Downlink Processing Algorithms for Multi-Antenna Wireless Communications

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ABSTRACT

The recent development of communication theory and radio technology has intensified interest in multi-antenna systems as an effective technique to combat fading of the desired signal, tackle interference from other signals, and increase the data rate in wireless communications. This article provides a survey of downlink processing algorithms for multi-antenna systems. The understanding of fundamental downlink processing strategies is extremely important in analyzing the future of high-capacity/high-quality wireless communications.

INTRODUCTION

Wireless communication and multimedia services have created a growing demand for increased bandwidth and better quality of service (QoS). Improvement in the efficiency of wireless systems requires the design of novel transmission techniques. Also, how to use the available spectral and power resources effectively presents a challenge. The issue of improving link reliability and increasing transmission rates is an essential priority in the theory and practice of data transmission. Approaches that increase spectral and energy efficiency are therefore of great interest. Smart antennas are one way to accommodate this ever growing demand for bandwidth and QoS. Smart antenna arrays have been given new impetus recently by the migration to third-generation (3G) systems and the proposals for fourth-generation (4G) standards. Smart antennas provide numerous benefits to service providers, including longer range, better coverage, greater capacity, higher data throughput, and more successful technology migration. The multiple-antenna approach is believed to be one of the most promising techniques since it is known to significantly increase the capacity of wireless systems on the uplink as well as the downlink.

Wireless Internet and multimedia services are likely to be asymmetrical in data requirements [1]. Moreover, downlink traffic is much higher than uplink traffic. Due to the asymmetry in downlink and uplink multimedia data traffic, it is necessary to consider different requirements (e.g., modulation, duplex, and multiple access techniques) for both links. The type of downlink processing used depends on whether the wireless system uses time-division duplex (TDD) or frequency-division duplex (FDD).

Figure 1 shows one base station (BS) that serves K users or mobile stations (MSs), where N_t transmit antennas and N_r receive antennas are employed. This is a multiple-input multiple-output (MIMO) model. In general, antenna arrays may be used at either a BS or an MS or at both, and in both receiving and transmitting regimes. Therefore, due to the propagation and reception characteristics, the algorithms for space-time signal processing for uplink and downlink at the MS and BS may have to be different. Figure 1 should be transformed accordingly for different transmission schemes and scenarios. This article provides an introduction to the topic of downlink processing algorithms for multi-antenna wireless communication systems, and shows different ways in which spectral and energy efficiency of a system can be achieved.

The remainder of this article is organized as follows. The next section discusses FDD and TDD modes. The following section considers the downlink transmission including transmit diversity (TD) principles. Then we investigate the issues of space-time coding (STC) and its applications. Later, we introduce the MIMO system to discuss Bell Laboratories layered space-time (BLAST) architecture. The final parts of this article look at the downlink beamforming, pre-RAKE, and multi-user transmission approaches. Then a summary and conclusions are presented to finish the article.

FDD OR TDD REGIMES?

In TDD systems, uplink and downlink transmissions are conducted at the same carrier frequency but in different time slots [1]. Thus, the TDD channel will be known at the transmitter. Given the reciprocity principle, the downlink and uplink channels should be identical; the BS can use the uplink channel as the downlink channel. This can be achieved provided that there is limited user movement between transmission and reception. TDD uses channel reciprocity, which also presumes that the same antenna configuration is

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used in both uplink and downlink directions and temporal changes are negligible. In the FDD counterpart the uplink and downlink transmissions are conducted at different carrier frequencies. The uplink and downlink channels may be considered independent. Feedback signals from the MS can be used to estimate the channel.

DOWNLINK TRANSMISSION PRINCIPLES

Diversity and beamforming are two main smart antenna operations. Diversity assumes rich scattering; thus, the signal arrives over several paths. An example of signal amplitude variations in a Rayleigh fading channel with time is illustrated in Fig. 2. It shows the fading signals corresponding to three different antennas. This shows the large amplitude variations in the received signal, termed signal fading, due to time-variant characteristics of the channel. We notice that fading is less in the diversity case.

While diversity techniques improve the reliability of a wireless link, beamforming is used to form an antenna pattern with a single main beam that enhances the desired user signal radiating from a specific location and suppresses co-channel interference from other directions. Systems with multiple transmit and receive antennas have extra channels that allow the receiver to see different and redundant versions of the information. In order to achieve the maximum diversity in TD schemes (as in receive diversity, RD) it is necessary that fading signals corresponding to the different antennas are uncorrelated or slightly correlated. In contrast, beamforming requires signals to be correlated.

Although the ideology of diversity techniques remains unchanged, the channel characteristics (new frequency bandwidth, severe propagation conditions, multi-user interference, etc.) and transmission methods are changed. TD is a simple technique to realize spatial diversity gain without knowledge of the channel in the transmitter. The order of diversity can be increased when TD is used with other conventional forms of diversity (time, frequency, polarization, etc.). Many TD techniques have been suggested using different approaches to provide diversity and coding gains [2–5]. One approach that uses multiple transmit antennas and, if possible, multiple receive antennas to provide reliable and high data communication is STC, considered next.

SPACE-TIME CODING

There are several approaches to STC, which are different in coding structures (STBC, space-time block coding, and STTC, space-time trellis coding). STC has been shown to be the generalization of delay diversity [2].

SPACE-TIME BLOCK CODING

Alamouti proposed a simple scheme to achieve a diversity gain called STBC [3]. Figure 3 shows the principles of STBC with two transmit antennas and one receive antenna. In such a scenario, symbols transmitted from these antennas are transformed in space and time according to a specific rule to ensure that transmissions from both antennas are orthogonal to each other. The original symbol stream, **s**, is divided into two symbol streams, s_1 and s_2. The input symbols to the space-time block encoder are divided into groups of two symbols each. The signals are transmitted pair by pair. Thus, two symbols represented by s_1 and s_2 are sent simultaneously during two consecutive symbol periods $2T$. Also, information sent on each antenna must be dependent to ensure diversity (i.e., each information symbol passes through all channels). The overall transmitted power is equally split between the antennas ($P_{t1} = P_{t2} = 0.5P_t$). h_1 and h_2 are channels from the first and second transmit antennas to the receive antenna, respectively.

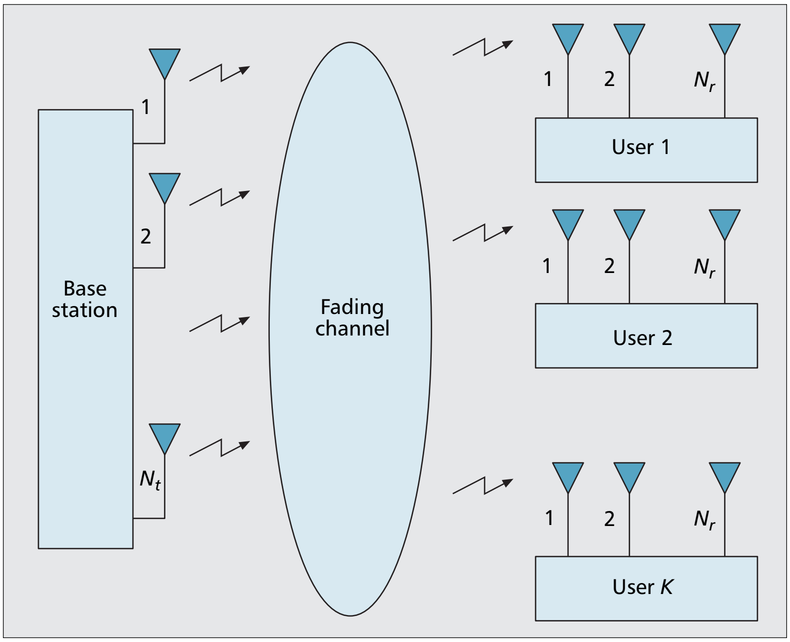

Figure 1. *A diagram of a multi-user wireless communications system with antenna arrays.*

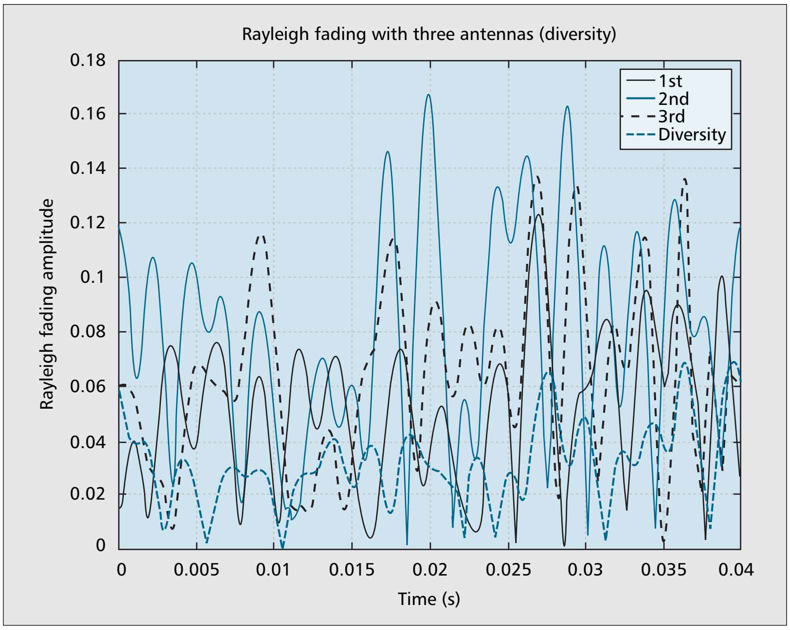

Figure 2. *Typical signal amplitude variations in a Rayleigh fading channel with time.*

The received signals over two consecutive symbol periods $2T$ are denoted as r_1 and r_2 with noise n_1 and n_2, respectively. After channel estimation the decision variables y_1 and y_2 are then calculated, and a threshold is applied to get the maximum likelihood estimates $\hat{s}_1$ and $\hat{s}_2$ of the data symbol. The problem of detecting the symbol streams s_1 and s_2 thus decouples. Therefore, STBC can decouple the vector maximum likelihood decoding problems into scalar problems. This reduces receiver complexity dramatically. This STBC scheme provides a performance gain similar to that obtained by using one transmit antenna and two receive antennas with maximum ratio combiner (MRC) except for a power reduction of 2 (3 dB). STBC can thus realize full diversity.

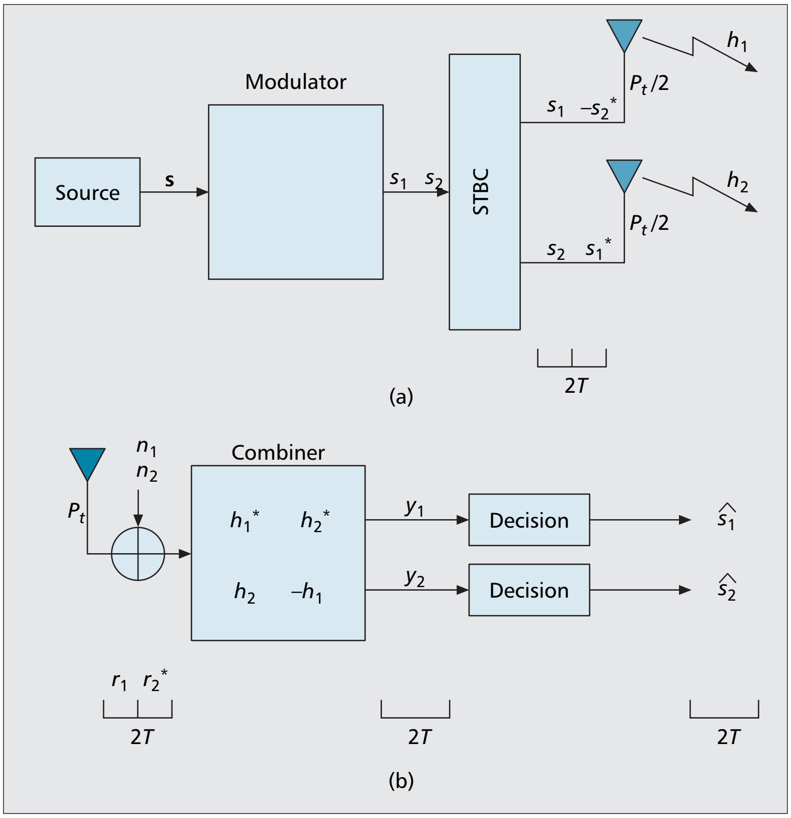

Figure 3. *A diagram showing the principle of STBC: a) transmitter and b) receiver structures.*

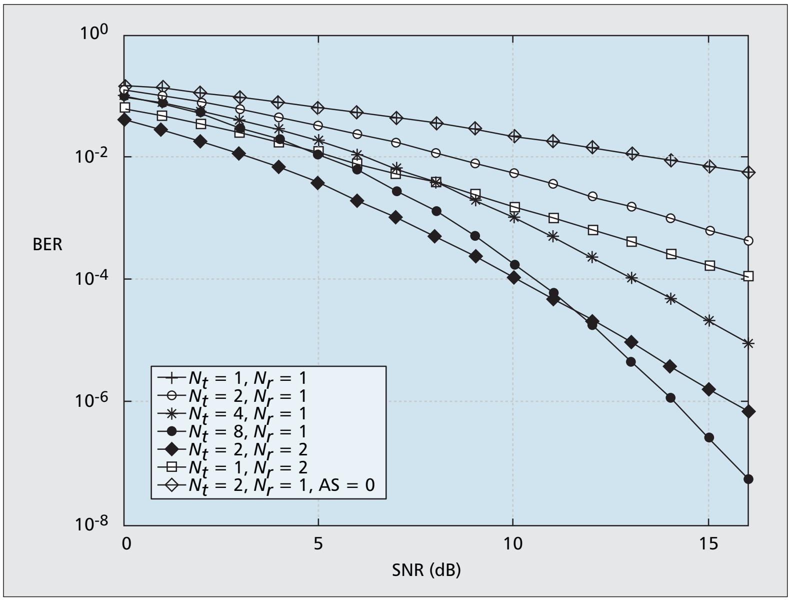

Figure 4. *Performances of the STBC and RD schemes.*

The simulation results of STBC for (N_t, N_r) = (1, 1), (1, 2), (2, 1), (2, 2), (4, 1), and (8, 1) are plotted in Fig. 4. This figure shows the bit error rate (BER) against signal-to-noise ratio (SNR) for angular spread (AS) as high as 120° (uncorrelated channels). We have also shown the performance for AS = 0° (correlated channels) in the (2, 1) case. The correlation affects the performance [6]. The BER for no diversity (1, 1) and two-branch RD (1, 2) cases is also plotted for comparison. Comparing the results for (2, 1) and (1, 2) we notice the power reduction (3 dB) mentioned above. This indicates that the scheme with more receive antennas gives better performance. This is because when the number of transmit antennas is increased, the transmitted power from each individual antenna is less, since the total available transmit power is constant and divided equally among all the antennas. This affects the capacity, as shown later.

TD schemes have been adopted in several 3G standards, such as wideband code-division multiple access (WCDMA) and IS-2000 (see the 3G Partnership Project, 3GPP, specifications). Due to the simple STBC decoder, some of these schemes are modified versions of STBC — a very popular TD mechanism. These issues will be highlighted below.

SPACE-TIME TRELLIS CODING

STBC, discussed previously, can achieve a near optimal (maximum possible) diversity gain with a very simple decoding algorithm. However, the coding gain due to the use of STBC is very limited. Tarokh [2] proposed an elegant method to achieve both diversity and coding gains. STTC is a coding technique that introduces temporal and spatial relationships between signals transmitted from different antennas and different time periods in order to realize diversity at the receiver, and coding gain over an uncoded system without reducing spectral efficiency and knowledge of the channel in the transmitter. STTC approach translates the code design task into an elegant mathematical problem and uses the space as the second dimension for encoding.

Different choices of data to antenna mapping can be manipulated. All antennas can use either the same modulation and carrier frequency or different modulation (symbol waveforms) and symbol delays. Other approaches include use of either different carriers (multicarrier, MC, and orthogonal frequency-division multiplexing, OFDM) or spreading codes (CDMA) or both (MC-CDMA). Another promising approach would use concatenated, turbo, or low density parity codes. STTC generally combines trellis code modulation for a Gaussian channel with TD techniques. Thus, in STTC the joint design of channel coding and modulation is important for efficient transmission. In addition, integration of STC with other techniques, such as power control, adaptive coding/modulation, and multi-user techniques are important, since these techniques have been shown to enhance performance.

In STTC, the encoded data is split into N_t multiple data streams, each modulated and simultaneously transmitted using N_t different transmit antennas. STTC uses a number of convolutional codes in order to create a relationship in the time and space domains. These space-time convolutional codes can be realized by shift registers and some generator coefficients to determine the multiple output symbols that are fed to different transmit antennas. That is, the encoder consists of N_t different generator polynomials to determine the simultaneously transmitted symbols. Figure 5 illustrates a simplified example of the space-time trellis coder and signal constellations (a), where D is a delay operator. It shows a trellis diagram of the coder (b) [2, 4]. Assume $N_t = 2$ and $N_r = 1$. The coding is performed using the alphabet of algebraic ring Z_8 (ring of integers with modulo 8 summation and multiplication operations). This allows transmitting 8-phase shift keying (PSK) signals over two transmit antennas and provides spectral efficiency of 3 b/s/Hz. The two output symbols of the convolutional coder, s_1 and s_2, are fed to two transmit antennas.

STTC performs better than STBC at additional encoding/decoding complexity. STTC achieves diversity gain since the encoded data arrives over uncorrelated faded branches. A coding gain is defined as a gain of the coded system over an uncoded system of an equivalent number of antennas with the same diversity gain.

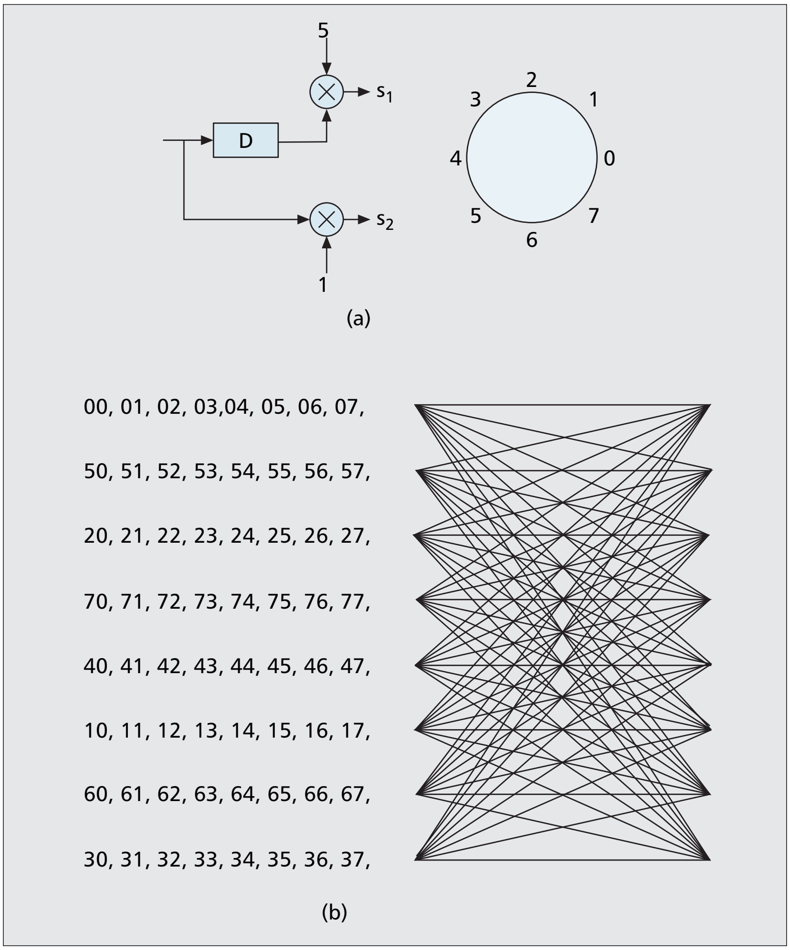

Figure 5. *An example of code construction of STTC: a) ST trellis coder and signal constellations; b) code trellis of the coder.*

Applications of STC: Open-Loop and Closed-Loop TD Schemes

TD schemes may be implemented as open-loop and closed-loop. Transmission schemes that do not require knowledge of the downlink channel coefficients to operate are called open-loop. Closed-loop TD schemes require knowledge of the channel in the BS via a feedback signal from the MS. Open-loop schemes are less complex than their closed-loop counterparts.

Open Loop Schemes

Two open-loop TD schemes were chosen for the WCDMA standard: time switched transmit diversity (TSTD) for the downlink WCDMA TDD and space-time transmit diversity (STTD) for the downlink WCDMA FDD. In TSTD the encoded symbols are transmitted from antennas 1 and 2 alternately in a known periodic way, so only one antenna is active in each time slot. The STTD is similar to Alamouti's method and applied to CDMA systems. Another scheme proposed for 3G CDMA is phase-switched transmit diversity. Two other open-loop TD schemes are supported by the IS-2000 standard: orthogonal transmit diversity and space-time spreading [5]. The former transmits orthogonal Walsh functions on different antennas. The latter was proposed for CDMA systems and is similar to STTD.

Closed Loop Schemes

WCDMA also considers closed-loop TD techniques: selective transmit diversity (STD) and transmit adaptive array (TxAA). The feedback information from the receiver can be exploited at the transmitter to choose which antenna to use for data transmission, as in STD. In TxAA the MS uses the channel estimates to choose the optimal weights that maximize the received power at the MS. These weights are fed back from the MS to the BS via a a feedback channel.

Antenna Selection Diversity

This technique was considered previously; however, here we discuss it in terms of TDD and FDD. Antenna selection diversity provides a diversity gain provided that knowledge of the signal strength at each antenna is perfect. Receive antenna selection diversity is where one out of all possible receive antennas is selected for demodulation at a given time instant. Transmit antenna selection diversity uses the reciprocity principle in TDD [1]. The best antenna for signal transmission at any particular time is selected based on the best instantaneous channel quality. For FDD a feedback channel is necessary. In the MIMO system considered in the next section, the transceiver can select a subset of antennas from the array to transmit (receive) and simply ignore the other antennas available.

MIMO Capacity

One way to improve the data rate is to use multiple antennas at both the transmitter and receiver (i.e., a MIMO system). STC and BLAST,

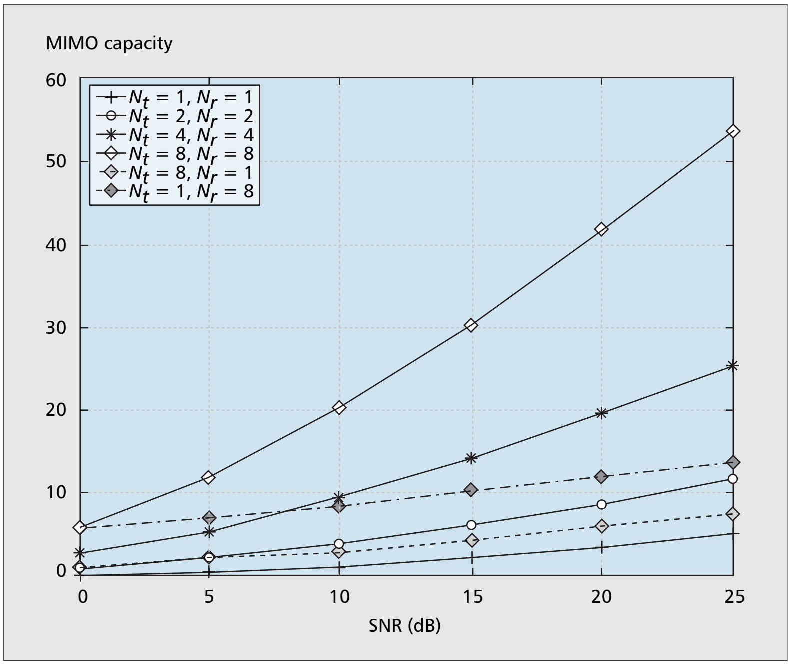

Figure 6. *10 percent outage capacity (b/s/Hz) vs. SNR in a flat fading MIMO channel.*

discussed later, are interesting solutions that exploit the inherent capabilities of MIMO channels [7–11]. The channel state information (CSI) available to the receiver and transmitter may include knowledge of channel characteristics. This knowledge (or lack of it) will impact system performance and thus channel capacity. In particular, the CSI plays a significant role on the receive side. Information theory has an important role to play in wireless communications and predicting capacity limits of using smart antennas. Thus, information theory has a direct impact on smart multiple antennas techniques.

Figure 6 shows the simulation results for the 10%-outage capacity (in bits per second per Hertz) of a flat fading MIMO channel [8]. The x%-outage capacity is the maximum data rate that could be transmitted error-free $(100 - x)$% of the time over a specific channel (i.e., we expect x% outage). The smaller number of antennas at the two link ends limits the performance. If $N_t = N_r$, diversity order of $N_r \times N_r$ is possible and capacity increases linearly with N_r; if N_t is fixed, diversity order increases linearly with N_r and capacity increases logarithmically with N_r. The increase in capacity is referred to as multiplexing gain in MIMO spatial multiplexing. However, the impact of propagation and antenna parameters (fading, correlation, spacing, polarization, etc.) on MIMO capacity and diversity is obvious [6]. In practice, the effect of imperfect channel estimation restricts the capacity of a system that can actually be realized [10].

BLAST ARCHITECTURE

STC schemes, discussed earlier, provide good performance (diversity and coding gains) through the use of a small number of receive antennas. This section considers BLAST architecture that, in contrast to STC, uses a relatively large number of receive antennas. Both BLAST and STC make use of both the space (antennas) and time domains while encoding and decoding information symbols. STC schemes aim to improve the signal quality (BER), while BLAST schemes aim to maximize data rate (throughput). BLAST is an extraordinarily bandwidth-efficient approach to wireless communication that takes advantage of the spatial dimension. Due to rich scattering in the multipath environment, the BLAST exploits rather than mitigates this rich scattering.

There are some modified versions of BLAST, such as diagonal and vertical BLAST [7]. Since the user's data is being sent in parallel over multiple antennas, the effective transmission rate is increased roughly in proportion to the number of transmit antennas used. Each of N_r receivers receives the signals transmitted from all the N_t transmit antennas. This feature of BLAST makes it similar to multi-user detection; when decoding one transmit antenna, other antennas are treated as interference. Thus, increasing data rate with BLAST widely opens a new dimension: space. Since frequency and time are expensive, using space allows high transmission rates.

DOWNLINK BEAMFORMING

The concepts of TD discussed so far can be extended to multiple antennas used for transmit beamforming. Transmit beamforming is another challenging issue in wireless communications since it enhances capacity by interference suppression. Beamforming is generally used at the BS for uplink reception and downlink transmission.

Transmit and receive beamforming are somewhat different. Receive beamforming acts as a spatial filter that passes desired signals and suppresses interfering signals. The aim of transmit beamforming is to send multiple signals into a propagation environment to several receivers so that each receiver gets its desired signal without interference from signals intended for other receivers. Downlink beamforming is complicated by the absence of knowledge of the downlink channel at the transmitter. However, transmit beamforming can exploit TDD reciprocity, while FDD transmit beamforming requires feedback.

As mentioned earlier, downlink diversity and beamforming schemes are different and show somewhat opposite but complementary characteristics. One may wish to exploit the advantages of both diversity and beamforming techniques. However, trade-offs between diversity and beamforming are expected [6]. Alternatively, one may wish to choose a better scheme (diversity or beamforming) based on certain circumstances. The next section will consider pre-RAKE techniques, which can exploit the benefits of diversity and beamforming as well [1].

PRE-RAKE SCHEMES

This section considers some approaches that are interesting in TDD mode. These approaches are applied not only to one transmit antenna, but also to multiple transmit antennas. The last case is referred to as pre-RAKE transmit diversity (or beamforming) or space-time pre-RAKE diversity [1, 12]. Pre-RAKE techniques provide greater capacity and a simpler receiver design in mobile handsets. Since the channel is known a priori, the transmitter can artificially predistort the signals with regard to the channel state. Using pre-RAKE, the multipath combiner is moved from the receiver to the transmitter. With a pre-RAKE transmitter at the BS, the MS just needs a matched filter receiver instead of a RAKE receiver.

The pre-RAKE transmit diversity system combines the advantages of pre-RAKE diversity, which can provide multipath diversity, and transmit antenna diversity, which can provide space diversity. One can use a combination of pre-RAKE transmitter and RAKE receiver schemes to obtain better performance [12]. Pre-RAKE represents a simpler solution to the capacity problem in the downlink than, for example, the multi-user approaches discussed next if the necessary channel conditions are known.

MULTI-USER DOWNLINK ISSUES

In TDD mode, multi-user detection can be used at the transmitter [1]. The receiver structure at the MS is then simplified from that for a multi-user receiver. This approach can be used efficiently with antenna arrays employed at the BS. There are several concepts for multi-user downlink transmission with one or more transmit antennas, such as transmitter precoding and joint transmission. Transmitter precoding performs multiple access interference cancellation at the transmitter rather than at the receiver. The idea of multi-user downlink joint transmission is that the BS jointly determines one common transmit signal for the service of all MSs. Thus, a received signal common to all users is jointly processed at the receiver in order to obtain the data sent by individual transmitters.

CONCLUSIONS

We have investigated multiple facets of using multiple antennas in highly capable wireless systems. Downlink antenna array processing provides an efficient and implementable avenue to the network capacity. One issue complicating downlink processing is the lack of efficient downlink algorithms even though the downlink channel information is available. Moreover, the effort to find the optimum downlink transmission strategy grows rapidly. Clearly, the interaction of different downlink processing algorithms is effective and the use of hybrid schemes is efficient. Antenna array downlink processing has a great impact on the performance of wireless systems. This improvement requires better and more accurate channel models and simulators, and new protocols. It is believed that despite the technical and economic obstacles, multiple-antenna systems have an important role to play in improving the performance of future wireless global networks and providing reliable wireless transmission at high bit rates. As widespread deployments of 3G systems begin, smart antenna technology is likely to be a key factor in their levels of success. Finally, let us note that due to increasing mobility of people, wireless communications is an indispensable part of our communications world and an integral part of modern society.

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