An Overview of Diversity Techniques in Wireless Communication Systems

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Abstract— **Fading problem is a major impairment of the wireless communication channel. In this paper we considers different techniques to mitigate the fading problem in wireless channel. The trivial solution for the fading problem would be to add a fading margin at the transmitter. However, this is not an efficient solution at all. One alternate solution is to take advantage of the statistical behavior of the fading channel. Here comes the basic concept of diversity; where two or more inputs at the receiver are used to get uncorrelated signals.**

Keywords—**Diversity, fading.**

I. INTRODUCTION

THE wireless communication channel suffers from many impairments such as the thermal noise often modeled as Additive White Gaussian Noise (AWGN), the path loss in power as the radio signal propagates, the shadowing due to the presence of fixed obstacles in the radio path, and the fading which combines the effect of multiple propagation paths, and the rapid movement of mobile units reflectors. Upon the signal transmission, different signal copies undergo different attenuation, distortion, delays and phase shifts. Due to this problem, the overall system performance can be severely degraded. One example is shown in Figure 1.

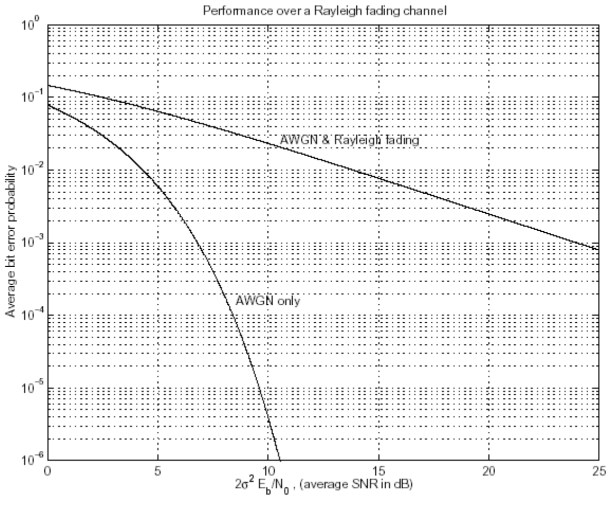


Figure 1. System performance degradation due to fading

II. FADING

In a typical wireless communication environment, multiple propagation paths often exist from a transmitter to a receiver due to scattering by different objects. Signal copies following different paths can undergo different attenuation, distortions, delays and phase shifts. Constructive and destructive interference can occur at the receiver. When destructive interference occurs, the signal power can be significantly diminished. This phenomenon is called *fading*. The performance of a system (in terms of probability of error) can be severely degraded by fading.

Very often, especially in mobile communications, not only do multiple propagation paths exist, but they are also time-varying. The result is a time-varying fading channel. Communication through these channels can be difficult. Special techniques may be required to achieve satisfactory performance.

A. Parameters of fading channels

The general time varying fading channel model is too complex for understanding and performance analysis for wireless channels. One approximate channel model is the *wide-sense stationary uncorrelated scattering* (WSSUS). In WSSUS model, the time-varying fading process is assumed to be wide-sense stationary random process and the signal copies from the scatterings by different objects are assumed to be independent. The following parameters are often used to characterize a WSSUS channel:

1) Multipath Spread T_m

It tells us the maximum delay between paths of significant power in the channel

2) Coherence Bandwidth $(\Delta f)_c$

Gives an idea of how far apart –in frequency- for signals to undergo different degrees of fading

3) Coherence Time $(\Delta t)_c$

Gives a measure of the time duration over which the channel impulse response is essentially invariant (highly correlated)

4) Doppler Spread B_d

It gives the maximum range of Doppler shifts

B. *Classification of fading channels*

Based on the parameters of the channels and the characteristics of the signal to be transmitted, time-varying fading channels can be classified as:

1) *Frequency non-selective versus frequency selective*

If the bandwidth of the transmitted signal is small compared with $(\Delta f)_c$, then all frequency components of the signal would roughly undergo the same degree of fading. The channel is then classified as *frequency non-selective* (also called *flat fading*). We notice that because of the reciprocal relationship between $(\Delta f)_c$ and $(\Delta t)_c$ and the one between bandwidth and symbol duration, in a frequency non-selective channel, the symbol duration is large compared with $(\Delta t)_c$. In this case, delays between different paths are relatively small with respect to the symbol duration. We can assume that we would receive only one copy of the signal, whose gain and phase are actually determined by the superposition of all those copies that come within $(\Delta t)_c$.

On the other hand, if the bandwidth of the transmitted signal is large compared with $(\Delta f)_c$, then different frequency components of the signal (that differ by more than $(\Delta f)_c$) would undergo different degrees of fading. The channel is then classified as *frequency selective*. Due to the reciprocal relationships, the symbol duration is small compared with $(\Delta t)_c$. Delays between different paths can be relatively large with respect to the symbol duration. We then assume that we would receive multiple copies of the signal.

2) *Slow fading versus fast fading*

If the symbol duration is small compared with $(\Delta t)_c$, then the channel is classified as *slow fading*.

Slow fading channels are very often modeled as time-invariant channels over a number of symbol intervals. Moreover, the channel parameters, which are slow varying, may be estimated with different estimation techniques.

On the other hand, if $(\Delta t)_c$ is close to or smaller than the symbol duration, the channel is considered to be *fast fading* (also known as *time selective fading*). In general, it is difficult to estimate the channel parameters in a fast fading channel.

We notice that the above classification of a fading channel depends on the properties of the transmitted signal. The two ways of classification give rise to four different types of channel:

- Frequency non-selective slow fading
- Frequency selective slow fading
- Frequency non-selective fast fading
- Frequency selective fast fading

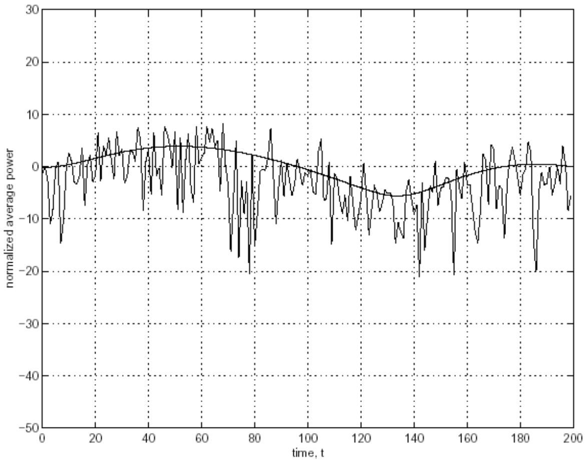


Figure 2. Fast fading vs. slow fading

III. DIVERSITY TECHNIQUES

Diversity techniques can be used to improve system performance in fading channels. Instead of transmitting and receiving the desired signal through one channel, we obtain L copies of the desired signal through *M* different channels. The idea is that while some copies may undergo deep fades, others may not. We might still be able to obtain enough energy to make the correct decision on the transmitted symbol. There are several different kinds of diversity which are commonly employed in wireless communication systems:

A. *Frequency Diversity*

One approach to achieve diversity is to modulate the information signal through *M* different carriers.

Each carrier should be separated from the others by at least the coherence bandwidth $(\Delta f)_c$ so that different copies of the signal undergo independent fading. At the receiver, the L independently faded copies are "optimally" combined to give a statistic for decision. The optimal combiner is the *maximum ratio combiner*, which will be introduced later. Frequency diversity can be used to combat frequency selective fading.

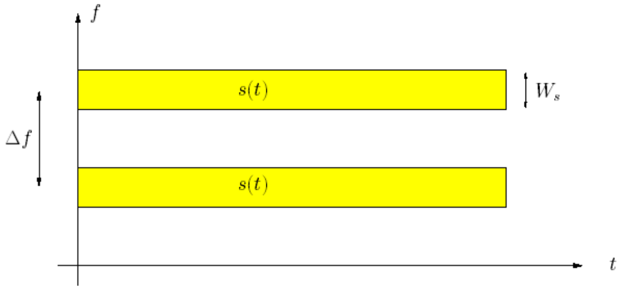


Figure 3. Frequency diversity

B. Time Diversity

Another approach to achieve diversity is to transmit the desired signal in M different periods of time, i.e., each symbol is transmitted M times. The intervals between transmissions of the same symbol should be at least the coherence time $(\Delta t)_c$ so that different copies of the same symbol undergo independent fading. Optimal combining can also be obtained with the maximum ratio combiner. We notice that sending the same symbol M times is applying the *(M,1)* repetition code. Actually, non-trivial coding can also be used. Error control coding, together with interleaving, can be an effective way to combat time selective (fast) fading.

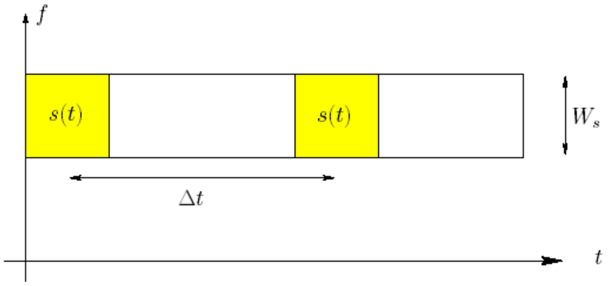


Figure 4. Time Diversity

C. Space Diversity

Another approach to achieve diversity is to use M antennas to receive M copies of the transmitted signal. The antennae should be spaced far enough apart so that different received copies of the signal undergo independent fading. Different from frequency diversity and temporal diversity, no additional work is required on the transmission end, and no additional bandwidth or transmission time is required.

However, physical constraints may limit its applications. Sometimes, several transmission antennae are also employed to send out several copies of the transmitted signal. Spatial diversity can be employed to combat both frequency selective fading and time selective fading.

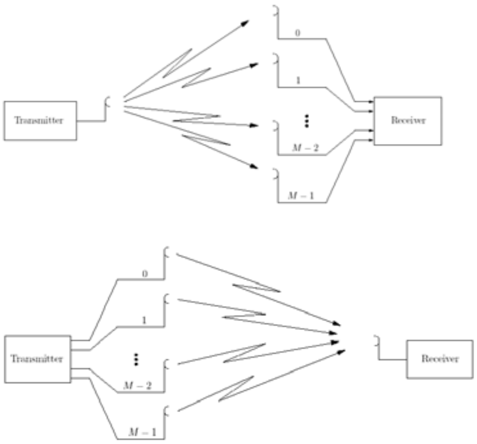


Figure 5. Space Diversity

IV. DIVERSITY COMBINING METHODS

The idea of diversity is to combine several copies of the transmitted signal, which undergo independent fading, to increase the overall received power. Different types of diversity call for different combining methods. Here, we review several common diversity combining methods.

For a slowly flat fading channel, the equivalent lowpass of the received signal of branch i can be written as

$$r_i(t) = A_i e^{j\theta_i} s(t) + z_i(t), \quad i = 0, 2, \ldots, M-1$$

where $s(t)$ is the equivalent lowpass of the transmitted signal, $A_i e^{j\theta_i}$ is the fading attenuation of branch i, $z_i(t)$ is the AWGN.

Out of M branches, M replicas of the transmitted signal are obtained

$$\mathbf{r} = \begin{bmatrix} r_1(t) & r_2(t) & \cdots & r_{M-1}(t) \end{bmatrix}$$

A. Selection Combining

In this method, the strongest signal branch is selected as shown in Figure 6.

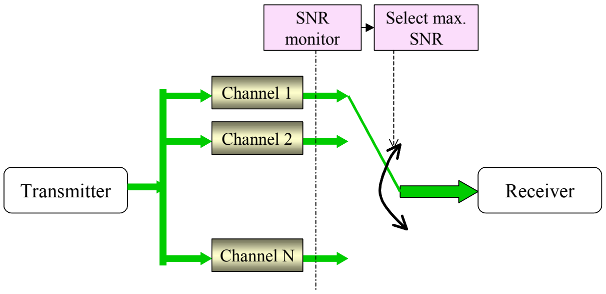


Figure 6. Selection Combining

The combiner output is given by

$$y(t) = A e^{j\theta} s(t) + z(t), \quad \text{with } A = \max\{A_0, A_1, \ldots, A_{M-1}\}$$

The received SNR can be written as follows:

$$\Gamma = \frac{A^2 E_b}{N_0} = \max\{\Gamma_0, \Gamma_1, \ldots, \Gamma_{M-1}\}$$

With uncorrelated branches, the CDF of Γ is

$$P_\Gamma(\gamma) = \Pr\{\Gamma < \gamma\} = \prod_{i=0}^{M-1} P_{\Gamma i}(\gamma)$$

For i.i.d branches, we have

$$P_\Gamma(\gamma) = \left[P_{\Gamma_0}(\gamma)\right]^M, \quad \text{and} \quad p_\Gamma(\gamma) = M p_{\Gamma_0}(\gamma)\left[P_{\Gamma_0}(\gamma)\right]^{M-1}$$

1) Example: Rayleigh Fading Channel

The outage probability is given by

$$P_\Gamma(\gamma) = \left(1 - e^{-\gamma/\gamma_0}\right)^M, \quad \gamma_0 = 2\sigma^2 E_b / N_0$$

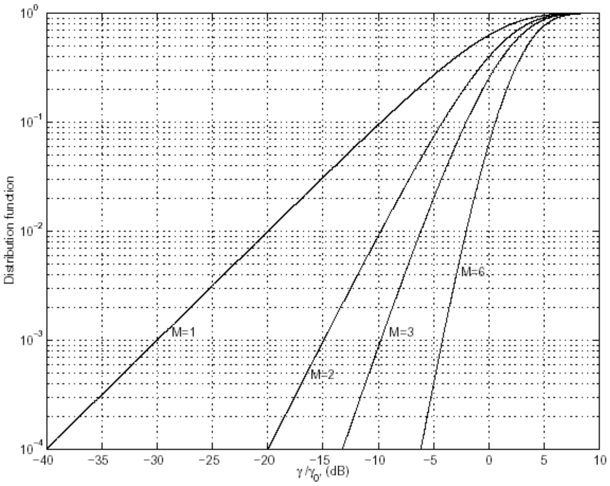


Figure 7. Selection Combining in Rayleigh Fading Channel

B. *Maximal Ratio Combining*

In this method, the diversity branches are weighted for maximum SNR as can be seen in Figure 8.

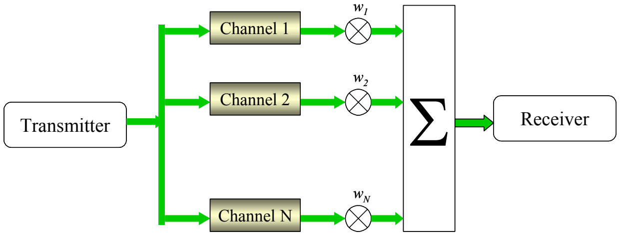


Figure 8. Maximal Ratio Combining

The combiner output is given by

$$y(t)=\sum_{i=0}^{M-1} w_i r_i(t)$$

Choose the weights to be the channel gain conjugate [must be estimated]

$$y(t)=\sum_{i=0}^{M-1} A_i e^{-j\theta_i} r_i(t)=\sum_{i=0}^{M-1} A_i e^{-j\theta_i}\left[A_i e^{j\theta_i} s(t)+z_i(t)\right]$$

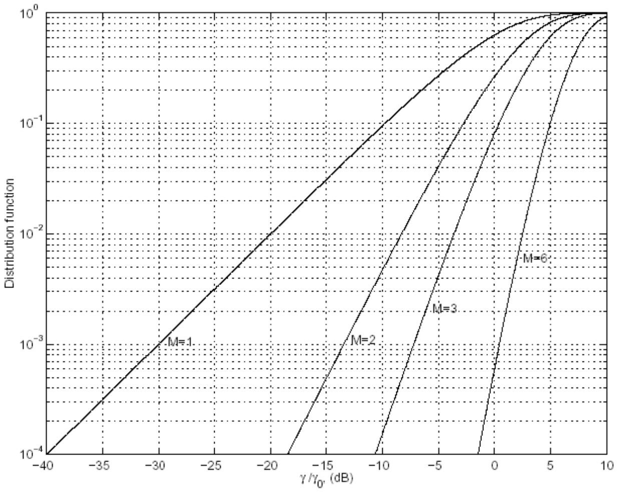
$$=\left(\sum_{i=0}^{M-1} A_i^2\right) s(t)+\sum_{i=0}^{M-1} A_i e^{-j\theta_i} z_i(t)$$

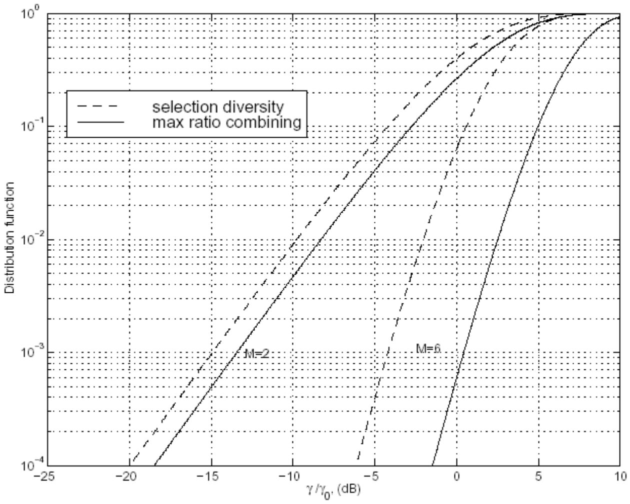
The SNR of the combined signal is

$$\Gamma=\frac{\sum_{i=0}^{M-1} A_i^2 E_b}{N_0}=\sum_{i=0}^{M-1}\Gamma_i$$

For Rayleigh Fading channel, the outage probability is given by:

$$P_\Gamma(\gamma)=1-e^{-\frac{\gamma}{\gamma_0}}\sum_{i=1}^{M}\frac{(\gamma/\gamma_0)^{i-1}}{(i-1)!}$$





C. *Equal Gain Combining*

Each branch signal is rotated by $e^{-j\theta_i}$, all branch signals are then added

The combiner output is given by

$$y(t)=\sum_{i=1}^{M} e^{-j\theta_i} r_i(t)=\left(\sum_{i=0}^{M} A_i\right) s(t)+\sum_{i=0}^{M} e^{-j\theta_i} z_i(t)$$

The SNR is given by

$$\Gamma=\left(\sum_{i=0}^{M-1} A_i\right)^2\frac{E_b}{MN_0}$$

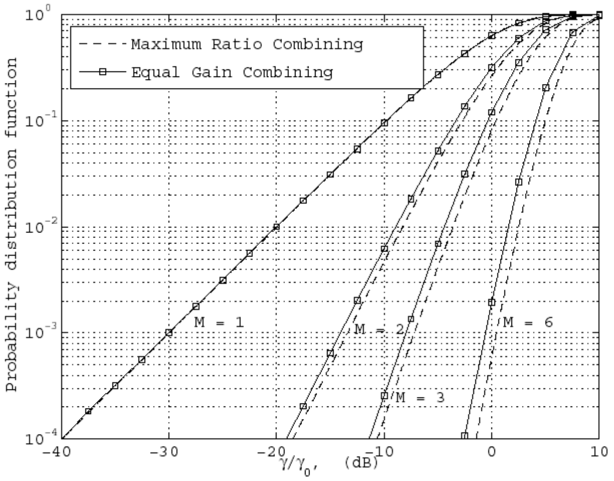


Figure 11. Equal Gain Combining

V. CONCLUSION

The diversity is used to provide the receiver with several replicas of the same signal. Diversity techniques are used to improve the performance of the radio channel without any increase in the transmitted power. As higher as the received signal replicas are decorrelated, as much as the diversity gain

Diversity Combining: MRC outperforms the Selection Combining; Equal gain combining (EGC) performs very close to the MRC. Unlike the MRC, the estimate of the channel gain is not required in EGC

Among different combining techniques MRC has the best performance and the highest complexity, SC has the lowest performance and the least complexity

REFERENCES

[1] Aalborg University, Lecture notes, URL: http://kom.aau.dk/~imr/RadioCommIII/

[2] Markku Juntti, et. al. ,"*MIMO Communications with Applications to 3G and 4G*", Oulu University,

[3] ROYAL INSTITUTE OF TECHNOLOGY, STOCKHOLM, LECTURE NOTES, URL: HTTP://WWW.S3.KTH.SE/RADIO/COURSES/RKBASIC_2E1511_2004/DOWNLOADS/LECTURENOTES/