Chapter 2
Spatio-Temporal Processing

2.1 Introduction

Spatio-temporal processing emerged as one of the key achievements towards the provision of high data rate, reliable wireless communications. Most recently, the rationale behind this concept has been mapped onto networked systems under the name of cooperative transmission. This chapter provides a general background on spatio-temporal processing to form the basis of further investigations outlined in the remainder of this book. In particular, the gains achievable in Multiple Input Multiple Output Channels are first quantified. Then, the relevant diversity techniques are discussed together with the role of diversity order and diversity gain. Following, Space-Time Block Coding and Space-Time Trellis Coding techniques are introduced and supported with performance results. Eventually, the context of Layered Space-Time Coding is provided. This analysis is further complemented in the next chapter with the definition of Equivalent Distributed Space-Time Block Encoder.

2.2 Multiple Input Multiple Output Channel

Traditionally, before the emergence of systems capable of exploiting the transmit diversity over spatial dimension, signals were generally transmitted in time and frequency domains [25]. This was performed either with the aid of Single Input Single Output (SISO) or Single Input Multiple Output (SIMO) radio channels. Afterwards, when it turned out that additional information may be equally well conveyed using spatial diversity, global research started focusing on Multiple Input Single Output (MISO) and Multiple Input Multiple Output (MIMO) technologies. The latter forms the most general approach with the former being, in fact, its special case. Soon after, the MIMO technology was mapped onto cooperative networked systems [2], as it will be explained in the following chapters [3], [26]. The wireless MIMO channel (Figure 2.1) is usually defined with the aid of a channel matrix $H_{N\times M}$ (2.1),

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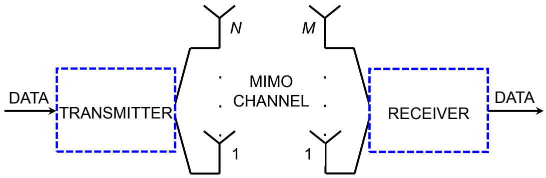

Fig. 2.1 Multiple Input Multiple Output System

containing the coefficients $h_{i,j}$ referring to the radio links between each transmitting antenna i ($1 \leq i \leq N$) and each receiving antenna j ($1 \leq j \leq M$).

$$H_{N\times M} = \begin{bmatrix} h_{1,1} & h_{1,2} & \ldots & h_{1,M} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N,1} & h_{N,2} & \cdots & h_{N,M} \end{bmatrix} \tag{2.1}$$

As it was shown in [15] for an SISO system featuring Additive White Gaussian Noise (AWGN) channel, the data rate boundary for a single user can be expressed as (2.2), where $|h|^2$ represents the channel gain. This equation combines the channel capacity C with channel bandwidth B and the Signal-to-Noise Ratio (SNR). The latter is expressed as the quotient of the transmitted signal power P_T to the noise power σ^2. It might seem then that the easiest way to increase the capacity, and thus the attainable data rate, would be to widen the bandwidth. Unfortunately, at least from the commercial perspective, taking into account that the bandwidth is scarce and deficit component, such an approach would render it too costly, inefficient, and, consequently, hardly acceptable.

$$C = B\log_2\left(1 + \frac{P_T}{\sigma^2}|h|^2\right) \tag{2.2}$$

Another potential approach would be to increase the SNR. Unfortunately, it would require an increase in the power of the transmitted signal, and, consequently, it would enlarge the co-channel and inter-channel interference levels. Moreover, due to the logarithmic relation between both parameters, the effective channel capacity gain would be less significant compared to the first case.

The most relevant way of addressing this issue is then to employ the MIMO processing [20]. Generally, if the number of both transmitting antennas N and receiving antennas M antennas is equal to 1, it is possible to gain merely about 1 bit/Hz for the increase in SNR of 3 dB [5]. However, if Multi-Element Arrays (MEAs) are employed at both sides of the wireless link, and they are of the same size equal to N, the capacity may scale linearly with N [11] and, consequently, it becomes feasible to achieve almost N bits per Hz [5]. This phenomenon may be very neatly explained with the aid of the Singular Value Decomposition (SVD) theorem, as described in [22]. In particular, the channel matrix $H_{N\times M}$ can be written in the following way (2.3):

$$H = UDV^H \tag{2.3}$$

where D is a non-negative and diagonal matrix of size $M \times N$, U and V are unitary matrices of size $M \times M$ and $N \times N$, respectively, and the upper index ^{H} denotes the Hermitian transpose. It means that $UU^H = I_M$ and $VV^H = I_N$, where I_M is an identity matrix of size $M \times M$, and I_N is an identity matrix of size $N \times N$. The diagonal entries of D are then non-negative square roots of the eigenvalues of the matrix HH^H, denoted by λ, and, defined as (2.4) [22]:

$$HH^H y = \lambda y, \qquad y \neq 0 \tag{2.4}$$

where y is an eigenvector of size $M \times 1$, associated with λ. For the remaining details the reader is referred to [22]. What is necessary for the further analysis carried out in this book is that one may now think of an equivalent MIMO channel comprising k uncoupled parallel sub-channels, where k is the rank of the channel matrix H, and, at most, is equal to m, i.e. the minimum value of both N and M. Consequently, the channel capacity formula can be expressed as (2.5) [22]:

$$C = B \log_2 \det \left[I_m + \frac{P_T}{N\sigma^2} Q \right] \tag{2.5}$$

where Q equals to HH^H for $N < M$ and to $H^H H$ for $N > M$, respectively.

Now, taking into account the case where $M = N$, and assuming that transmitting and receiving antennas are connected exclusively by the aforementioned orthogonal parallel sub-channels, H may be written as (2.6) [22]:

$$H = \sqrt{N} I_N \tag{2.6}$$

where $\sqrt{N}$ is a scaling factor pertaining to power normalisation. Finally, after including (2.6) in (2.5), the obtained capacity C is equal to (2.7):

$$C = NB \log_2 \left(1 + \frac{P_T}{\sigma^2} \right) \tag{2.7}$$

This indeed shows clearly that it is possible to achieve extremely high throughputs in MIMO systems. In general, two approaches are possible [13]. On the one hand, one can create a highly effective diversity scheme for the purposes of increasing the robustness of the system against the impairments induced by the wireless radio channel [24]. On the other hand, one can transmit multiple parallel data streams instead, and therefore increase the system throughput.

2.3 Diversity Techniques

Before the idea of space-time coding has been introduced, the relevant diversity techniques are first briefly characterised [23], [22], [8]. These techniques are common means of combating the effects of multipath fading, as well as improving the transmission reliability [25]. The diversity phenomenon is based on the assumption that there are multiple replicas of the transmitted signal available at the receiver. Each of them conveys the same information but the fading, they are subject to, is usually almost uncorrelated. Consequently, it is very unlikely that all the replicas might encounter a deep fade simultaneously, and, hence, the probability of proper reception increases. The most general classification mentions diversity in time, frequency and space domains.

Time diversity is also known as temporal diversity [8], and it assumes the transmission of multiple replicas of the signal in different time slots. The required separation between these slots must be at least equal to the coherence time of the radio channel [22]. The coherence time is defined as the time during which the autocorrelation function of the channel impulse response is approximately non-zero [6]. Such an approach to diversity results in decoding delays and it is most suitable for fast fading environments where the coherence time is short. Frequency diversity, in turn, exploits different frequencies for the purposes of transmitting the replicas of the original signal. Obviously, these frequencies must be appropriately separated to ensure that different parts of the spectrum will be subjected to independent fades [8]. Such a separation is determined by the coherence bandwidth defined as the frequency range across which the entire signal bandwidth is highly correlated. In other words, it means that fading is roughly equal over this range [6]. Consequently, if the fading statistics for different frequencies are supposed to be essentially uncorrelated, the frequency separation of the order of several times the channel coherence bandwidth is necessary [22]. Space diversity, unlike the other two techniques, induces no loss in bandwidth efficiency [22]. In this case, multiple antennas are used, which must be separated by a few wavelengths[1] to guarantee that the replicas of the transmitted signal are uncorrelated. There are two examples of space diversity: polarisation diversity and angle diversity [22], [8]. In the first case, signals of horizontal and vertical polarisation are transmitted and received by two sets of differently polarised antennas. This is to ensure that there would be no correlation between the two signals, even if the antennas were not separated by a few wavelengths. The angle diversity, in turn, is applicable to carrier frequencies larger than 10 GHz. Such environments are characterised by rich scattering in the space domain and, therefore, it suffices to use two highly directional receiving antennas, pointed at two different directions, to fully gain from this type of diversity.

Given the scope of this book, in the following, more attention is paid to the categorisation of spatial diversity. One should note that depending on whether multiple antennas, separated spatially, are located at the transmitter or at the receiver, two subcategories can be distinguished: reception diversity and transmission diversity.

[1] In [8] this type of separation is also referred to as the coherence distance.

One of the least sophisticated approaches to reception diversity is selection com-

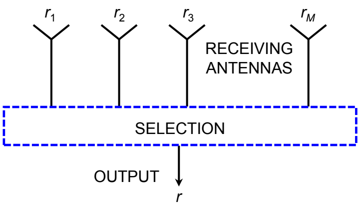

Fig. 2.2 Selection combining

bining [22], as depicted in Figure 2.2. In this method this signal r_i, $(i = 1, \ldots, M)$ is chosen which is characterised by the highest value of the instantaneous SNR. For this purpose, all the diversity branches would need to be monitored continuously and simultaneously. Therefore, a suboptimal solution is also known which is referred to as switched combining or scanning diversity. Here, the reduced complexity is traded off against the lower performance. In other words, this diversity branch remains selected which is able to maintain the SNR above a specified threshold. Following, there is the commonly known Maximal Ratio Combining (MRC) solu-

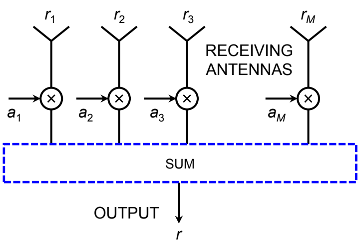

Fig. 2.3 Maximal ratio combining

tion, as described in Figure 2.3. It is a linear method, where signals coming from distinct diversity branches are first weighted with the use of a_i coefficients, and, then, added together. Each coefficient a_i is defined as (2.8):

$$a_i = A_i e^{-j\varphi_i} \tag{2.8}$$

where A_i is the amplitude and φ_i is phase of the signal r_i received by the receiving antenna i. The total received signal r can be then obviously expressed as (2.9):

$$r = \sum_{i=1}^{M} a_i r_i \tag{2.9}$$

MRC is an optimum combining method in the sense that it maximises the output SNR [22]. Finally, there is also a suboptimal version of the MRC known, which does not require estimation of the fading amplitude for each of the diversity branches. Instead, it assumes the amplitudes A_i are all equal to 1, and, hence, it is known under the name of Equal Gain Combining (EGC). The performance of EGC is only slightly worse compared to MRC and the implementation complexity is significantly reduced [22]. In general, the implementation of reception diversity is considered at the Base Station (BS), because it might be very difficult to equip User Terminals (UTs) in the form of mobile phones with multiple antennas and provide batteries that would be capacious enough to survive the existence of separate Radio Frequency (RF) chain for each of these antennas.

This is why, in general, the focus is on the transmit diversity, even though it is perceived more difficult to exploit for some reasons [22]. Firstly, once the signals transmitted from multiple antennas arrive at the receiver, they are spatially mixed. Therefore, additional processing both at the transmitter and the receiver is definitely required. Secondly, unless it is fed back from the receiver, the transmitter does not have instantaneous information about the channel parameters. This is in stark contrast to receive diversity, where the receiver is usually able to estimate the channel coefficients. There are a number of schemes and the delay transmit diversity will be presented here as the classic example [22], [9]. In this case, the copies of the transmitted signal are delayed according to the scheme presented in Figure 2.4. As

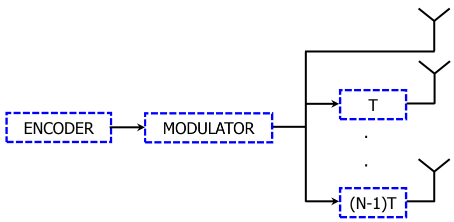

Fig. 2.4 Delay transmit diversity

a result, the receiver observes the original copy of the signal, as if it was distorted by a multipath propagation and can use a Maximum Likelihood Sequence Estimator (MLSE) or Minimum Mean Square Error (MMSE) equaliser to obtain diversity gain [22]. In comparison, Space-Time Coding (STC) combines both space diversity and temporal diversity.

Analysing diversity methods, one also needs to define the so called diversity order and diversity gain. In general, the higher the number of independent fading branches, paths or receiving antennas in SIMO channels, the higher the diversity order, and thus the better performance of such a system [8]. In particular, assuming maximum-likelihood detection or maximum-ratio combining, the average probability of error for high SNR values can be written as (2.10) [9]:

$$P(e) \sim G_c \,(SNR)^{-G_d} \tag{2.10}$$

where G_c denotes the coding gain[2] provided by block or convolutional coding in the time domain, whereas G_d is the aforementioned diversity order. If the $P(e)$ curve is plotted as a function of SNR on a log-log scale, then G_c determines the horizontal position of this curve and G_d corresponds to its slope [13]. Thanks to the diversity order, the diversity gain is observable which is defined as the gain provided by spatial diversity across channels either at the transmitter, receiver, or both of them [8]. Generally, complete Channel State Information (CSI) is required at the transmitter when transmission diversity techniques are employed [8]. However, space-time block coding, to be presented in the following section, does not require CSI at the transmitter [1]. What is more, it is characterised by full diversity order equal to the product of the number of transmitting and receiving antennas [8].

2.4 Space-Time Block Coding

There are a few spatio-temporal processing techniques which can be employed for the purposes of pre-processing the transmitted signals in such a way that they are more robust to the impairments induced by wireless radio propagation [25]. Among them there is space-time block coding introduced by Alamouti in [1] which offers diversity gain but no coding gain. For this reason, despite its name, space-time block coding also happens to be perceived as a modulation technique rather than a coding technique. In particular, it was designed to provide additional spatio-temporal diversity in wireless systems for the purposes of enhancing transmission reliability. As already mentioned, when compared to the classic solutions based on reception diversity, space-time block coding allows to shift the complexity connected with multiple antennas from small mobile UTs to BSs. Among the most significant advantages of this approach is the reduced complexity of UTs, lower cost of installing one MEA at the BS only, as well as the possibility of guaranteeing reasonable spacing among elements of such an antenna array. The base G_2 space-time block code is defined as follows (2.11):

$$G_2 = \begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix} \tag{2.11}$$

This code may be used in a system employing two transmitting and any number of receiving antennas. More specifically, in the first time slot, the x_1 and x_2 symbols are sent by the first and second transmitting antenna, respectively, and then, in the second time slot, the $-x_2^*$ and x_1^* symbols are transmitted alike. For further details, the reader is referred to [1]. Besides, also other space-time block codes are known [17], [16], such as e.g. G_3 (2.12), G_4 (2.13), H_3 (2.14) and H_4 (2.15). These codes may be especially applicable to antenna arrays of greater sizes. One should also note that there is a trade-off between the robustness of each of these codes and their rate R,

[2] In [9] coding gain is also referred to as coding advantage.

which is strictly connected with the number of transmitting antennas. In fact, the code rate is equal to 1 in the case of the G_2 code only.

$$G_3 = \begin{bmatrix} x_1 & x_2 & x_3 \\ -x_2 & x_1 & -x_4 \\ -x_3 & x_4 & x_1 \\ -x_4 & -x_3 & x_2 \\ x_1^* & x_2^* & x_3^* \\ -x_2^* & x_1^* & -x_4^* \\ -x_3^* & x_4^* & x_1^* \\ -x_4^* & -x_3^* & x_2^* \end{bmatrix} \tag{2.12}$$

$$G_4 = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2 & x_1 & -x_4 & x_3 \\ -x_3 & x_4 & x_1 & -x_2 \\ -x_4 & -x_3 & x_2 & x_1 \\ x_1^* & x_2^* & x_3^* & x_4^* \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_3^* & x_4^* & x_1^* & -x_2^* \\ -x_4^* & -x_3^* & x_2^* & x_1^* \end{bmatrix} \tag{2.13}$$

$$H_3 = \begin{bmatrix} x_1 & x_2 & \frac{x_3}{\sqrt{2}} \\ -x_2^* & x_1^* & \frac{x_3}{\sqrt{2}} \\ \frac{x_3^*}{\sqrt{2}} & \frac{x_3^*}{\sqrt{2}} & \frac{\left(-x_1-x_1^*+x_2-x_2^*\right)}{\sqrt{2}} \\ \frac{x_3^*}{\sqrt{2}} & -\frac{x_3^*}{\sqrt{2}} & \frac{\left(x_2+x_2^*+x_1-x_1^*\right)}{\sqrt{2}} \end{bmatrix} \tag{2.14}$$

$$H_4 = \begin{bmatrix} x_1 & x_2 & \frac{x_3}{\sqrt{2}} & \frac{x_3}{\sqrt{2}} \\ -x_2^* & x_1^* & \frac{x_3}{\sqrt{2}} & -\frac{x_3}{\sqrt{2}} \\ \frac{x_3^*}{\sqrt{2}} & \frac{x_3^*}{\sqrt{2}} & \frac{\left(-x_1-x_1^*+x_2-x_2^*\right)}{\sqrt{2}} & \frac{\left(-x_2-x_2^*+x_1-x_1^*\right)}{\sqrt{2}} \\ \frac{x_3^*}{\sqrt{2}} & -\frac{x_3^*}{\sqrt{2}} & \frac{\left(x_2+x_2^*+x_1-x_1^*\right)}{\sqrt{2}} & -\frac{\left(x_1+x_1^*+x_2-x_2^*\right)}{\sqrt{2}} \end{bmatrix} \tag{2.15}$$

Although more reliable, the other codes offer worse rates. In particular, the H_3 and H_4 codes are characterised by rate equal to $\frac{3}{4}$, whereas G_3 and G_4 achieve the rate equal to $\frac{1}{2}$.

Looking at the process of reception, space-time block decoder could operate solely with the use of a single receiving antenna. However, for the best performance, it is strongly recommended to use a larger receiving antenna array. The signal received by a receiving antenna j may be written as (2.16):

$$r_t^j = \sum_{i=1}^{N} h_{i,j} s_t^i + \eta_t^j \tag{2.16}$$

where $h_{i,j}$ denotes the channel coefficient (see MIMO channel matrix 2.1), s_t^i represents the symbol transmitted by antenna i and the noise samples η_t^j are modelled by the complex Gaussian process with zero mean and $N_0/2$ variance per dimension. The main feature of space-time block codes, being also the main condition under which the operation of decoding may be successfully performed, is their orthogonality [1], [16], [10]. This condition is defined as (2.17):

$$G_N G_N^H = \left(\sum_{i=1}^{N} |x_i|^2 \right) I_N \tag{2.17}$$

where N is equal to the number of transmitting antennas and I_N is an identity matrix of size $N \times N$. The process of decoding is based on a maximum-likelihood detection aiming to minimise the decision metric given by the formula (2.18) [16], which can be easily derived on the basis of the theory provided, for example, in [6].

$$z = \sum_{t=1}^{L} \sum_{j=1}^{M} \left| r_t^j - \sum_{i=1}^{N} h_{i,j} s_t^i \right|^2 \tag{2.18}$$

It means that, for a given code, these potentially transmitted symbols are chosen, which minimise this metric. In this section, the validation results of three different systems featuring the AWGN MIMO channel are provided. The power emitted by each of the transmitting antennas is always normalised so that the total transmitted power is guaranteed to be equal to 1. The SNR at the receiving antenna j is then defined as the total received signal power to the noise power ratio. Each time 10 million bits are transmitted and up to 4 receiving antennas are used. In Figure 2.5, Figure 2.6 and Figure 2.7, the results showing performance of G_2, G_3 and H_3 under the above conditions and for different numbers of receiving antennas are presented, respectively [25].

2.5 Space-Time Trellis Coding

Space-time trellis coding was introduced by Tarokh[3] in [18] and then further investigated in [19]. In contrast to space-time block coding, mostly perceived as a modulation technique (see Section 2.4), space-time trellis coding aims to introduce additional relations among specific sequences transmitted by distinct antennas, as well as the symbols constituting these sequences. As a result, apart from diversity gain, additional coding gain may be observed. The base space-time trellis code proposed in [18], which exploits the Phase Shift Keying (PSK) modulation scheme (4-PSK) is presented in Figure 2.8 [25]. The numbers placed to the left of the trellis diagram should be interpreted in the following way: the most significant digit represents the current state, whereas the least significant one corresponds to the in-

[3] However, one should also note that besides Alamouti, Tarokh and Poon investigated a concatenation of a space-time block encoder with an outer trellis code in [12].

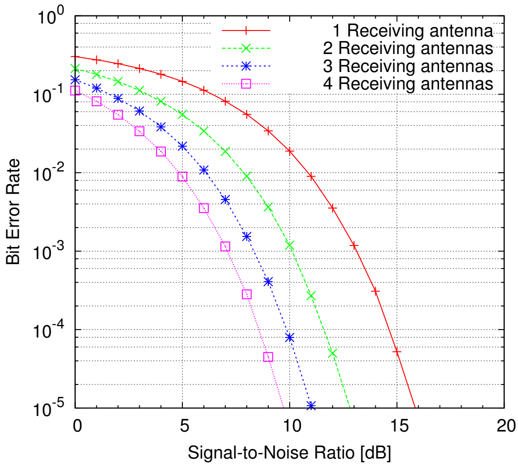

Fig. 2.5 Performance of G_2 code for 1, 2, 3 and 4 receiving antennas

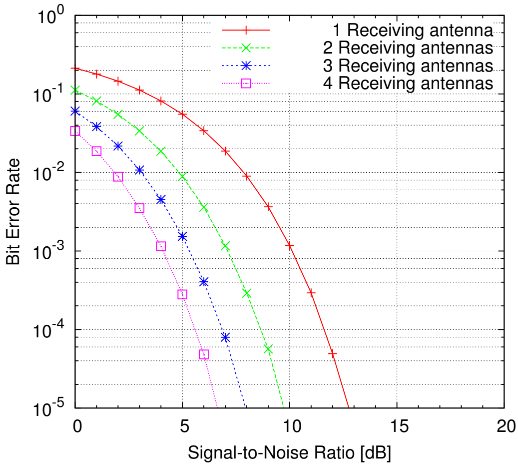

Fig. 2.6 Performance of G_3 code for 1, 2, 3 and 4 receiving antennas

put and, therefore, also to the next state. It means that the consecutive pairs of the encoder input bits determine the transition from the current state to the following one. In other words, two symbols are relayed to transmitting antennas, so the first antenna transmits the channel symbol informing about the current state, while the second antenna transmits the channel symbol informing about the next state.

The process of decoding is based on the well-known Viterbi algorithm [21] and each transition on the trellis is assigned a metric, which is calculated according to the formula (2.19) [18]:

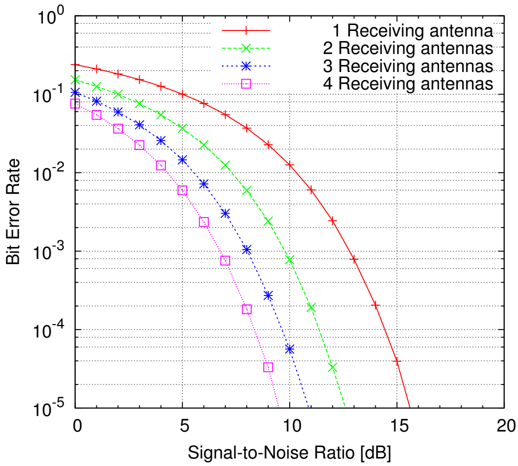

Fig. 2.7 Performance of H_3 code for 1, 2, 3 and 4 receiving antennas

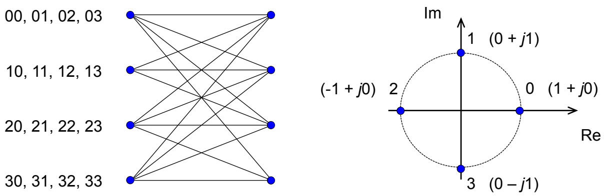

Fig. 2.8 Basic space-time trellis code exploiting 4-PSK modulation

$$w_{x,y} = \sum_{j=1}^{M} \left| r_t^j - \sum_{i=1}^{N} h_{i,j} s_t^i \right|^2 \tag{2.19}$$

where x and y denote the states, being the beginning and the end of a given transition. In case there are no channel impairments, the decoding procedure for an example input sequence $\{1,0,3,1,2,2\}$ and the space-time trellis code from Figure 2.8 would be carried out as shown in Figure 2.9. Let us assume that initially the encoder remains in the zero state, and at each moment t, it is possible to move from the current state to the next one, in the subsequent moment $t+1$, under one of the input values $\{0,1,2,3\}$. That is why, the example input sequence will result in relaying the following sequence of symbol pairs $\{01,10,03,31,12,22\}$ to transmitting antennas. Therefore, the first antenna will transmit signals corresponding to the symbol sequence $\{0,1,0,3,1,2\}$, and at the same time, the second antenna will transmit signals corresponding to the symbol sequence $\{1,0,3,1,2,2\}$. It means that the following modulated sequences $\{1, j, 1, -j, j, -1\}$ and $\{j, 1, -j, j, -1, -1\}$ will be observed at the output of the modulator.

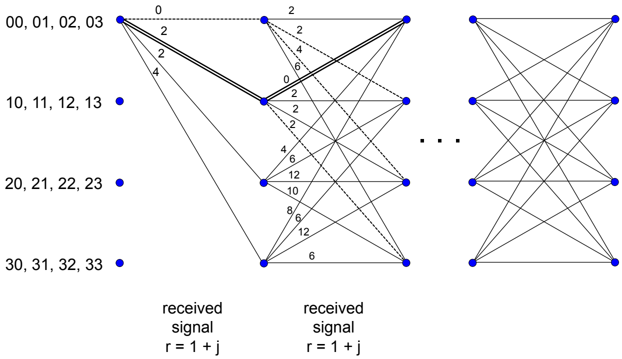

Fig. 2.9 STTC decoding process according to Viterbi algorithm

In particular, in the first modulation interval, the (s_0, s_1) pair, equal to $(1 + j0, 0 + j1)$ is transmitted, and the received signal (defined as 2.16) may be written as $r_1^1 = 1 + j$. Consequently, according to (2.19), the following metrics are calculated for the corresponding transitions: $w_{0,0} = 2, w_{0,1} = 0, w_{0,2} = 4, w_{0,3} = 2$. Next, the same procedure is performed in the second modulation interval, where the pair $(s_0, s_1) = (0 + j1, 1 + j0)$ is transmitted. Here, the received signal may be written as $r_2^1 = j + 1$ and so the metrics are: $w_{0,0} = 2, w_{0,1} = 0, w_{0,2} = 2, w_{0,3} = 4, w_{1,0} = 0, w_{1,1} = 2, w_{1,2} = 2, w_{1,3} = 2, w_{2,0} = 4, w_{2,1} = 8, w_{2,2} = 10, w_{2,3} = 2, w_{3,0} = 2, w_{3,1} = 0, w_{3,2} = 4, w_{3,3} = 2$. According to the Viterbi algorithm, in case there are a number of paths ending up in the same state, the one characterised by the lowest cumulative metric is chosen. In the presented example, there are four candidate paths selected. Therefore, if the decision were to be made at this stage, the path visible as double line would be finally picked. However, one should note that usually the trellis should be as deep as 3 to 5 times the constraint length of the convolutional code in order to make the decisions reliable [23]. There were also other space-time trellis codes proposed in [18] and two additional examples are depicted in Figure 2.10 and Figure 2.11.

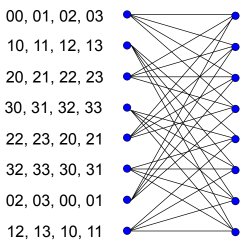

Fig. 2.10 Example space-time trellis code for 4-PSK modulation

Similarly to the simulation assumptions made in Section 2.4, up to 4 receiving antennas are utilised and each time 10 million bits are transmitted over AWGN chan-

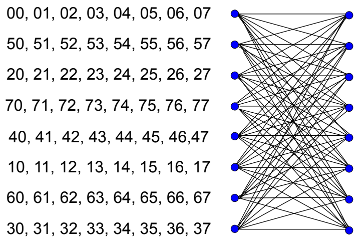

Fig. 2.11 Example space-time trellis code for 8-PSK modulation

nel. The power emitted by each of the transmitting antennas is always normalised and, as a result, the total transmitted power is equal to 1. The SNR at the receiving antenna j is defined as a ratio between the cumulative received signal power and the noise power. The obtained results are depicted in Figure 2.12 [25].

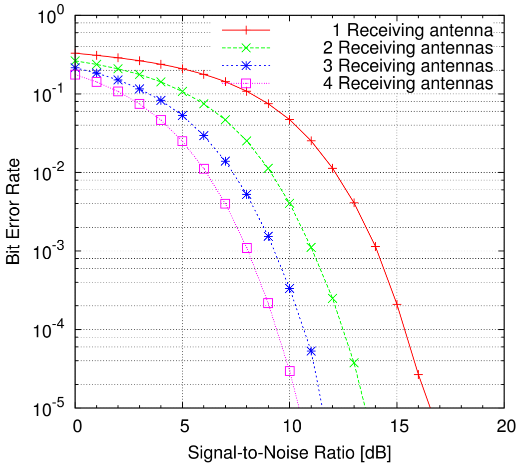

Fig. 2.12 Performance of STTC code for 1, 2, 3 and 4 receiving antennas

2.6 Layered Space-Time Coding

By contrast with Space-Time Block Coding and Space-Time Trellis Coding, in the classic Layered Space-Time Coding (LSTC) case, proposed in [4], N information streams are transmitted simultaneously over the same frequency band with the use of N transmitting antennas [22]. The simplest, uncoded Layered Space-Time Architecture, which is commonly referred to as Vertical Layered Space-Time or Vertical Bell Laboratories Layered Space-Time system, is outlined in Figure 2.13. Here, the

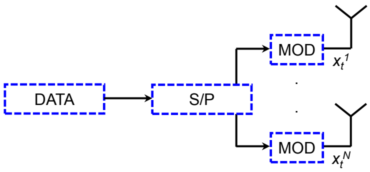

Fig. 2.13 Vertical layered space-time architecture

input data stream is demultiplexed into N sub-streams, which are then modulated separately and transmitted. Each processing chain is referred to as a separate layer which explains the name of this approach. An example of a transmission matrix X for a system employing three transmitting antennas is given by (2.20):

$$X = \begin{bmatrix} x_1^1 & x_2^1 & x_3^1 & x_4^1 & \cdots \\ x_1^2 & x_2^2 & x_3^2 & x_4^2 & \cdots \\ x_1^3 & x_2^3 & x_3^3 & x_4^3 & \cdots \end{bmatrix} \tag{2.20}$$

It means that the entry x_t^i is transmitted from antenna i at time t. Additional improvements to this approach are outlined, e.g. in [7].

The receiver, in turn, exploits $M = N$ receiving antennas for the purposes of performing the process of detection comprising interference suppression and cancellation. The distinguished signals are then decoded with the aid of the relevant conventional, one-dimensional block or convolutional decoding algorithm, which results in a much lower complexity as compared to Space-Time Trellis Coding (STTC). In general, the structure of the LSTC system can be also perceived as a synchronous Code Division Multiple Access (CDMA), where the number of transmitting antennas is equal to the number of users [22], [14]. More sophisticated approaches were also proposed, where the conventional, one-dimensional[4] block or convolutional codes are exploited for the purposes of improving the performance of the system. These include the Horizontal Layered Space-Time, Diagonal Layered Space-Time or Threaded Layered Space-Time architectures.

2.7 Conclusion

In this chapter, the most important aspects of spatio-temporal processing were highlighted to pave the ground for the investigations to be carried out in the following chapters. In particular, the MIMO channel was introduced and the reasons for the achievable gain in throughput were explained. Then the rationale behind the relevant diversity techniques was discussed before both the Space-Time Block Coding and Space-Time Trellis Coding techniques were introduced and contrasted with Layered Space-Time Coding. Especially the notion of STBC will be further extended to be

[4] In the space domain [22].

mapped onto the Cooperative Relaying case in the following chapter, where these concepts are applied to networked systems operating in a distributed manner.

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