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Antenna Diversity Techniques

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Abstract: Antenna diversity uses two or more antennas to improve the quality and reliability of a wireless link where there is not a clear line-of-sight (LOS) between transmitter and receiver. Instead the signal is reflected along multiple paths before finally being received. Each of these bounces can introduce phase shifts, time delays, attenuations, and even distortions can destructively interfere with one another at the aperture of the receiving antenna. Antenna diversity is effective at mitigating these multipath situations. This paper investigates the various antenna diversity techniques and combining techniques.

Keywords: Correlated channels, wireless communication, multiple antennas, multipath fading.

I. INTRODUCTION

Antenna Diversity is a transmission method using more than one antenna to receive or transmit signals along different propagation paths to compensate for multipath interferences. Due to multipath propagation, interference effects between different transmitters, the received signal strength may strongly vary, even for small changes of the propagation conditions, affecting the link quality. These fading effects can result in an increased loss of the connection between transmitters and receivers. Applying Antenna Diversity transmission techniques in such scenarios improves the reliability of a wireless channel [1]. Diversity schemes provide two or more inputs at the receiver such that the fading phenomena among these inputs are uncorrelated. If one radio path undergoes deep fade at a particular point in time, another independent (or at least highly uncorrelated) path may have a strong signal at that input. If probability of a deep fade in one channel is p, then the probability for N-channels is p^N. Antenna diversity can be realized in several ways. Depending on the environment and the expected interference, designers can employ one or more of these methods to improve signal quality [2]. In fact, multiple methods are frequently used to further increase reliability.

II. ANTENNA DIVERSITY TECHNIQUES

There are different types of diversity technique which utilize multiple antennas to achieve diversity - spatial, pattern and polarization, transmit/receive diversities. At the mobile terminal, a combination of these different types of antenna diversity techniques is often used.

A. Spatial Diversity

Spatial diversity employs multiple antennas, usually with the same characteristics, that are physically separated from one another. Depending upon the expected incidence of the incoming signal, sometimes a space on the order of a wavelength is sufficient. Other times much larger distances are needed. Cellularization or sectorization, for example, is a spatial diversity scheme that can have antennas or base stations miles apart [2]. This is especially beneficial for the mobile communications industry since it allows multiple users to share a limited communication spectrum and avoid co-channel interference.

Spatial diversity utilizes more than one antenna which are sufficiently separated from each other so that the relative phases of the multipath contributions are significantly different at the two antennas. This is the most fundamental technique to achieve diversity. The phase differences between the total signals received at each of the antennas are proportional to the differences in the path lengths from the scatterers to each antenna [10]. When large phase differences are present, they give rise to a low correlation between the signals at the antennas. Therefore it is expected that the correlation decreases with an increase in the distance between the scatterers or an increase in the distance between the antennas.

By assuming angular density function to be uniform in azimuth of the mobile environment and no angular density function in elevation (i.e. Two-dimensional scenario), the correlation coefficient for a distance separation d can be obtained from the zero order Bessel function, $J_o(x)$:

$$\rho_{12} = J_0(\beta d)$$

where β is the phase constant.

The first null of J_0 (β d) is at d=0.4λ, as shown in Fig. 1. As shown graphically in Fig. 1, the correlation coefficient starts to increase after d =0.4λ. However, in suburban areas the measurements show that the first null appears at about d = 0.8λ.This may be due to a lack of uniform angular distribution of wave arrival. It shows that the angular distribution of wave arrival does affect the correlation coefficient for a given spacing d, whereby if the angular density function is restricted to a limited range then ρ_{12} will increase. Generally, spacing, d of 0.5λ is practically used to obtain two uncorrelated signals at mobile terminals.

Apart from the effect of the angular density functions $P_\theta(\theta, \varphi)$ and $P_\varphi(\theta, \varphi)$, it should be noted that since the two antennas are horizontally spaced with d=0.5λ, mutual coupling also affects the performance of diversity as well.

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However, above equation does not consider the mutual coupling between the antennas. It has been shown in theory and experimentally that mutual coupling reduces the correlation coefficient. Recently it has been reported that the MIMO capacity is still relatively large when the four antennas are closely spaced down to d=0.2λ in the indoor environment. In the outdoor environment, the MIMO capacity for antennas with spacing of d=0.2λ is even larger than when the antennas spacing is d=2.5λ.

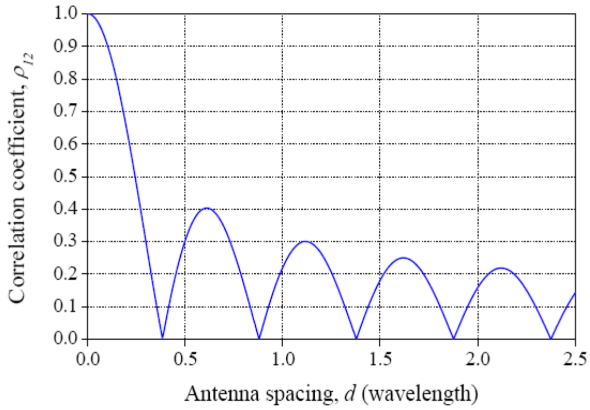

Fig. 1: Diagram showing the effect of antenna spacing to correlation coefficient.

B. Pattern Diversity
Pattern diversity occurs in many instances at the mobile terminals because the antennas will pick up signals coming from different angles. Since the fading signals coming from different directions are independent so pattern diversity can be implemented [2]. This has been considered at the base station in some cases and compared with spatial diversity.

At the mobile terminal, two omni-directional antennas interacting with each other whilst closely spaced can also obtain pattern diversity. Basically, the antennas act as parasitic elements to each other and their patterns change to allow signals to be picked up at different angles. Antennas with beam steering at the mobile terminals (by changing the feed point impedance of parasitic elements) have been developed. Recent studies conducted on pattern diversity in the MIMO systems have shown that with appropriate dissimilarity in the antenna pattern, the system can achieve large channel capacity [11].

Pattern diversity system which implements different beam patterns on the two different antennas is shown. Referring to Fig. 2 below, the yellow antenna is designed to produce an omni-directional toroid pattern (looks like a donut) with maximum gain in a horizontal circle direction around the device. The blue antenna is designed to produce a unidirectional cone-shaped pattern with maximum gain focused at zenith straight overhead from the device [3]. Again the receiver switches between antennas depending on which one has the strongest signal. This is pattern diversity with the same two antennas. This combination results in a higher overall gain pattern throughout the entire upper hemisphere than could be achieved with two similar patterned antennas.

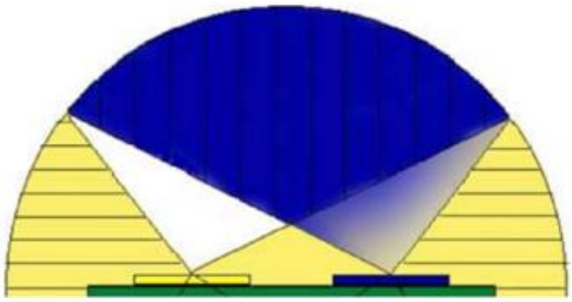

Fig. 2 Representing Pattern Diversity for an example

C. Polarization Diversity
Polarization diversity combines pairs of antennas with orthogonal polarizations (i.e. horizontal/vertical, ± slant 45°, Left-hand/Right-hand CP etc). Reflected signals can undergo polarization changes depending on the media. By pairing two complementary polarizations, this scheme can immunize a system from polarization mismatches that would otherwise cause signal fade [3]. Additionally, such diversity has proven valuable at radio and mobile communication base stations since it is less susceptible to the near random orientations of transmitting antennas.

Polarization diversity can be achieved when two or more differently polarized antennas are used as the branches of a diversity receiver or transmitter. Previously, spatial diversity has been widely used in base stations but the size of the antenna structures is too large. With the use of polarization diversity the size of the antenna structures can be reduced significantly [10]. Early theoretical analysis has been undertaken to show that at the base station the largest diversity gain can be obtained when the two antennas are polarized at ± 45° where the vertical is used as a single reference. Further, it has also been shown that polarization diversity can be integrated with spatial diversity. Polarization diversity is an attractive option to apply at the mobile terminal due to the reduced size of the antenna structures [4]. Hence, recent studies on the MIMO systems have sought to exploit the MIMO channels by using polarization diversity.

D. Transmit/Receive Diversity – Transmit/Receive diversity uses two separate, collocated antennas for transmit and receive functions [9]. Such a configuration eliminates the need for a duplexer and can protect sensitive receiver components from the high power used in transmit.

E. Adaptive Arrays – Adaptive arrays can be a single antenna with active elements or an array of similar antennas with ability to change their combined radiation pattern as different conditions persist. Active electronically scanned arrays (AESAs) manipulate phase shifters and attenuators at the face of each radiating site to provide a near instantaneous scan ability as well as pattern and polarization control [4]. This is especially beneficial for radar applications since it affords a single antenna the ability to switch among several different modes such as searching, tracking, mapping and jamming counter measures.

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III. DIVERSITY COMBINING TECHNIQUES

Fig. 3 illustrates four different types of diversity combining techniques that can be employed in the 'combiner'.

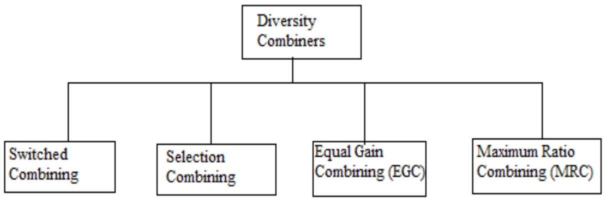

Fig. 3: Diagram showing four types of diversity combining techniques can be employed at the receive diversity.

A. Switched Combining

The switched combining technique requires only one receiver radio between the N branches as shown in Fig. 4. The receiver is switched to other branches only when the SNR on the current branch is lower than a predefined threshold. Whereby, other combining techniques require N receivers to monitor the received instantaneous signals level of every branch when there are N element antennas [5]. Due to size restrictions, battery life and complexity, the switched combining technique is presently implemented in mobile terminals with diversity antennas [11]. The optimum performance that a switched combiner can achieve is similar to that of a selection combiner.

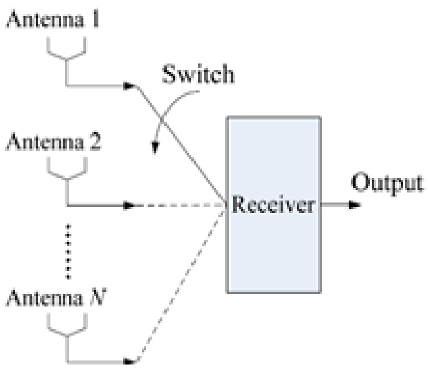

Fig. 4: Block diagram of switched combining for N branches/antenna elements with only one receiver.

B. Selection Combining

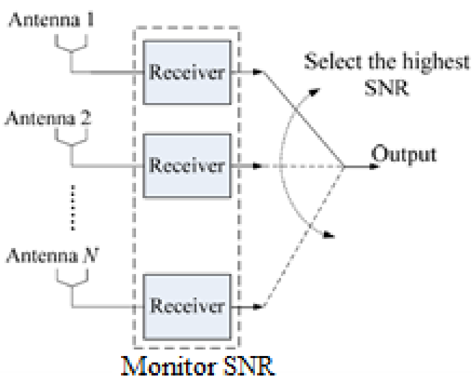

Fig. 5: Block diagram of selection combining for N branches/antenna elements

The selection combining technique is similar to the switched combining technique except that N receivers are required to monitor instantaneous SNR at all branches [5]. The branch with the highest SNR is selected as the output signal.

C. Equal Gain Combining

Both switched and selection combining techniques only use the signal from one of the branches as the output signal. In order to improve SNR at the output, the signals from all branches are combined to form the output signal [5]. However, the signal from each branch is not in-phase. Therefore, each branch must be multiplied by a complex phasor having a phase -θi, where θi is the phase of the channel corresponding to branch i (i.e. co-phased) as shown in Fig. 6 When this is achieved, all signals will have zero phase and are combined coherently.

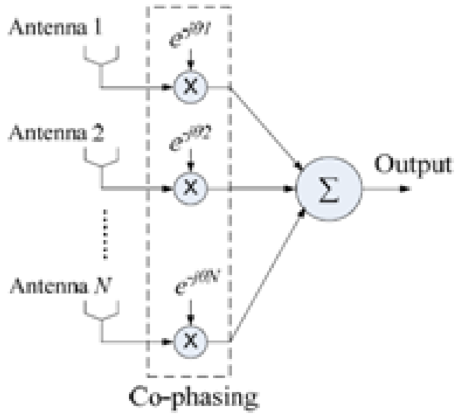

Fig. 6: Block diagram of equal gain combining for N branches/antenna elements.

D. Maximum Ratio Combining

In the equal gain combining technique, all the branches may not have a similar SNR. Sometimes one of the branches has a much lower SNR than the other branches and this will reduce the overall SNR to a lower value at the output. In order to maximize the SNR at the output, each branch is applied with a weight, w_i before all the signals are combined coherently as shown in Fig. 7 [6]. In order to maximize the SNR at the output, a branch with a higher SNR will be given a higher weighting.

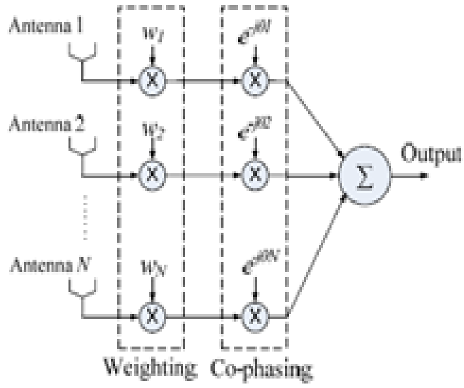

Fig. 7: Block diagram of maximum ratio combining for N branches/antenna elements.

E. Diversity Gain

Diversity gain is defined as the improvement in the SNR of the combined signals relative to the SNR from a single antenna element. Here, the Rayleigh channels are assumed in the multipath environment [7]. The cumulative distribution function (CDF) of a Rayleigh channel is given as

$$P(\gamma < \gamma_s) = (1 - e^{\frac{\gamma_s}{\Gamma}}) \quad \text{--------------------- (1)}$$

where Γ is the mean SNR, γ is the instantaneous SNR, $P(\gamma<\gamma_s)$ is the probability that the SNR will fall below the given threshold, γ_s. For a selection combiner with N independent branches, assuming that the N branches have independent signals and equal mean SNRs, the probability of all branches having a SNR below γ_s is equivalent to the probability for a single branch raised to the power N as:

$$P(\gamma < \gamma_s)_N = (1 - e^{\frac{\gamma_s}{\Gamma}})^N \quad \text{------------------- (2)}$$

where N is the number of antennas/branches.

Equations (1) and (2) are plotted in Fig. 8 to show the reduction of the probability of fading below a given threshold when increasing the number of antenna, N. In this Fig., diversity gain is also illustrated in terms of the increase in SNR of a combined output compared to a single antenna [9]. Here, the diversity gain is marked off where $P(\gamma<\gamma_s)$ of 1% (i.e. 99% reliability). The Fig. shows that there is a 10dB and 13dB of diversity gain for the two branches and three branches selection combiner respectively. For low instantaneous SNR i.e. $\gamma \ll \Gamma$, equation (2) can be approximated by:

$$P(\gamma < \gamma_s)_N = (\frac{\gamma_s}{\Gamma})^N \quad \text{------------------------- (3)}$$

Therefore, by re-arranging the equation (3) the diversity gain for a 100% efficient two branches selection combiner is 10dB with $P(\gamma<\gamma_s)$ at 1%. Mobile terminals currently available in the Japan market use two antennas for diversity.

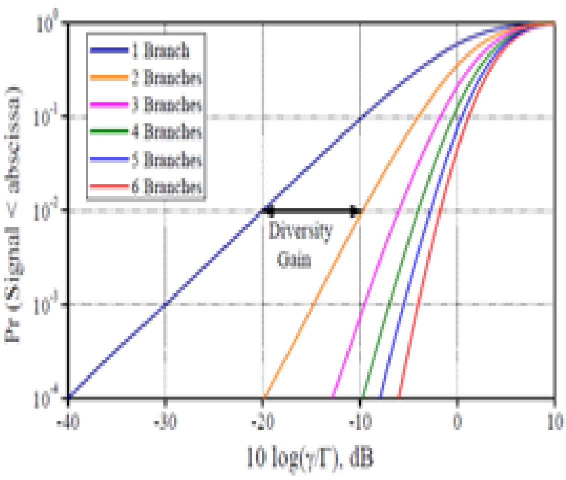

Fig. 8: Cumulative distribution functions of Rayleigh fading signals for a different number of diversity branches.

F. Branch Power Ratio and Mean Effective Gain

The other essential condition for good diversity is that the power levels of all the antennas in the diversity system must not be too different. One way of illustrating this is by using the ratio of two branch power levels, k, as follows in linear form:

$$k = \frac{P_{min}}{P_{max}} \quad \text{-------------------------- (4)}$$

where min P [W]

is the power from the antenna with the lower power and max P [W] is the power from the antenna with the higher power in each pair of antennas [8].

The ratio of the two antennas' power levels, k, is multiplied by the diversity gain to obtain the new diversity gain for a selection combiner. Hence when N = 2, equation (3) becomes:

$$P(\gamma < \gamma_s)_2 = \frac{1}{k}(\frac{\gamma_s}{\Gamma})^2 \quad \text{------------------------- (5)}$$

Equation (3) is for the ideal case when k is equal to unity. An alternative method to obtain the branch power ratio is derived from the mean effective gain (MEG) of the antennas as follows (assuming only two branches):

$$k = \min\left(\frac{MEG_2}{MEG_1}, \frac{MEG_1}{MEG_2}\right) \quad \text{-------------------- (6)}$$

The MEG is the average gain of an antenna in a mobile environment and is defined as the ratio between the mean received power of the antenna (P_{rec}) and the total mean incident power ($P_V + P_H$).

The MEG is a Fig. of merit for the average performance of an antenna on a mobile terminal taking into account the incident radio waves in the multipath environment and the gain patterns of the antenna [9].

This parameter determines how effective the mobile terminal antenna will be in a multipath environment. It is important to evaluate the MEG of the antennas to determine their diversity performance.

Assuming the correlation is low enough to obtain good diversity, k should be greater than -3dB to avoid a significant loss in diversity gain [11].

In order for diversity gain to be achievable k should also be above -10dB, otherwise the diversity system is not effective.

IV. 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 over a wireless link. This paper concludes that higher the received signal replicas are decorrelated, more will be the diversity gain.

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