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Wireless Systems

The increasing demand for high data rates in wireless communications due to emerging new technologies makes wireless communications an exciting and challenging field. The spectrum or bandwidth available to the service provider is often limited and the allotment of new spectrum by the federal government is often slow in coming. Also, the power requirements are that devices should use as little power as possible to conserve battery life and keep the products small. Thus, the designers for wireless systems face a two-part challenge, increase data rates and improve performance while incurring little or no increase in bandwidth or power. The wireless channel is by its nature random and unpredictable, and in general error rates are poorer over a wireless channel than over a wired channel.

1.1 Wireless Channel

The wireless channel contains objects and particles which scatter the transmitted signal. These scattered signals take different paths with different path lengths and thus arrive at the receiver out of phase and create interference. These scatters introduce a variety of impairments in the wireless channel such as fading, delay spread and attenuation. This results in severe attenuation of the signal, referred to as deep fade. This instantaneous decrease of the signal-to-noise ratio (SNR) results in error bursts which significantly degrade the performance.

1.2 Fading

Fading can be classified as long term fading and short term fading. Long term fading is due to shadowing and the relative distance between the source and destination. It is also referred to as path loss. Short term fading is due to the multipath propagation of the transmitted signal due to reflections from various objects. When the delay differences between the multipath components are small as compared to the symbol interval, these components can add constructively or destructively at the receiver depending upon the carrier frequency and delay differences. Multipath fading can be controlled by techniques like diversity and channel coding.

1.3 Channel Coding

Channel coding is a technique to overcome transmission errors over a noisy channel. Here redundancy is introduced at the transmitter and utilized at the receiver for error correction. Channel coding is effective in correcting independent random symbols. However when the fading is correlated, channel coding is not an effective technique, in this scenario interleaving is used. In this method, at the transmitter, the coded signals are first interleaved to reduce the effect of correlation. Interleaving is effective in combating the correlated fading at the cost of increased delay and extra hardware.

1.4 Diversity

Diversity is one of the techniques to combat channel fading [1]-[4]. Diversity makes use of more than one independently faded version of the transmitted signal to improve the overall reception. This is because if several copies of the original signal are sent through different paths, they encounter different channel characteristic and therefore the probability that all the paths will experience deep fading at the same instant is greatly reduced. Diversity can be achieved using the following technique:

Frequency diversity: Here the message is transmitted simultaneously over several frequency slots. This form of diversity is effective when the transmission bandwidth is large enough such that different sub-bands will experience different amounts of fading.

Temporal Diversity: Here the message is transmitted over several time slots. This form of diversity is effective when the fading is time selective. The time slots must be separated such that the channel fading experienced by each transmission is independent of the channel fading experienced by other transmissions. Therefore this form of diversity introduces a significant delay in processing. Temporal diversity can be achieved through techniques like interleaving, forward error correction and automatic repeat request (ARQ) protocols.

Spatial diversity: Here the message is transmitted using multiple transmitting and/or receiving antennas. The requirement for using spatial diversity is that the separation between adjacent antennas should be large enough that signals from different antennas undergo independent fading.

1.5 Multiple-Input Multiple-Output (MIMO)

In most wireless systems, antenna diversity is a practical, effective, and hence, a widely applied diversity technique [5]. It is shown in [6], [7] that a system with multiple antennas on both ends of the communication link (referred to as multiple-input multiple-output (MIMO)) improves the received signal reliability through diversity [8]-[10]. In these systems, each pair of transmitter and receiver antennas provides an independent path from the transmitter to the receiver. By proper encoding, multiple independent faded replicas of a signal are obtained at the receiver side, hence, creating spatial diversity. Furthermore, it is possible to have much higher spectral efficiency in MIMO systems compared to single-input single-output (SISO) systems through spatial multiplexing.

A typical MIMO system is depicted in Figure 1.1. As shown in the figure, the transmitter is equipped with M transmit antennas and the receiver is equipped with N receive antennas. The channel between the m^{th} transmit antenna and the n^{th} receive antenna can be represented by the random propagation coefficient h_{mn}. To send information to the receiver, at every transmission time, the transmitter feeds signals s_1, s_2, ..., s_M to its M antennas respectively. The antennas then send the signals simultaneously to the receiver. Every receive antenna obtains a signal that is a superposition of the signals from every transmit antenna sent through the fading channels.

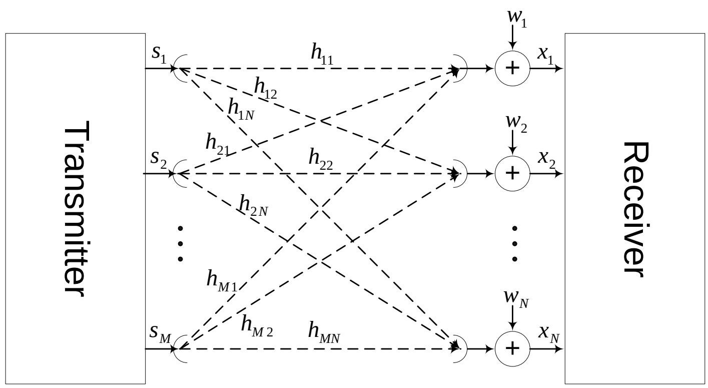

Figure 1.1 *Centralized MIMO system.*

Information theoretic investigations over the past decade have shown that very high capacity can be obtained by employing multiple antenna elements at both the transmitter and the receiver of a wireless system [6], [8]. These investigations have led to the development of a novel multiple transmit-receive architecture called bell labs layered space-time architecture (BLAST) [6]. Using BLAST, it was shown that rates close to the channel capacity can be attained. Another approach that uses multiple transmit antennas and (optionally) multiple receive antennas is space-time coding (STC), which was introduced in [1], [9], [11], [12] to provide reliable communications over fading channels. This concept of STC combines coding, modulation, and spatial diversity into a two-dimensional coded modulation technique. Examples of STCs include space-time block codes (STBC)

[11], and space-time trellis codes (STTC) [12]. STTCs are known to provide full diversity and coding gain at the cost of a complex receiver. On the other hand, STBCs offer only diversity gain (compared to single-antenna schemes) and not coding gain. The design of STBCs is based on the so-called diversity criterion derived by Tarokh et al. in their earlier paper on STTCs.

The down side of MIMO technology, however, is the associated complexity. For instance, for every antenna employed, it is required to employ a radio frequency (RF) chain, which is bulky and costly. Also, the power consumption is relatively high due to the complex circuitry. In addition, the overhead required for training can be significant especially when the underlying channel changes relatively fast. In light of these constraints, MIMO technology is deemed not practical for certain applications where power consumption and/or physical size are an issue. Such applications include cellular networks where it is not practical to mount multiple antennas along with their associated circuitry on a small mobile phone while keeping its size small and its cost affordable. Another example is wireless sensor networks, where the nodes are battery-operated and thus prolonging the battery life as much as possible is a crucial requirement.

As an alternative to using collocated antennas as in MIMO systems, one can achieve the same spatial diversity gain through cooperative diversity [13]-[17]. In cooperative communications, multiple nodes in a wireless network cooperate among themselves to form a virtual antenna array. Using cooperation, it is possible to exploit the spatial diversity of the traditional MIMO techniques without each node necessarily having multiple antennas. The destination receives multiple versions of the message from the source and one or more relays and combines these to obtain a more reliable estimate of the transmitted signal. These cooperative techniques utilize the broadcast nature of wireless signals by observing that a source signal intended for a particular destination can be overheard at neighboring nodes. These nodes, called relays, partners, or helpers process the signals they overhear and transmit towards the destination. At any given time, any node can be a source, relay, or destination. The function of the relay node is to assist in the transmission of the source information to the destination node.

Owing to its significant advantages, cooperative communications has recently emerged as a strong candidate for the underlying technology for most future wire- less applications, including 4G cellular networks, wireless sensor networks (IEEE 802.15.4), and fixed broadband wireless systems (WiMax, IEEE 802.16j). Among these advantages are 1) the great flexibility in the network configurations whereby the number of cooperating nodes can be changed according to a specified system performance criterion; 2) the relaying strategy can be adapted to fit various scenarios; 3) adaptive modulation and coding can be employed to achieve certain performance objectives; 4) the coverage is expected to be better since users will always find relaying nodes close by even if they are at the far end of their cell; and 5) a consequence of this is an increased user capacity since the user transmitted power can be better controlled which in turn controls the level of multiple access interference at the access point. In Figure 1.2, we depict an example of a virtual MIMO system where there is one source, L relays, and one destination node. The fading coefficients are denoted by $h_{SD,}h_{SR_m}$ and $h_{R_m D}$ $m=1, 2, \ldots, L$. Other forms of virtual MIMO systems are also possible, including those that have multi-hop stages.

With all these great advantages of cooperative communications, there are challenges that must be tackled for such technology to be brought to a successful deployment, including the sensitivity of the overall performance to the detection reliability at the relays, and determining the relaying framework that would yield the best performance. In terms of the end-to-end performance of cooperative communication networks, it has been demonstrated that it significantly depends on the detection reliability at the relay nodes [15]-[17]. In the ideal situation where detection at the relays is perfect, the diversity of the system is maintained, that is, as if the relay node is collocated with the transmitting source node [15]-[17]. However, with imperfect detection, the diversity degrades. The severity of this degradation depends on the detection reliability level at the relay nodes. From what we have seen, the diversity starts degrading when the source-relay link is worse in terms of reliability than the source-destination link and/or the relay-destination link. One immediate solution that comes to mind to improve the detection reliability at the relay nodes is to use coding in conjunction with decode-and-forward (DF) relaying. This has been investigated before but in a different context. In particular, all coded cooperation schemes have assumed ideal detection at the relay nodes, which is idealistic. This motivates us to develop coded cooperation schemes under practical situations. In particular, we will develop efficient ways of achieving useful cooperation while reducing the impact of error propagation.

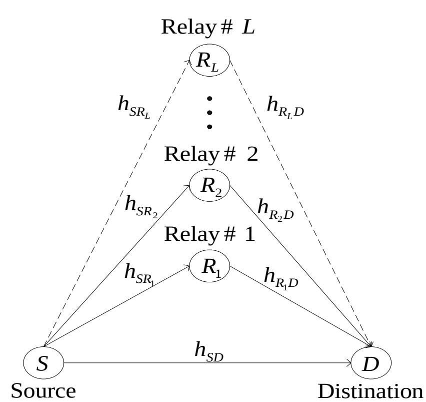

Figure 1.2 *Distributed MIMO system using relay nodes.*

Multiple antennas are considered at the relay and destination nodes are considered in [18]-[20]. In [18] a system with five-node network with two sources, two relays and one common destination is considered. The source and relay nodes are equipped with a single antenna while the destination node is equipped with multiple antennas. Also, perfect source-relay channels are assumed in [18]. Also in [19], a two-hop system is investigated with one source, one destination and multiple relays with multiple antennas. Threshold-based MRC and threshold-based selection combining (SC) of this multiple antenna system are studied in [19]. In [20], the authors considered cooperative relaying system with multiple sources, one relay and one destination. The relay and destination nodes are equipped with multiple antennas while the source is equipped with a single antenna.