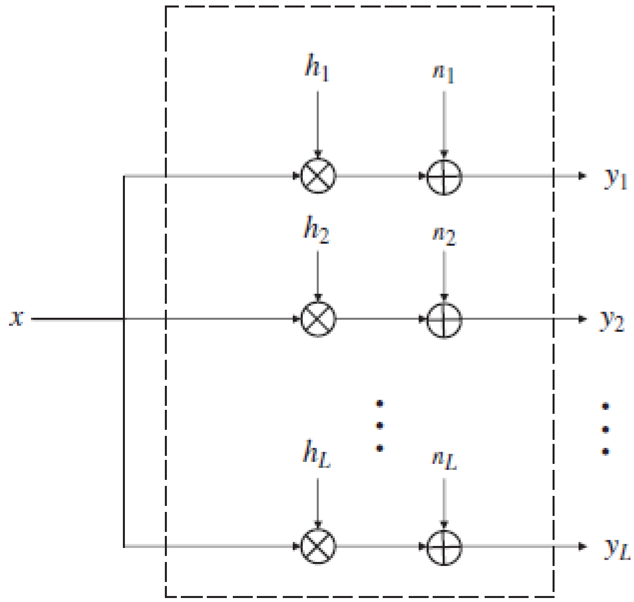


Figure 10 Channel model for an *L*th order diversity scheme

Mathematically, the set of received signals is given as

$$\begin{aligned} y_1 &= \sqrt{\rho} h_1 x + n_1, \\ y_2 &= \sqrt{\rho} h_2 x + n_2, \\ &\vdots \\ y_L &= \sqrt{\rho} h_L x + n_L. \end{aligned}$$

The problem is to demodulate the transmitted signal from the set of received signals. There are different ways to accomplish this. In the following subsections we consider several approaches

Maximal Ratio Combining (MRC)

Equivalent Channel Model with MRC

Let us now consider the performance of a digital communication system when *L* diversity branches are available. The effective channel model with MRC is given

$$\hat{x} = \arg\max_{j=1,2,\ldots,M} p(y_1, y_2, \ldots, y_L | h_1, h_2, \ldots, h_L, x_j),$$

where $p(\cdot|\cdot)$ denotes conditional (joint) p.d.f. Since, conditioned on the channel gains and the transmitted signal, the received signals are independent, the above expression can be written as

$$\hat{x} \models \arg\max_{j=1,2,\ldots,M} \prod_{l=1}^{L} p(y_l | h_l, x_j),$$

$$= \arg\max_{j=1,2,\ldots,M} \prod_{l=1}^{L} \frac{1}{\pi} \exp\left(-|y_l - \sqrt{\rho} h_l x|^2\right).$$

Furthermore, if we assume that the constellation points have equal energies, e.g., as in PSK, the expression is further simplified to

$$\underline{\hat{x}} = \arg\min_{j=1,2,\ldots,M} \mathrm{Re}\left\{\left(\sum_{l=1}^{L} h_l^* y_l\right) x_j^*\right\}.$$

Therefore, the optimal decision rule linearly combines the received signals through different diversity branches after co-phasing and weighting them with their respective channel gains. This result illustrates that the branches that have better channel gains, i.e., larger instantaneous signal-to-noise ratios, will be emphasized more than others. This is intuitive since the received signals through better channels are more reliable, and thus provide us with more accurate information. After the received signals are combined, the decision rule is the same as the case with no diversity. The resulting combining scheme is named *maximal ratio combining*.

We note that we have not made any assumptions on the statistics of the channel gains or on their independence. The maximal ratio combining rule above is general and will apply as long as the noise terms have identical variances, and they are independent. If their variances are not the same, it is straightforward to scale each observation appropriately, and apply the same rule.

Equivalent Channel Model with MRC

Let us now consider the performance of a digital communication system when L diversity branches are available. The effective channel model with MRC is given by

$$y = \left(\sum_{l=1}^{L} |h_l|^2\right) x + n',$$

Outage Probability with MRC

Let us compute the outage probability for the case of independent Rayleigh fading branches hen

MRC is employed. It is easy to see that this expression decays with $1/\rho L$ at high signal-to-noise ratios. This is in contrast to the $Pout \sim 1\ \ \rho$ behavior for the system with no diversity. Therefore, the system performance is improved considerably.

Explain with equation

$$\leq \frac{1}{2\ \rho^{L}},$$

Suboptimal Combining Algorithms

MRC is not the only way of combining signals observed through different diversity branches. There are many other alternatives including

- selection combining (SC),
- equal-gain combining (EGC),
- switch-and-stay combining (SSC), etc.

In **selection combining,** the main idea is to work with the branch that sees the best channel conditions for any given transmission. Among all the L transmissions, the branch with the highest signal-to-noise ratio is picked, and the decision is made based on this link alone.

In **equal-gain combining**, the signals of all branches are co-phased (multiplied by $e\ {-j\angle hl}$ using baseband notation) and summed together to form the equivalent channel output.

In **switch-and-stay combining,** we use a particular branch for demodulation until the signal-to-noise ratio of the branch falls below a certain threshold. When it falls below the threshold, we switch to another branch (for instance, the one with the largest instantaneous signal-to-noise ratio), and stay with it until its signal-to-noise ratio falls below the given threshold. This combining algorithm is also called threshold combining due to the way it is implemented.

Different combining algorithms have their advantages and disadvantages. For instance, MRC is optimal, however its implementation requires exact knowledge of the instantaneous channel gains, and thus is more complicated.

On the other hand, for selection combining the performance is inferior, however the implementation is simpler as exact knowledge of the channel gains is not needed in practice. We can simply measure the received signal power for different branches (perhaps this can be done at the radio frequency stage), and make the selection based on the received signal power. This may result in a performance degradation, but doing this will allow us to work with the channel estimate of a single branch, i.e., the best one at a given time.

We can even go one step further and eliminate the channel estimation requirement altogether by using differential modulation schemes. Furthermore, we can tradeoff the performance with the complexity even further by employing switch-and-stay combining as this technique will avoid frequent changes in the branch used for demodulation. Different diversity techniques are covered in many digital communications and wireless communications texts (see the end of the chapter for a list).

Therefore, we will not go into too much depth. However, we will consider selection combining in the following in more detail as it will become important for one of the later topics, i.e., antenna selection for MIMO systems.

Selection Combining:-
As summarized in the previous section, in selection combining, at any given transmission interval, the branch with the largest signal-to-noise ratio is used in demodulation. Therefore, mathematically, we have the following input–output relationship between the transmitted and received signals

$$y = \left(\max_{j=1,2,\ldots,L} |h_j| \right) x + n',$$

Channel Coding as a Means of Time Diversity

Time diversity can be considered as repetition coding where different parts of the codeword corresponding to a particular symbol are transmitted using different time intervals which are separated by at least the coherence time of the wireless channel.

This is clearly very sophisticated channel code, as we will discuss in this section, to obtain the same diversity performance with a smaller overhead. Block coding or convolutional coding techniques can be employed to obtain time diversity.

As for the specific modulation scheme, for simplicity, one may employ BPSK. However, if the bandwidth efficiency is a concern, higher order modulation techniques can also be used in almost the same manner, i.e., one can design a coded modulation scheme (based on an underlying block code) or a trellis coded modulation scheme

As described earlier, fading channels exhibit correlation in time, that is, in a typical wireless channel, consecutive bits normally see very similar channel fades, depending on the coherence time of the channel. However, in order to obtain diversity using a channel code, different parts of the codeword should undergo different channel fades.

Therefore, the use of an interleaver, whose role is to scramble the coded bits (or, symbols) before transmission, is necessary. Clearly, a de-interleaver whose function is exactly the opposite is needed at the receiver before channel decoding can be performed. See Figure 11 for a generic block diagram of the system.

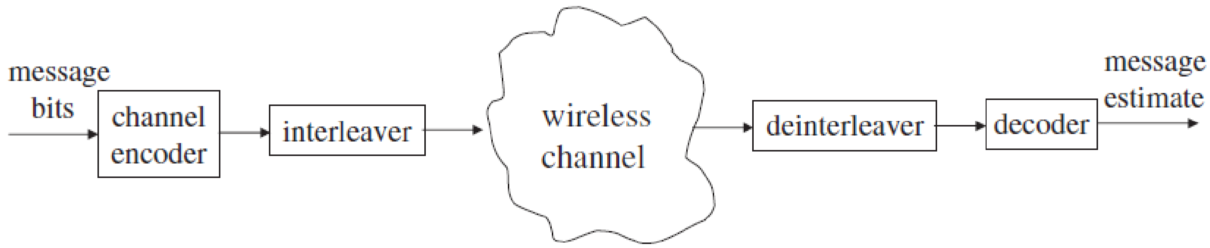


Figure 11 Coding over a wireless channel.

The exact design of the interleaver is not essential. Its function is simply to decorrelate the "effective" channel that consecutively transmitted bits see, thereby providing a means of recovery of information bits even when some of the components of the corresponding codeword are deeply faded.
A popular choice which is simple to implement is the "block interleaver" which basically writes the bits to be transmitted into the rows of a matrix, and reads them columnwise. The corresponding de-interleaver needs to write incoming bits to the columns of a matrix (of the same size as the one used for interleaving), and then read them row-wise.

Block Coding over a Fully Interleaved Channel:

Assume that a linear block code with minimum distance *dmin* is used over a fully interleaved fading channel. Let us compute an upper bound on the codeword error probability. At this point we note that the value of the PEP, hence the bound on the error probability, depends on the decoding method employed. We consider two different cases: hard-decision decoding and soft-decision decoding. In each case, we use the corresponding maximum likelihood decoder and compute an upper bound on the error probability above.

In information theory, a soft-decision decoder is a kind of decoding methods – a class of algorithm used to decode data that has been encoded with an error correcting code. Whereas a hard-decision decoder operates on data that take on a fixed set of possible values (typically 0 or 1 in a binary code), the inputs to a soft-decision decoder may take on a whole range of values in-between. This extra information indicates the reliability of each input data point, and is used to form better estimates of the original data. Therefore, a soft-decision decoder will typically perform better in the presence of corrupted data than its hard-decision counterpart. Soft-decision decoders are often used in Viterbi decoders and turbo code decoders.

Hard-Decision Decoding (HDD):

In hard-decision decoding, tentative hard decisions are made first (based on matched filter or correlator outputs) without using the code constraints. The received sequences then nothing but a binary sequence of bits. Therefore, the equivalent channel is a binary symmetric channel (BSC) with a certain cross-over probability, say p. Without loss of generality, assume that $p \leq 1\ 2$. With the assumption that the channel is fully interleaved, the BSC is memoryless, and errors that occur in bit transmissions are independent of each other. In HDD, the maximum likelihood decoding rule picks the codeword closest to the received sequence in the Hamming distance sense as the decoder output.

Soft-Decision Decoding (SDD):

Although HDD is relatively simple to implement, it does not give the best possible performance. Instead, using soft-decision decoding may be a better idea if the receiver complexity is not a major issue. In this case, the channel decoder directly works with the matched filter outputs to perform maximum likelihood decoding.

Convolutional Coding:

In addition to block coding techniques, one can also employ convolutional coding over fading channels to obtain diversity. For a convolutional code, long sequences of message bits are encoded using a finite state machine implemented with shift registers. The memory of the encoder (specified by the number of shift registers) determines the complexity of the code. If for each set of k information bits input to the encoder, there are n output bits produced, then the code rate is k/n.

These codes are significantly different than the block codes since they are not obtained by mapping a fixed-length message to a fixed-length codeword. Instead, for convolutional codes, both the messages and the coded sequences are of infinite length. An example of a convolutional code with rate 1/2 produced by $(21, 37)_{octal}$ generators is shown in Figure 12.

Figure 15

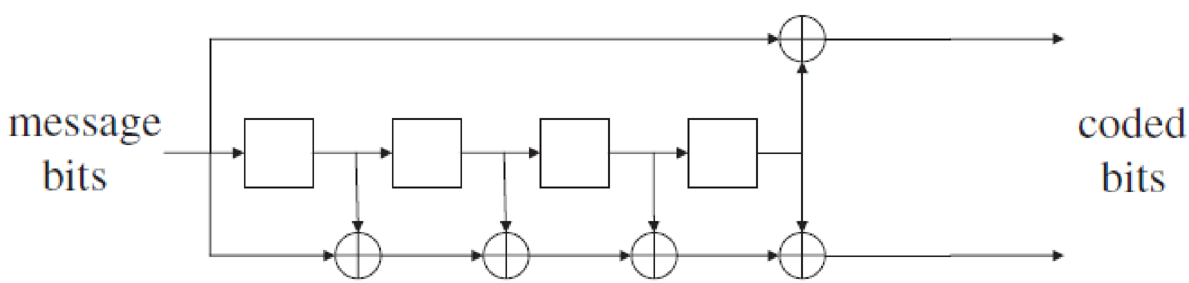


Figure 12 An example of a convolutional code with generators $(21, 37)_{octal}$

Multiple Antennas in Wireless Communications

An important resource in achieving reliable communications over unreliable wireless links is “space”, i.e., the use of multiple antennas. Different ways of using multiple antenna elements can be identified as described below.

We have already talked about the use of multiple receive antennas that can be employed to provide spatial diversity. This is a well-known technique,

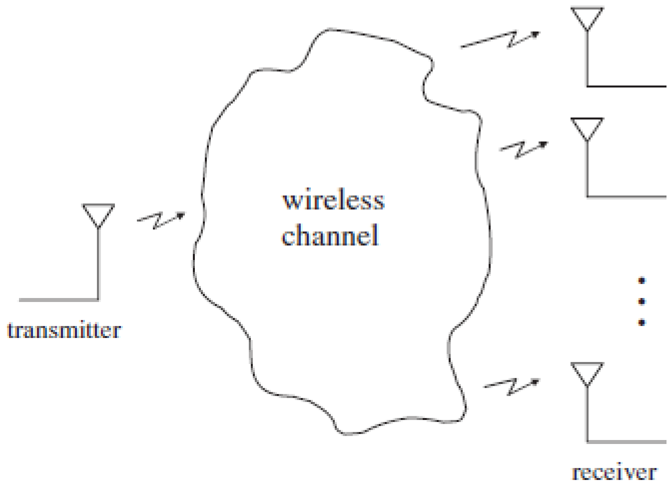


Figure 13 Spatial diversity scheme

For receive diversity, as shown in Figure 13, we simply have L replicas of the transmitted signal where each replica is effectively transmitted through a different (spatial) channel. If the receive antennas are placed sufficiently far apart, then the signals received by these antennas undergo (almost) independent fading. For instance, in a uniform scattering environment, half a wavelength separation is sufficient. For other environments, a larger separation may be needed. Using any of the diversity combining techniques, these signals can be used to make a decision on the transmitted symbol and an Lth order diversity can be achieved over a Rayleigh flat fading channel. Multiple antennas can also be employed at the transmitter as discussed in the following two subsections

Smart Antennas and Beamforming

Consider an environment that has a relatively small number of local scatterers, and hence the wireless communication is achieved mainly through line of sight, or a small number of specular components. For instance, this may be the scenario in an ad-hoc network formed by mobile computers in a large conference room. A simple illustration is provided in Figure 16.

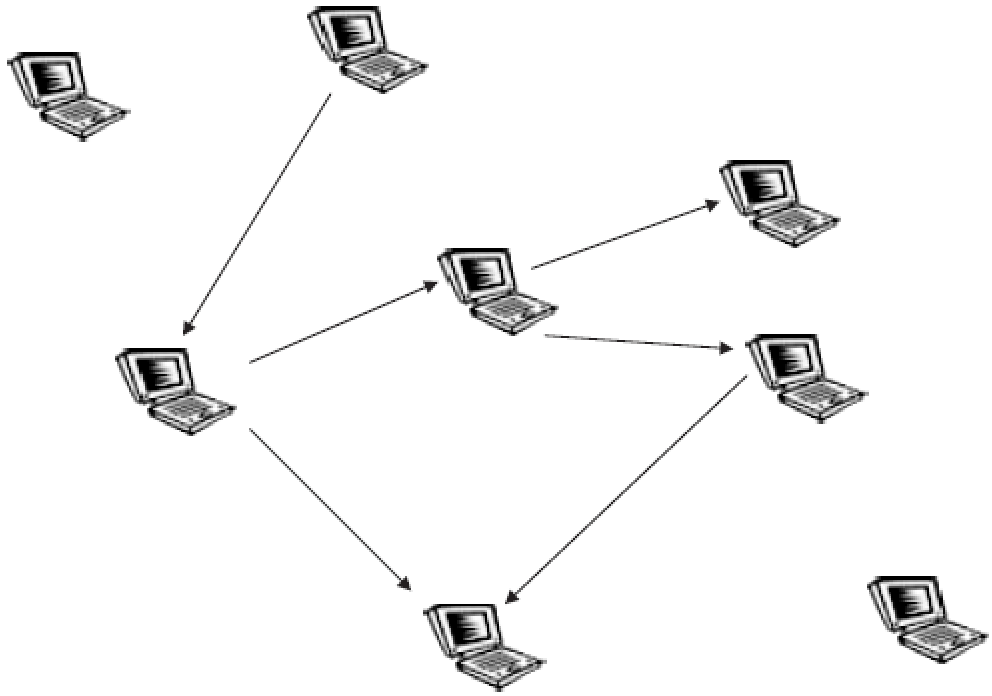


Figure 14 A simple ad-hoc network illustration

formed by mobile computers in a large conference room. A simple illustration is provided in Figure 14.

In such an environment, multiple antenna elements can be employed at the transmitters in order to provide directionality for the electromagnetic waves, hence improving the effective signal-to-noise ratio of the channel.

For instance, as shown in Figure 15, mobile A can “focus” on the intended receiver (mobile B), thus significantly increasing the received signal power at the intended destination, and dramatically reducing possible interference caused to other users in the system. In fact, multiple antennas can also be employed at the receiver. For instance, node B can effectively obtain a receive antenna pattern as shown in the figure to pick up the transmitted signal efficiently, and to reduce the amount of interference it sees.

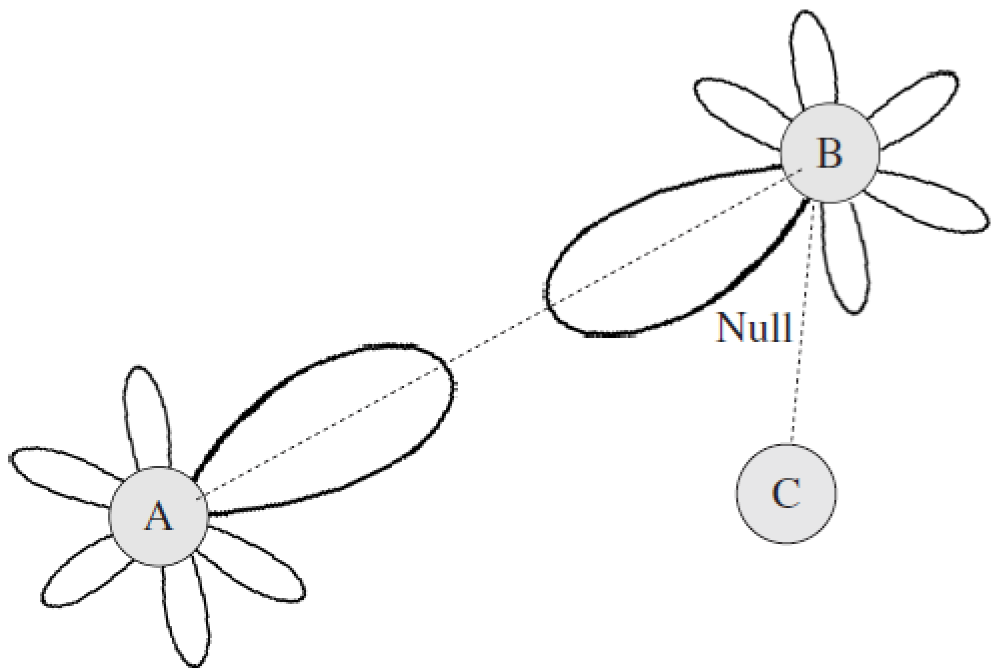


Figure 15 Illustration of beamforming being used for improving signal-to-noise ratio and reducing interference

The use of multiple antenna elements (antenna arrays, or smart antennas) in such an environment, either at the transmitter or at the receiver side, is referred to as “beamforming. This technique has been known for over fifty years, and it is used successfully in many applications, including cellular systems to provide sectoring (that will give a better spatial reuse) and underwater acoustic communications.

A fundamental approach that makes beamforming work is simply the transmission of the same signal from each of the antenna elements, with a certain gain and a phase shift (or, equivalently, with a complex gain). This can be implemented either by analog or digital means, though using digital techniques offer much more flexibility.

Different techniques can be used to find suitable coefficients for use. For instance, a direction-of-arrival algorithm can be used (which could be training based), and the coefficients can be computed to make the effective antenna pattern have a main beam in this direction. At the transmitter side, with some feedback from the receiver, position information can be obtained to accomplish the same.

Interference suppression can also be accomplished where some of the interference being suppressed could be due to the different replicas of the desired signal

Although beamforming or the use of smart antennas is a very important subject, we do not go into its details in this book. Our main objective is to consider a completely different wireless scenario, and study the recent techniques of space-time communications

Space-Time Coding – Basic Ideas

Consider again a wireless communications scenario, but assume that unlike the set-up in the previous subsection, there are many local scatterers, and the channel between the transmitter and the receiver is not due to a line of sight, or a specular component, hence it is a "rich scattering" fading channel. In such a case, there is no specific direction of arrival for the desired signal (or the interference), instead we observe a large number of multipath components that are not resolvable, i.e., the proper channel model is that of fading.

The idea in space-time coding is to encode information both spatially and temporally and transmit the encoded sequence over multiple antenna elements using the same bandwidth.

Encoding in either dimension is in fact optional, and results in variations of space-time coding. For instance, if independent uncoded streams of symbols are transmitted over different transmit antenna elements, we simply obtain what is called a spatial multiplexing scheme It is worth emphasizing the fundamental difference between "beamforming" and "spacetime coding".

In a beamforming scenario, there is a certain desired direction of transmission and reception, and antenna arrays are used at the transmitter and the receiver to place the main beams of the antenna patterns in this direction, while suppressing possible interference.
The transmitted signals are the same (scaled by certain coefficients), and the received signals are simply phase-shifted versions of each other. The block diagram of the transmitter and the receiver is illustrated in Figure 16.

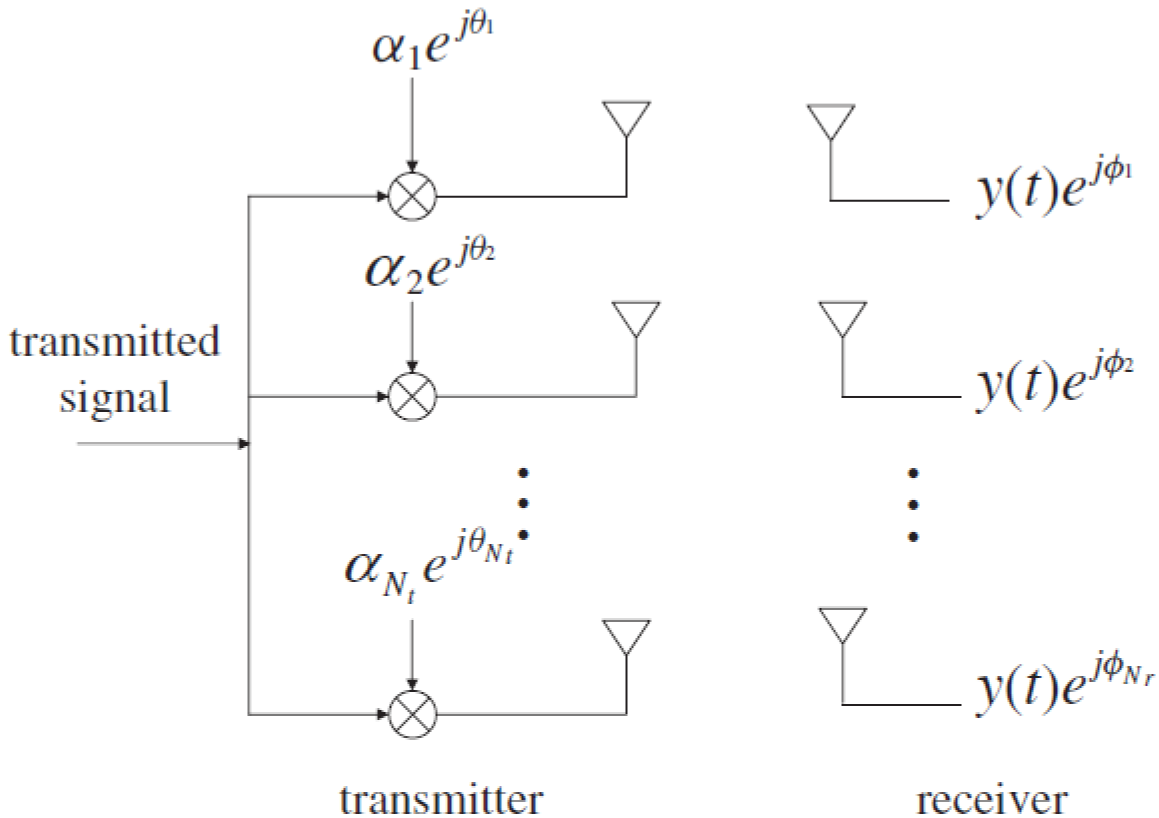


Figure 16 Multiple antennas being used for beamforming

The main objective is to increase the effective signal-to noise (plus interference) ratio. In the space-time coding set-up, there is no specific direction that we would like to communicate. In general, the transmitted signals are completely different, i.e., they may be produced by the same encoder, so they may be correlated, or they may be completely independent information streams. The received signals are obtained via completely different fading channels. This is illustrated in Figure 17

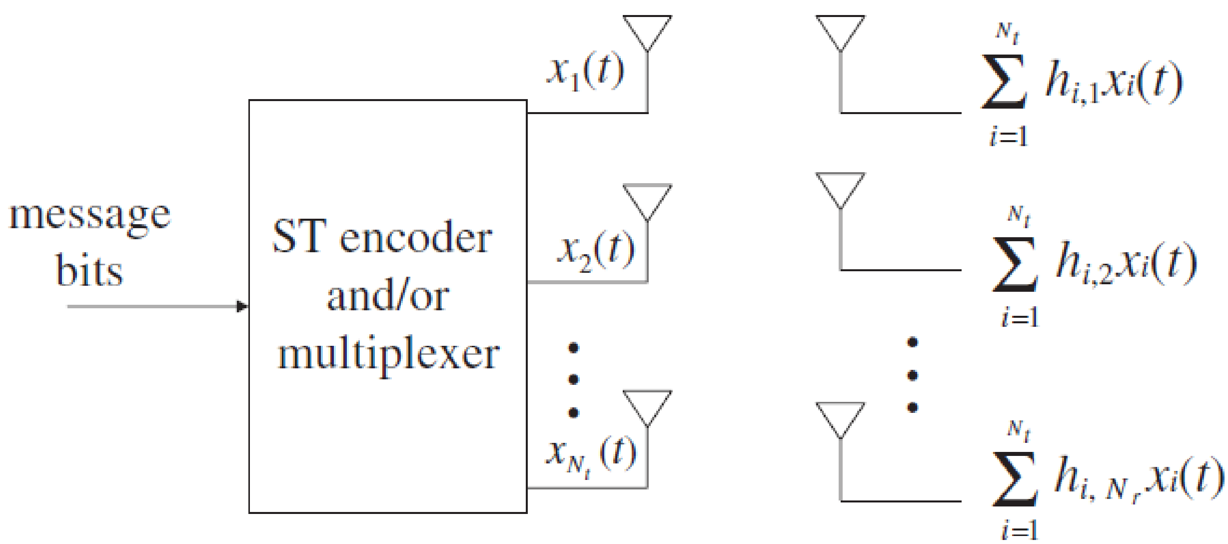


Figure 17 multiple antennas being used for space-time coding or spatial multiplexing

Acknowledgment: This material is based on the text book authored by Tolga M. Duman and Ali Ghrayeb, "Coding for MIMO Communication systems", John Wiley & Sons, West Sussex, England, 2007. Some additional material are taken and/or inspired by material from various paper and / or electronic resources.

Multiple choice Questions:

a)---------, which processes the redundantly received signals
i) **Combiner** ii) equalizer iii) PCM iv) Sampler
b) Diversity is used to combat
i) fading ii)Co Channel Interference iii) error bust **iv) all of mentioned**
c) Diversity techniques may exploit the ------- propagation, resulting in a diversity gain
i) Single path **ii) Multipath** iii) Narrow path iv) Fading path
d) In Diversity redundant -------code may be added and different parts of the message transmitted over different channels.
i) BEC **ii)FEC** iii)CSI iv) CQI
e) In ------------Combiner, the first fully received and valid data packet will be immediately further processed, whereas the later arriving redundant packets will be immediately discarded after reception.
i) Max-Ratio ii) Equal gain iii) Scanning/Switching **iv) Selection**
f) Space diversity means using different physical paths for the signal, at a -------frequency.
i) Multiple **ii) Single** iii) Co Channel iv) Orthogonal
g) -------order means how many degrees of freedom u can have in your design.
i) Rank ii) Selection iii) **Diversity** iv) Uplink/Downlink
h) Path loss is the reduction in ----------- (attenuation) of an electromagnetic wave as it propagates through space.
i) Frequency density **ii) Power density** iii) Data density iv) Amplitude
i) The signal radiated by a transmitter may also travel along many and different paths to a receiver simultaneously is ---------
i) Fading ii) Single Path **iii) Multipath** iv) Scattering
j) In WiFi, multiple antennae working at spatial Diversity helps to improve -----reliability.
i)Link ii) router iii)Base Station iv) signaling
k) Position the Router antenna upward for a better ---------reach.
i) vertical **ii) horizontal** iii) Diagonal iv) None
l) Position the Router antenna sidways for a better ---------reach.
i) vertical ii) horizontal iii) Diagonal iv) None

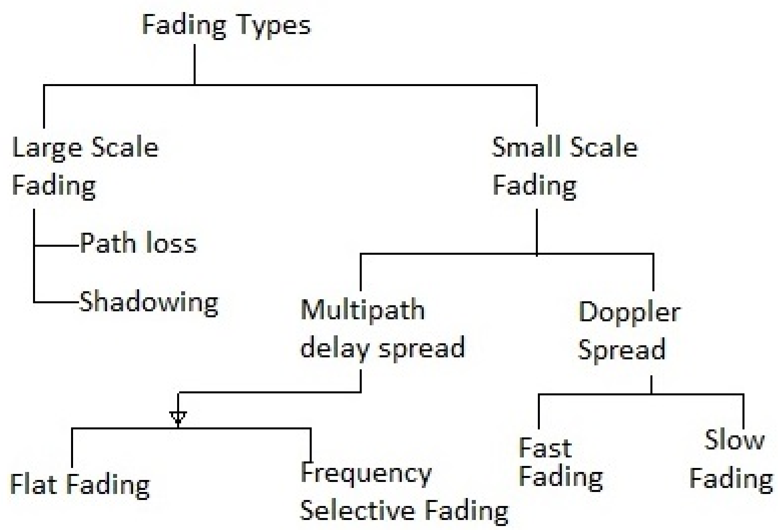
Q1. Define Channel Fading.

As we know wireless communication system consists of transmitter and receiver. The path from transmitter to the receiver is not smooth and the transmitted signal may go through various kinds of attenuations including path loss, multipath attenuation etc. The signal attenuation through the path depends on various factors. They are time, radio frequency and path or position of transmitter/receiver. The channel between transmitter and receiver can be time varying or fixed depending upon whether the transmitter/receiver are fixed or moving with respect to each other.
The time variation of received signal power due to changes in transmission medium or paths is known as fading. In fixed scenario, fading depends on atmospheric conditions such as rainfall,

lightening etc. In mobile scenario, fading depends on obstacles over the path which are varying with respect to time. These obstacles create complex transmission effects to the transmitted signal.

Q2. List the classification in Channel Fading.

Fading types



Considering various channel related impairments and position of transmitter/receiver following are the types of fading in wireless communication system.

➢Large Scale Fading: It includes path loss and shadowing effects.

➢Small Scale Fading: It is divided into two main categories viz. multipath delay spread and doppler spread. The multipath delay spread is further divided into flat fading and frequency selective fading. Doppler spread is divided into fast fading and slow fading.

Q3. Illustrate large scale fading.

Large scale fading occurs when an obstacle comes in between transmitter and receiver. This interference type causes significant amount of signal strength reduction. This is because EM wave is shadowed or blocked by the obstacle. It is related to large fluctuations of the signal over distance.

PATH LOSS

The free space path loss can be expressed as follows.

➢ $Pt/Pr = \{(4 * \pi * d)^2 / \lambda^2\} = (4*\pi*f*d)^2/c^2$

Where,

Pt = Transmit power

Pr = Receive power

λ = wavelength

d = distance between transmitting and receiving antenna

c = speed of light i.e. 3×10^8

From the equation it implies that transmitted signal attenuates over distance as the signal is being spread over larger and larger area from transmit end towards receive end.

SHADOWING EFFECT

- It is observed in wireless communication. Shadowing is deviation of received power of EM signal from average value.
- It is result of obstacles over the path between transmitter and receiver.
- It depends on geographical position as well as radio frequency of EM (ElectroMagnetic) waves.

Q4. Examine small scale fading.

Small scale fading is concerned with rapid fluctuations of received signal strength over very short distance and short time period.Based on multipath delay spread there are two types of small scale fading viz. flat fading and frequency selective fading. These multipath fading types depend on propagation environment.

1. FLAT FADING

The wireless channel is said to be flat fading if it has constant gain and linear phase response over a bandwidth which is greater than the bandwidth of the transmitted signal.

In this type of fading all the frequency components of the received signal fluctuate in same proportions simultaneously. It is also known as non-selective fading.

• Signal BW << Channel BW
• Symbol period >> Delay Spread

The effect of flat fading is seen as decrease in SNR. These flat fading channels are known as amplitude varying channels or narrowband channels.

2. FREQUENCY SELECTIVE FADING

It affects different spectral components of a radio signal with different amplitudes. Hence the name selective fading.

• Signal BW > Channel BW
• Symbol period < Delay Spread

Based on **doppler spread** there are two types of fading viz. fast fading and slow fading. These doppler spread fading types depend on mobile speed i.e. speed of receiver with respect to transmitter.

3. FAST FADING

The phenomenon of fast fading is represented by rapid fluctuations of signal over small areas (i.e. bandwidth). When the signals arrive from all the directions in the plane, fast fading will be observed for all directions of motion.

Fast fading occurs when channel impulse response changes very rapidly within the symbol duration.

• High doppler spread
• Symbol period > Coherence time
• Signal Variation < Channel variation
This parameters result into frequency dispersion or time selective fading due to doppler spreading. Fast fading is result of reflections of local objects and motion of objects relative to those objects.

In fast fading, receive signal is sum of numerous signals which are reflected from various surfaces. This signal is sum or difference of multiple signals which can be constructive or destructive based on relative phase shift between them. Phase relationships depend on speed of motion, frequency of transmission and relative path lengths.

Fast fading distorts the shape of the baseband pulse. This distortion is linear and creates ISI (Inter Symbol Interference). Adaptive equalization reduces ISI by removing linear distortion induced by channel.

4. SLOW FADING

Slow fading is result of shadowing by buildings, hills, mountains and other objects over the path.

• Low Doppler Spread
• Symbol period <<Coherence Time
• Signal Variation >> Channel Variation
Slow fading results in a loss of SNR. Error correction coding and receiver diversity techniques are used to overcome effects of slow fading.

Q5.Distinguish between flat fading and frequency selective fading

Following points summarize difference between flat fading and frequency selective fading.
In flat fading, BW of signal is less than the BW of channel whereas in frequency selective fading, BW of signal is greater than BW of channel.
In flat fading, delay spread is less than symbol period where as in frequency selective fading, delay spread is greater than symbol period.
In flat fading, range of frequencies in a frequency spectrum are equally faded unlike in frequency selective fading where in one part of frequency spectrum is faded more than the other part of frequency spectrum.

Q6.Distinguish between Fast Fading and Slow Fading.

Fast Fading

It varies quickly with the frequency. Fast fading originates due to effects of constructive and destructive interference patterns which is caused due to multipath.

Doppler spread leads to frequency dispersion and time selective fading.

Fast Fading results due to following:
➨High Doppler Spread
➨Coherence Time < Symbol Period

➨Channel impulse response changes rapidly within the symbol duration.
➨Occurs if Ts > Tc, Bs < B_D
➨It occurs for very low data rates.

Slow Fading

It does not vary quickly with the frequency. It originates due to effect of mobility. It is result of signal path change due to shadowing and obstructions such as tree or buildings etc.

Slow Fading results due to following:
➨Low Doppler Spread
➨Coherence Time >> Symbol Period
➨Impulse response changes much slower than the transmitted signal.
➨It occurs if Ts << Tc, Bs >>B_D

Q7. Explain the following Terms:

Doppler spread: Doppler spread is a measure of the spectral broadening caused by the time rate of change of the mobile radio channel, and is defined as the range of frequencies over which the received Doppler spectrum is essentially non-zero.

Coherence Time: For an electromagnetic wave, the coherence time is the time over which a propagating wave (especially a laser or maser beam) may be considered coherent, meaning that its phase is, on average, predictable

Symbol Period: Data bits are transferred during each symbol period. A. symbol period is, therefore, 16 microseconds.

Channel: A communication channel, or channel, refers either to a physical transmission medium such as a wire or to a logical connection over a multiplexed medium such as a radio channel. Communicating data from one location to another requires some form of pathway or medium. These pathways, called communication channels, use two types of media: cable (twisted-pair wire, cable, and fiber-optic cable) and broadcast (microwave, satellite, radio, and infrared).

Signal Variation: It refers to any time varying voltage, current or electromagnetic wave that carries information. ... Any physical quantity that exhibits variation in space or time can be used as a signal to share messages between observers.

Channel Variation: Various sources of diversity are available to average out channel variations due to fading. This includes time and frequency diversity, as well as transmit and receive diversity.

Rayleigh fading: Rayleigh fading is a statistical model for the effect of a propagation environment on a radio signal, such as that used by wireless devices. ... Rayleigh fading is most applicable when there is no dominant propagation along a line of sight between the transmitter and receiver.

Rayeigh Model: In Rayleigh model, only Non Line of Sight(NLOS) components are simulated between transmitter and receiver. It is assumed that there is no LOS path exists between transmitter and receiver.

Rician fading: Rician fading or Ricean fading is a stochastic model for radio propagation anomaly caused by partial cancellation of a radio signal by itself — the signal arrives at the receiver by several different paths (hence exhibiting multipath interference), and at least one of the paths is changing (lengthening or shortening).

Rician Model: In rician model, both Line of Sight (LOS) and non Line of Sight(NLOS) components are simulated between transmitter and receiver.

Nakagami fading : Nakagami fading occurs for multipath scattering with relatively large delay-time spreads, with different clusters of reflected waves. Within any one cluster, the phases of individual reflected waves are random, but the delay times are approximately equal for all waves.

Weibull fading: Weibull fading, named after Waloddi Weibull, is a simple statistical model of fading used in wireless communications and based on the Weibull distribution. Empirical studies have shown it to be an effective model in both indoor and outdoor environments.

Q8.Elaborate Diversity Techniques in Wireless Communication

Diversity is a powerful communication receiver technique that provides wireless link improvement at a relatively low cost. Diversity techniques are used in wireless communications systems to primarily to improve performance over a fading radio channel.

In such a system, the receiver is provided with multiple copies of the same information signal which are transmitted over two or more real or virtual communication channels. Thus the basic idea of diversity is repetition or redundancy of information. In virtually all the applications, the diversity decisions are made by the receiver and are unknown to the transmitter.

Types of Diversity

Fading can be classified into small scale and large scale fading. Small-scale fades are characterized by deep and rapid amplitude fluctuations which occur as the mobile moves over distances of just a few wavelengths. For narrow-band signals, this typically results in a Rayleigh faded envelope. In order to prevent deep fades from occurring, microscopic diversity techniques can exploit the rapidly changing signal.

If the antenna elements of the receiver are separated by a fraction of the transmitted wavelength, then the various copies of the information signal or generically termed as branches, can be combined suitably or the strongest of them can be chosen as the received signal. Such a diversity technique is termed as Antenna or Space diversity.

Frequency Diversity

The same information signal is transmitted on different carriers, the frequency separation between them being at least the coherence bandwidth.

Time Diversity

The information signal is transmitted repeatedly in time at regularly intervals. The separation between the transmit times should be greater than the coherence time, T_c. The time interval depends on the fading rate, and increases with the decrease in the rate of fading.

Polarization diversity

Here, the electric and magnetic fields of the signal carrying the information are modified and many such signals are used to send the same information. Thus orthogonal type of polarization is obtained.

Angle Diversity

Here, directional antennas are used to create independent copies of the transmitted signal over multiple paths.

Space Diversity

In Space diversity, there are multiple receiving antennas placed at different spatial locations, resulting in different (possibly independent) received signals.

The difference between the diversity schemes lies in the fact that in the first two schemes, there is wastage of bandwidth due to duplication of the information signal to be sent. Thus problem is avoided in the remaining three schemes, but with the cost of increased antenna complexity.

The correlation between signals as a function of distance between the antenna elements is given by the relation −

$$\rho = J_0^2 \lgroup\frac{2\Pi d}{\lambda}\rgroup$$

Where,

- J_0 = Bessel function of zero order and first kind
- d = distance of separation in space of antenna elements
- λ = carrier wavelength.

Q9.Expalin the concept of Channel coding as a means of time diversity.

Time Diversity is used in digital communication systems to combat that the transmissions channel may suffer from error bursts due to time-varying channel conditions. ... Time diversity implies that the same data is transmitted multiple times, or a redundant error correcting code is added.

In telecommunications, a diversity scheme refers to a method for improving the reliability of a message signal by using two or more communication channels with different characteristics. ... It is based on the fact that individual channels experience different levels of fading and interference.

Atmospheric turbulence can cause significant performance degradation in free space communication systems. An efficient solution could be to exploit the temporal diversity to improve the performance of the transmission link. Depending on the tolerable delay latency, we can benefit from some degree of time diversity that we can exploit by employing channel coding and interleaving.

Time Diversity is used in digital communication systems to combat that the transmissions channel may suffer from error bursts due to time-varying channel conditions. The error bursts may be caused by fading in combination with a moving receiver, transmitter or obstacle, or by intermittent electromagnetic interference, for example from crosstalk in a cable, or co-channel interference from radio transmitters.

Time diversity implies that the same data is transmitted multiple times, or a redundant error correcting code is added. By means of bit-interleaving, the error bursts may be spread in time.

Q10. Evaluate the following terms:

Diversity gain of MIMO: Diversity gain is the increase in signal-to-interference ratio due to some diversity scheme, or how much the transmission power can be reduced when a diversity scheme is introduced, without a performance loss. ... For selection combining N signals are received, and the strongest signal is selected.

Polarization Diversity: Diversity transmission and reception wherein the same information signal is transmitted and received simultaneously on orthogonally polarized waves with fade-independent propagation characteristics.

Space Diversity: Space diversity means using different physical paths for the signal, at a single frequency. If these are wireless (RF) paths, multiple antennas are located usually at least between one-half and several wavelengths apart, at the source (transmitter diversity) or receiving points (receiver diversity), or both.

Spatial Multiplexing: In spatial multiplexing, each spatial channel carries independent information, thereby increasing the data rate of the system. ...

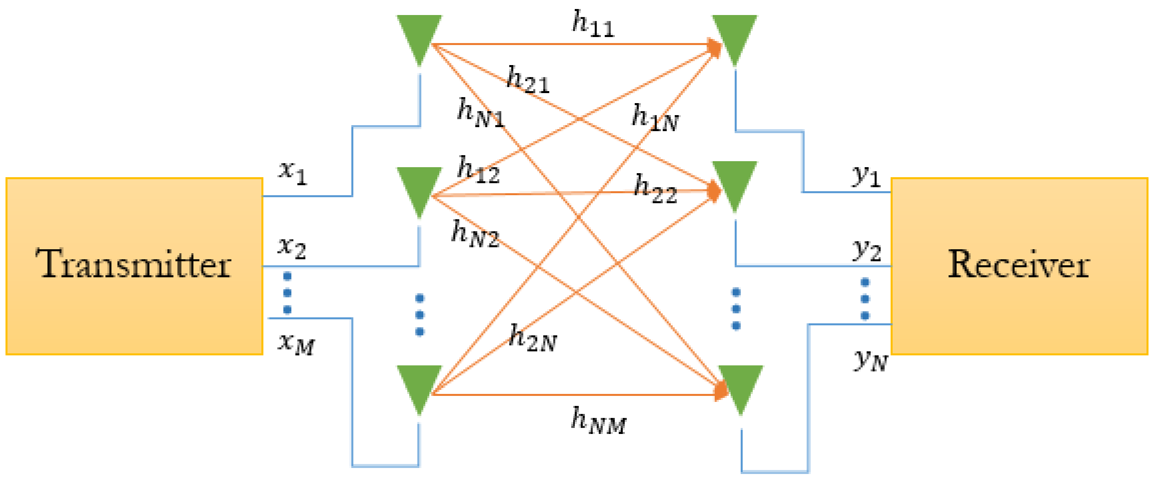
Transmit Diversity: In the transmit diversity technique shown below, same information is sent across different independent spatial channels by placing them on three different transmit antennas.

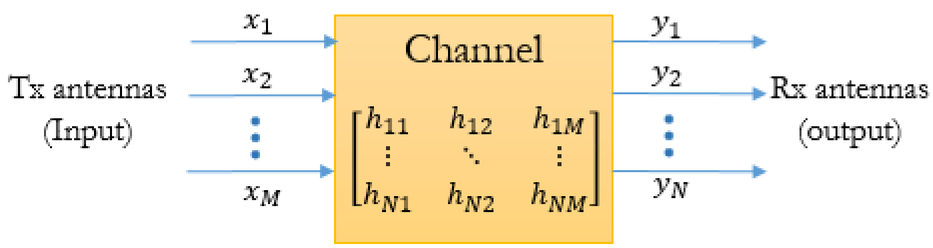
Diversity is a powerful communication receiver technique that provides wireless link improvement at a relatively low cost. ... In such a system, the receiver is provided with multiple copies of the same information signal which are transmitted over two or more real or virtual communication channels.

Q11. Evaluate multiple antennae in Wireless Communication.

Here, the system configuration typically contains ***M*** antennas at the transmitter and antennas at the receiver front end as illustrated in the next figure. Here, each receiver antenna receives not only the direct signal intended for it, but also receives a fraction of signal from other propagation paths. Thus, the channel response is expressed as a transmission matrix H. The direct path formed between antenna 1 at the transmitter and the antenna 1 at the receiver is represented by the channel response h_{11}. The channel response of the path formed between antenna 1 in the transmitter and antenna 2 in the receiver is expressed as h_{21} and so on. Thus, the channel matrix is of dimension $N \times M$.

Multiple Input Multiple Output (MIMO) System





MIMO from channel perspective

The received vector $\mathbf{y}$ is expressed in terms of the channel transmission matrix $\mathbf{H}$, the input vector $\mathbf{x}$ and noise vector $\mathbf{n}$ as where the various symbols are

For asymmetrical antenna configuration ($M \neq N$), the number of data streams (or the number of uncoupled equivalent channels) in the system is always less than equal to the minimum of the number of transmitter and receiver antennas – $min(M, N)$.

For a single user system, the capacity scales linearly with $min(M, N)$ relative to a SISO system. Regarded as a breakthrough in wireless communication system design, multiple antenna systems fuel the ever increasing data rate requirements of advanced technologies like UMTS, LTE, WLAN etc. Multiple antenna systems come in different flavors and are generally referred as Multiple Input Multiple Output systems (MIMO).

Diversity techniques are employed to make a communication system robust and reliable even over varying channel conditions. Diversity techniques exploit the channel variations rather than mitigating it. Diversity techniques combat fading and interference by presenting the receiver with multiple uncorrelated copies of the same information bearing signal. Essentially, diversity techniques are aimed at creating uncorrelated random channels -uncorrelated copies of the same signal (may also be in combined form) at the receiver front end. Combining techniques are employed at the receiver to exploit multipath propagation characteristics of a channel.

Broadly speaking, the term diversity broadly categorized as

● ***Time diversity:***
—-Multiple copies of information sent on different time slots. The time slots are designed in such a way that the delay between the signal replicas should be greater than the Coherence Time (T_c) of the channel. This condition will create uncorrelated channels over those time slots. Coding and interleaving are also equivalent techniques that break the channel memory into multiple chunks there by spreading and minimizing the effect of deep fades. This technique consumes extra transmission time.
● ***Frequency diversity:***
—-Signal replicas are sent across different frequency bands that are separated by at-least the Coherence Bandwidth (B_c) of the channel – thereby creating uncorrelated channels for the transmission. By this method, the level of fading experienced by each frequency bands are different and at-least one of the frequency bands may experience the lowest level of fading – strongest signal in this band. This technique requires extra bandwidth. Example : Orthogonal Frequency Division Multiplexing (OFDM) and spread spectrum.
● ***Multiuser diversity*** :
—-Employing adaptive modulation and user scheduling techniques to improve the performance of a multiuser system. In such systems, the channel quality information for each user is utilized by a scheduler to select the number of users, coding and modulation such that an objective function (throughput and fairness of scheduling) is optimized. Example: OFDMA and access scheme used in latest wireless systems such as IEEE 802.16e (Mobile WiMAX)
● ***Spatial diversity (antenna diversity)***:
—Aimed at creating uncorrelated propagation paths for a signal, spatial diversity is effected by usage of multiple antennas in the transmitter and/or the receiver. Employing multiple antennas at the transmitter is called "***Transmit Diversity***" and multiple antennas at the receiver is called "***Reception Diversity***".

Diversity combining techniques like ***Selection Combining (SC)***, ***Feedback or Scanning Combining (FC or SC)***, ***Maximum Ratio Combining (MRC)*** can be employed by the receiver to exploit the multiplath effects. Spatial diversity techniques can also be used to increase the data rates (spatial multiplexing) rather than improving the reliability of the channel. Example: ***MIMO, beamforming*** and ***Space-Time Coding (STC)***
● ***Polarization diversity (antenna diversity):***
—-Multiple copies of the same signal are transmitter and received by antennas of different polarization. Used the mitigate polarization mismatches of transmit and receiver antennas.
● ***Pattern diversity (antenna diversity)***:
—-Multiple versions of the signal are transmitted via two or more antenna with different radiation patterns. The antennas are spaced such that they collectively act as a single entity aimed at providing more directional gain compared to an omni-directional antenna.
● ***Adaptive arrays (antenna diversity)***:

—-Ability to control the radiation pattern of a single antenna with active elements or an array of antennas. The radiation pattern is adapted based on the existing channel conditions.

Q12. Illustrate about Soft Decision Decoding and Hard Decision Decoding.

Soft-Decision Decoding (SDD):

Although HDD is relatively simple to implement, it does not give the best possible performance. Instead, using soft-decision decoding may be a better idea if the receiver complexity is not a major issue. In this case, the channel decoder directly works with the matched filter outputs to perform maximum likelihood decoding.

Hard-Decision Decoding (HDD)

In hard-decision decoding, tentative hard decisions are made first (based on matched filter or correlator outputs) without using the code constraints. The received sequences then nothing but a binary sequence of bits. Therefore, the equivalent channel is a binary symmetric channel (BSC) with a certain cross-over probability, say p. Without loss of generality, assume that $p \leq 1\ 2$. With the assumption that the channel is fully interleaved, the BSC is memoryless, and errors that occur in bit transmissions are independent of each other. In HDD, the maximum likelihood decoding rule picks the codeword closest to the received sequence in the Hamming distance sense as the decoder output.

Q13. Model Channel Coding as a Means of Time Diversity.

Time diversity can be considered as repetition coding where different parts of the codeword corresponding to a particular symbol are transmitted using different time intervals which are separated by at least the coherence time of the wireless channel.

Block coding or convolutional coding techniques can be employed to obtain time diversity. However, if the bandwidth efficiency is a concern, higher order modulation techniques can also be used in almost the same manner, i.e., one can design a coded modulation scheme (based on an underlying block code) or a trellis coded modulation scheme.

Fading channels exhibit correlation in time, that is, in a typical wireless channel, consecutive bits normally see very similar channel fades, depending on the coherence time of the channel. However, in order to obtain diversity using a channel code, different parts of the codeword should undergo different channel fades. Therefore, the use of an interleaver, whose role is to scramble the coded bits (or, symbols) before transmission, is necessary. Clearly, a de-interleaver whose function is exactly the opposite is needed at the receiver before channel decoding can be performed.

The exact design of the interleaver is not essential. Its function is simply to decorrelate the “effective” channel that consecutively transmitted bits see, thereby providing a means of recovery of information bits even when some of the components of the corresponding codeword are deeply faded. A popular choice which is simple to implement is the “block interleaver” which basically writes the bits to be transmitted into the rows of a matrix, and reads them column wise. The corresponding de-interleaver needs to write incoming bits to the columns of a matrix (of the same size as the one used for interleaving), and then read them row-wise.

Q14. What is the function of Interleaver and scrambler in MIMO.

A scrambler is a device that transposes or inverts signals or otherwise encodes a message at the sender's side to make the message unintelligible at a receiver not equipped with an appropriately set descrambling device. Whereas encryption usually refers to operations carried out in the digital domain, scrambling usually refers to operations carried out in the analog domain.

Scrambling is accomplished by the addition of components to the original signal or the changing of some important component of the original signal in order to make extraction of the original signal difficult. A scrambler replaces sequences (referred to as whitening sequences) into other sequences without removing undesirable sequences, and as a result it changes the probability of occurrence of vexatious sequences. Clearly it is not foolproof.

There are two main reasons why scrambling is used:

- To enable accurate timing recovery on receiver equipment without resorting to redundant line coding. It facilitates the work of a timing recovery circuit (see also Clock recovery), an automatic gain control and other adaptive circuits of the receiver (eliminating long sequences consisting of '0' or '1' only).
- For energy dispersal on the carrier, reducing inter-carrier signal interference. It eliminates the dependence of a signal's power spectrum upon the actual transmitted data, making it more dispersed to meet maximum power spectral density requirements (because if the power is concentrated in a narrow frequency band, it can interfere with adjacent channels due to the intermodulation (also known as cross-modulation) caused by non-linearities of the receiving tract).

Q15. Evaluate Maximal ratio combining.

Maximum-ratio combining (MRC) is a method of diversity combining in which:

1. the signals from each channel are added together,
2. the gain of each channel is made proportional to the rms signal level and inversely proportional to the mean square noise level in that channel.
3. different proportionality constants are used for each channel.

It is also known as ratio-squared combining and predetection combining. Maximum-ratio combining is the optimum combiner for independent additive white Gaussian noise channels.

MRC can restore a signal to its original shape.

Q16. Explain about optimal Combining techniques other then MRC.

Suboptimal Combining Algorithms MRC is not the only way of combining signals observed through different diversity bran- ches. There are many other alternatives including selection combining (SC), equal-gain combining (EGC), switch-and-stay combining (SSC), etc. In selection combining, the main idea is to work with the branch that sees the best channel conditions for any given transmission. Among all the L transmissions, the branch with the highest signal-to-noise ratio is picked, and the decision is made based on this link alone. In equal-gain combining, the signals of all branches are co-phased (multiplied by $e^{-j\angle h_l}$ using baseband notation) and summed together to form the equivalent channel output. In switch-and-stay combining, we use a particular branch for demodulation until the signal-to-noise ratio of the branch falls below a certain threshold. When it falls below the threshold, we switch to another branch (for instance, the one with the largest instantaneous signal-to-noise ratio), and stay with it until its signal-to-noise ratio falls below the given threshold. This combining algorithm is also called threshold combining due to the way it is implemented. Different combining algorithms have their advantages and disadvantages.

For instance, MRC is optimal, however its implementation requires exact knowledge of the instantaneous channel gains, and thus is more complicated. On the other hand, for selection combining the performance is inferior, however the implementation is simpler as exact knowledge of the channel gains is not needed in practice. We can simply measure the received signal power for different branches (perhaps this can be done at the radio frequency stage), and make the selection based on the received signal power. This may result in a performance degradation, but doing this will allow us to work with the channel estimate of a single branch, i.e., the best one at a given time. We can even go one step further and eliminate the channel estimation requirement altogether by using differential modulation schemes. Furthermore, we can trade- off the performance with the complexity even further by employing switch-and-stay combining as this technique will avoid frequent changes in the branch used for demodulation.

Q17. Summarize Error/Outage Probabilities over Fading Channels.

In basic digital communications, error rates for digital modulation techniques such as phase shift keying (PSK), quadrature amplitude modulation (QAM) and frequency shift keying (FSK) all reduce exponentially with the signal-to-noise ratio for additive white Gaussian noise (AWGN) channels. However, for fading channels, the situation is quite different, and if not mitigated properly, the effects of channel fading are deleterious on the digital communication system performance.

Outage Probability for Rayleigh Fading Channels:

We first consider a scenario where fading is extremely slow, and we observe only a single state of the channel over an entire frame of data, i.e., quasi-static fading. Assume that a certain frame error rate or bit error rate is tolerable for a particular application, however if the error rate goes above this level, the resulting performance is simply unacceptable. The communication failure probability is inversely proportional to the average signal-to-noise ratio. For many applications, this is simply unacceptable, because, to make the outage probability low, excessive transmission powers will be required.

Average Error Probabilities over Rayleigh Fading Channels:

The error probability for a Rayleigh fading channel is only inversely proportional to the signal-to-noise ratio. This is in sharp contrast with error rates over AWGN channels as they decay exponentially with ρ(mean).

Extension to other Fading Channels:

Due to the existence of the specular component, the outage probability expressions and average error rates for the case of Rician fading will be better than those of Rayleigh fading.

Performance over Frequency Selective Fading Channels:

Although the existence of ISI may seem like a degrading factor, it effectively provides frequency diversity (or, multipath diversity), that is, effectively each signal gets transmitted through several differently faded channels. Therefore, error rates may improve with frequency selectivity compared with flat fading channels.