Study of MIMO, orthogonal codes and architecture design of core operator for ML decoder

Master thesis performed in Electronics systems

By

Sevelimedu Veeravalli Vinodh

LiTH-ISY-EX--06/3856—SE

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Abstract
In the high-end research process of wireless systems and in the race for the development of the new technologies, MIMO (Multiple Input, Multiple Output) is getting more attention nowadays. It has a high potential usage in the 3G and 4G communications and beyond. The MIMO based system has got the ability to increase the data throughput in spectrum-limited conditions. With the increase and complexity of wireless applications, the spectrum efficiency improvement in the physical layer will be saturated. MIMO is predicted to be one of the major features for the next generation wireless networking. This thesis work is a part of an ongoing project of the Generic MIMO decoder design carried out at the research laboratory, LESTER at Lorient, France. I was involved in the study of MIMO concepts, orthogonal and Space-time codes and later involved in the design and optimization of the architecture for the core operator for the ML decoder used in the reception of the MIMO system, which is presented in this report work.

Keywords: Orthogonal codes, Multi Input Multi Output, 802.11n.
ABSTRACT

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1 Introduction

1.1 Motivation

The telecom industry is experiencing a tremendous growth for past few years and in specific the wireless communication. It has become a part of everyone’s life in one way or other. The growth is of telecom industry is supported by the wide spread usage of mobile telephones and wireless devices. Even though the throughput rate is limited when compared to that of the wired connections, the recent advent in the wireless industry are able to provide a competitive solutions. Further, with the increase of wireless subscribers and the growth of Internet industry, it clearly suggests that the usage of wireless medium and devices is going in rise exponentially in next few years. As the usage increases the need and the demand of the customers for a better application and high performance and speed is expected.

It has been kind of dream few years back to bring into the fast and inexpensive wireless network solutions. Wireless based services based on IEEE 802.11 standards has become a blessing to the industry and provides cost effective and efficient solutions for the industry as well as the public for past few years. However the radio spectrum used for the wireless communication is a finite resource. Various effort and researches are being done in making use of the available limited spectrum. This enables to use the spectrum more effectively and fulfills the increasing need and demand of the wireless industry and makes it possible for efficient communication. Recently a major research focus is done using multiple antennas for transmitting and receiving instead of the traditional single antenna systems [1].
To solve the need of the growing bandwidth in the near future, a new development called MIMO – Multi Input / Multi Output is used which offers greater throughput and reliability and uses two or more antennas in both transmitters and receivers. This kind of antenna system can be brought under the lineage of “Smart antennas”. Such Multi-Antenna transmission has become a suitable way to fulfill the demand for the increased bandwidth capacity with profound gain in range and reliability as well. This type of multi antenna system is beneficial, as they don’t require extra transmission bandwidth unlike the other traditional systems. MIMO wireless research has key applications in the future high-speed high-spectrum efficiency wireless communication networks.

1.2 MIMO Background

Normally the standard and conventional Wi-Fi system uses one antenna to receive and one to transmit data. MIMO overcomes the bottlenecks in the conventionally used Single Input, Single Output (SISO) system in the last decade and has evolved as a prime and promising area of research in the field of wireless communication. The possibilities to increase the channel capacity in the SISO wireless system is quite limited, provided the bandwidth is increased allowing the corresponding increase in the bits per second or to increase the transmit power, allowing a higher level modulation scheme to be utilized for a given bit error rate, effectively increasing the bits per second within the same bandwidth. The problem with both of these techniques is that any increase in power or bandwidth can negatively impact other communications systems operating in adjacent spectral channels or within a given geographic area. As such, bandwidth and power for a given
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communications system are generally well regulated, limiting the ability of the system to support any increase in the capacity or performance.

MIMO uses two or more antennas at each end of a connection to send and receive data, enabling transmitter and receiver to accept signals more efficiently than with a single antenna and thus overcomes the problems and restrictions compared to the conventional system. The multiple antennas at the transmitter and receiver can achieve a data rate, which is very much higher than that of the SISO system. In order to support the larger data rate coupled with high quality and to fight against effects of multipath fading and additive noise in the channel multiple copies of signal over various paths to multiple receivers is used.

The success of MIMO lies in its ability to utilize the multipath reception, which was considered to be an unavoidable byproduct of radio communications, and convert it into a distinct advantage that actually multiplies transmission speed and improves throughput. The multiple antennas improve the performance of the system through various diversity techniques like time, frequency, space and polarization. It basically uses the principle of spatial diversity to distinguish among different signals on the same frequency. The Data’s are transmitted over N transmit antennas through a specifically designed MIMO channel to M receive antennas. Moreover, the transmission can be encoded so that information on each can be used to help reconstruct the information on the others. Just like error detection / correction codes, space-time block coding here allows us to increase reliability in addition to throughput. Space-time diversity has the advantage of using the same bandwidth as that of SISO system with high data rate transfer and quality [2]. To be precise, MIMO utilizes a multiple antenna system to take advantage of the multi-path affect in
RF technology, rather than fight against it as conventional 802.11 Access Points do, as a result the improvement in both range and capacity provides substantially more reliable signal quality and greater bandwidth.

The multipath radio reception is one of the driving force behind the usage and outcome of MIMO based system. The signal being send to the receiver contains not only a direct line-of-sight radio signal, but also a large number of reflected radio waves. For example if a radio is listed in a running car, the received signals are not only from the direct station transmitter but also it receives many other signals from other directions. Obstacles block the line-of-sight and the mobile antenna with a delay receives different waves. This is illustrated in Figure 1. This delay results in out of phase with the original and it the signal is boosted or cancelled due to this effect. More over the reflected waves interfere with the direct wave and results in the degradation in the performance of the link. Also this phase difference introduces noise and distortion and fading of the signals, which results in the increase in the error rate.

Fig 1: Multipath radio reception

To mention a few of the multi path effects, in a moving car it results in rapid fluctuations of the signal amplitude and phase, for a wideband signal it results
in intersymbol interference, for a MultiCarrier signal its different attenuation at different locations, for a stationary user of a narrowband system- good reception at some locations and frequencies; poor reception at other locations and frequencies. So to overcome these effects, addition of antennas helps to sort out signals and enables the receiver to pick the antenna getting the strongest signal at any given point. This resulted in the design of smart antennas to bring into reality the diversity reception using multiple antennas.

MIMO concepts have been under development for many years for both wireless and wire-line systems. The usage of multiple antennas is not a newly discovered method. It is been used in few of the radio transmission many years back and in early 80’s Bell labs came out with few of MIMO based wireless applications. From then on many of the research centers and wireless companies started developing it. The theoretical work was developed by Teletar [3] and Foschini [4], which used multiple antennas for both transmission and reception that increases the capacity of the wireless channel. Later it got developed further when space-time trellis coding techniques was introduced by Tarokh et al. [5] and the space-time block codes introduced by Alamouti [6]. But until recent time the amount of signal processing needed has been too expensive to be practical. MIMO systems use spatial multiplexing to distinguish among different signals on the same frequency and yield an impressive increase in spectral efficiency. It has been proposed that using multiple transmitting and receiving antennas, and associated coding techniques could increase the performance of wireless communication systems [6, 7]. The main reason for the possibility and the reality of MIMO based system in the current trend is the advent of inexpensive, high-speed chips with millions of transistors.
1.3 Multiantenna Systems and MIMO

Let's now have a view of different Multiantenna system. Figure 2 illustrates Single-input single-output (SISO) in which one antenna is used for transmission and reception as well. This configuration is a well known and is widely used for many applications. Figure 3 shows single-input multiple-output (SIMO) uses a single transmitting antenna and multiple (MR) receive antennas, Figure 4 shows, multiple-input single-output (MISO) has multiple (MT) transmitting antennas and one receive antenna.

Figure 2: SISO – Single Input Single Output

Figure 3: SIMO – Single Input Multi Output
In multi-antenna systems with $nT$ transmitting and $nR$ receiving antennas, the data is sent simultaneously and synchronously from the transmitting antennas. The signal received at each antenna is therefore a superposition of the $nT$ transmitted signals corrupted by additive noise and multiplicative fading. Information theoretic results have demonstrated that the ability of a system to
support high link quality and higher data rates in the presence of Rayleigh fading improves significantly with the use of multiple transmit and receive antennas [8,9].

1.4 Advantages and applications

The main advantages of using multiple antennas when transmitting over a wireless link are:

Array gain: Using multiple antennas can considerably increase the range and the coverage; as a result more areas can be covered with minimum base stations. Also it reduces the transmitting power.

Spatial diversity: The high data throughout can be achieved as the spatial diversity increases the robustness of the wireless link.

Interference suppression: Spatial dimensions of the multiple antennas help to suppress the interfering signals, and this improves the capacity of the system.

The MIMO bases system are used widely in various application in modern wireless system such as,

- Wireless LANs
- Wireless local loop
- Broadband systems
- High-speed fixed and mobile wireless
- Voice/data wireless networks
- Acoustic communications
- HDTV
2 Orthogonal codes

2.1 Space time block codes

The space-time block codes provides an advantageous method to the transmission of data using multiple transmit and receive antennas. Data is encoded using a space-time block code. The encoded data is split into $N$ streams and is simultaneously transmitted using $N$ transmitting antennas. Space-time coding introduces spatial and temporal correlation between the signals transmitted from different antennas, to provide diversity at the receiver and thereby a reliable reception of the transmitted symbols. The received signal at each antenna is a linear superposition of the $N$ transmitted signals.

In number of occasions because of the reason that wireless channel is neither significantly time-variant nor highly frequency selective, the possibility of deploying multiple antennas at the transmitter and receiver is considered to achieve spatial diversity. By using STBC, a larger symbol constellation set can be used to decrease the difference in bit rate somewhat, compared to spatial multiplexing. STBC has low complexity since the receiver is linear, and it requires no CSI at the transmitter. It is reliable due to the diversity property but the bit rate is low. STBC performance depends on the average of the eigenvalues instead of the smallest eigenvalue. This unique property of the STBC makes them robust to channel conditions and therefore attractive although they have a bit rate which is lower than the bit rate for a spatial multiplexing transmission scheme [10].

One of the types of space-time codes is space-time trellis code (STTC) that combines the diversity advantage with a coding advantage but has got the
disadvantage of detection complexity, since a Viterbi detector is required and the number of states increases. This problem is overcome by using a, orthogonal space-time block codes which belong to a family of linear codes.

### 2.2 Alamouti code

As the name indicates the Alamouti code, was developed by S.M Alamouti in [6], is a special type of Space-Time Block Codes (STBC) and it is coded across space by using multiple transmitter and receiver antennas and time by using multiple symbol periods. Alamouti space-time block codes are a special class of orthogonal block codes achieving a code rate of 1. The Alamouti code operates on blocks of input bits namely STBC which are represented by a \( m \times t \) matrix, where \( m \) represents number of transmission antennas and \( t \) represents the number of time slots required for transmission of a block.

The matrix shown below represents the functionality of 2 antennas of transmission and one or more antennas of reception.

\[
S = \begin{bmatrix}
S_0 & S_1 \\
S^{*}_1 & S^{*}_0 \\
\end{bmatrix}
\]

The lines of the matrix represent the symbols transmitted by the two sending antennas at the moment \( T \) (1st line) and \( T + Ts \) (2nd line). Where the matrix identity of order 2 is represented by equation 2.2 below,
The orthogonality of $S$ is an important property that has to be taken into account in the development of the space-time decoder.

Expression of the received signal

$$R = S.H + N$$

Where, $R$ is a vector of signals received by the 2 sensors with the reception

$H$ represents the matrix of channel

$N$ represents the noise

The criterion of the maximum of probability “ML” leads us to the expressions of the variables of decision on the symbols $s_0$ and $s_1$ respectively as shown in the expression 2.4 below

$$y_0 = h_1^* r_1 + h_2^* r_2^* = \left( |h_1|^2 + |h_2|^2 \right) s_0 + h_1^* n_1 + h_2^* n_2^*$$

$$y_1 = h_2^* r_1 - h_1^* r_2^* = \left( |h_1|^2 + |h_2|^2 \right) s_1 - h_1^* n_2^* + h_2^* n_1$$

and in the matrix from it becomes,
Using the properties of orthogonality of the matrix of code space-time worked out by Alamouti, the expressions of the variables of decision are a function only of one symbol of information. Thus, one recovers the values of the symbols transmitted except for a coefficient.

\[ \begin{bmatrix} y_0 \\ y_1 \end{bmatrix} = \begin{bmatrix} h_1^* & h_2 \\ h_2^* & h_1 \end{bmatrix} \begin{bmatrix} r_1^* \\ r_2^* \end{bmatrix} \] (2.5)

2.3 Orthogonal STBC codes

2.3.1 selection of the codes

In this section we deal with the decoding of the orthogonal codes. A set of orthogonal codes (ten codes) is chosen and its studied and analyzed to identify the operations to be performed by the decoder given by [11]. The orthogonal codes used in MIMO communications have properties of facilitating their decoding by the mechanism of the maximum probability. Initially the studies of ten orthogonal codes given by [12] are done in order to come up with the equations necessary for decoding. Then the equations are connected to those, which provide the authors of [13]. Coding space-time is represented in matrix form where the columns represent the sending antennas and the lines times symbols of transmission.

Space Time Coding is represented in matrix form where the columns represent the transmitting antennas and the line times symbols of emission. Lets consider the number of reception antennas as \( n_r \).
2.3.2 Generalized matrix representation

The equation 2.6 represents the form of the matrix of the received symbols, where nTS represents the number of times symbol of transmission and the equation 2.7 gives the form of the channel matrix between the nt transmitting antennas and the antenna j of reception.

\[
\begin{pmatrix}
    r_{1j} \\
    r_{2j} \\
    \vdots \\
    r_{nTS,j}
\end{pmatrix}
\]  \hspace{1cm} (2.6)

\[
\begin{pmatrix}
    h_{j1} & h_{j2} & \ldots & h_{jn_t}
\end{pmatrix}
\]  \hspace{1cm} (2.7)

Few notations are also used in the following codes such as,

Cc is the complexity of the code C,

Ce is the complexity of transmission C,

Yi is the variable of decision of the i-th symbol.

2.4 Ten Orthogonal STBC codes

2.4.1 Code-1

Code-1 represents the Alamouti Code [6], and is represented by the equation 2.8, The complexity of this code is:

- Cc = 2
- Ce = 2
The received symbols are given by the equation 2.9 and the decision variables are represented by the equations 2.10 and 2.11.

\[
\begin{pmatrix}
  r_{1j} \\
  r_{2j}
\end{pmatrix} =
\begin{pmatrix}
  h_{j1}S_0 + h_{j2}S_1 \\
  -h_{j1}S_1^* + h_{j2}S_0^*
\end{pmatrix}
\]  
(2.9)

\[
Y_0 = h_{j1}^* r_{1j} + h_{j2}^* r_{2j}
\]
\[
= S_0(|h_{j1}|^2 + |h_{j2}|^2)
\]
\[
Y_1 = h_{j2}^* r_{1j} - h_{j1}^* r_{2j}
\]
\[
= S_1(|h_{j1}|^2 + |h_{j2}|^2)
\]  
(2.10)

(2.11)

2.4.2 Code-2

The code-2 is represented by the equation 2.12 and the complexity of this code $C_c$ is 3 and the complexity of the emission $C_e$ is also 3.

- $C_c = 3$
- $C_e = 3$. 

\[
\begin{pmatrix}
  S_0 & S_1 \\
  -S_1^* & S_0^*
\end{pmatrix}
\]  
(2.8)
The three variables of decision are given by the equations 2.13, 2.14 and 2.15 respectively

\[
\begin{pmatrix}
S_0 & -S_1^* & 0 \\
S_1 & S_0^* & S_2^* \\
0 & -S_2 & S_0 \\
S_2 & 0 & -S_1^*
\end{pmatrix}
\] (2.12)

\[
Y_0 = h_{j1}^* r_{1j} + h_{j2}^* r_{2j} + h_{j3}^* r_{3j}
\]
\[
= S_0(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2)
\] (2.13)

\[
Y_1 = -h_{j2}^* r_{1j} + h_{j1}^* r_{2j} - h_{j3}^* r_{4j}
\]
\[
= S_1(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2)
\] (2.14)

\[
Y_2 = h_{j3}^* r_{2j} - h_{j2}^* r_{3j} + h_{j1}^* r_{4j}
\]
\[
= S_2(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2)
\] (2.15)

2.4.3 Code-3

The code-3 is represented by the equation 2.16 and the complexity is as follows,

- Ce = 4
- Ce = 3
\[
\begin{pmatrix}
S_0 & S_1 & S_2 \\
-S_1 & S_0 & -S_3 \\
-S_2 & S_3 & S_0 \\
-S_3 & -S_2 & S_1 \\
S_0^* & S_1^* & S_2^* \\
-S_1^* & S_0^* & -S_3^* \\
-S_2^* & S_3^* & S_0^* \\
-S_3^* & -S_2^* & S_1^*
\end{pmatrix}
\quad (2.16)
\]

The Four decision variables are given by the equations 2.17, 2.18, 2.19, and 2.20.

\[
Y_0 = h_{j1}^* r_{1j} + h_{j2}^* r_{2j} + h_{j3}^* r_{3j} + h_{j4}^* r_{4j} + h_{j5}^* r_{5j} + h_{j6}^* r_{6j} + h_{j7}^* r_{7j} \\
= 2S_0(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2) \quad (2.17)
\]

\[
Y_1 = h_{j2}^* r_{1j} - h_{j1}^* r_{2j} + h_{j3}^* r_{4j} + h_{j4}^* r_{5j} - h_{j5}^* r_{6j} + h_{j6}^* r_{7j} \\
= 2S_1(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2) \quad (2.18)
\]

\[
Y_2 = h_{j3}^* r_{1j} - h_{j1}^* r_{3j} - h_{j2}^* r_{4j} + h_{j5}^* r_{5j} - h_{j6}^* r_{7j} - h_{j7}^* r_{8j} \\
= 2S_2(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2) \quad (2.19)
\]

\[
Y_3 = -h_{j3}^* r_{2j} + h_{j2}^* r_{3j} - h_{j1}^* r_{4j} - h_{j3}^* r_{6j} + h_{j2}^* r_{7j} - h_{j1}^* r_{8j} \\
= 2S_3(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2) \quad (2.20)
\]

2.4.4 Code-4

The code-4 is represented by the equation 2.21 and the complexity is as follows,
Study of MIMO, orthogonal codes and core operator architecture design for ML decoder

- $C_c = 3$
- $C_e = 3$

\[
\begin{pmatrix}
S_0 & S_1 & \frac{\sqrt{2}}{2} S_2 \\
-S_1^* & S_0^* & \frac{\sqrt{2}}{2} S_2 \\
\frac{\sqrt{2}}{2} S_2^* & \frac{\sqrt{2}}{2} S_2^* & -S_0 - S_0^* + S_1 - S_1^* \\
\frac{\sqrt{2}}{2} S_2^* & -\frac{\sqrt{2}}{2} S_2^* & S_0 - S_0^* + S_1 + S_1^*
\end{pmatrix}
\]  

(2.21)

The decision variables are given by the equations 2.22, 2.23 and 2.24

\[
Y_0 = h_{j1}^* r_{1j} + h_{j2} r_{2j}^* + \left( \frac{h_{j3}^*}{2} r_{3j} - \frac{h_{j3}}{2} r_{3j}^* \right) + \left( \frac{h_{j3}^*}{2} r_{4j} - \frac{h_{j3}}{2} r_{4j}^* \right)
\]

\[
= S_0 (|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2)
\]  

(2.22)

\[
Y_1 = h_{j2}^* r_{1j} - h_{j1} r_{2j}^* + \left( \frac{h_{j3}^*}{2} r_{3j} - \frac{h_{j3}}{2} r_{3j}^* \right) + \left( \frac{h_{j3}^*}{2} r_{4j} + \frac{h_{j3}}{2} r_{4j}^* \right)
\]

\[
= S_0 (|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2)
\]  

(2.23)

\[
Y_2 = h_{j3}^* r_{1j} + h_{j3}^* r_{2j} + (h_{j1} + h_{j2}) r_{3j}^* + (h_{j1} - h_{j2}) r_{4j}^*
\]

\[
= \sqrt{2} S_2 (|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2)
\]  

(2.24)

2.4.5 Code-5

The code-5 is represented by the equation 2.25 and the complexity is as follows,
This code is similar to code 2 for the case with 4 sending antennas. The decision variables are given by the equations 2.26, 2.27, and 2.28

\[
Y_0 = h_{j1}^* r_{1j} + h_{j2}^* r_{2j} + h_{j3}^* r_{3j} + h_{j4}^* r_{4j} \\
= S_0(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2) \tag{2.26}
\]

\[
Y_1 = -h_{j2}^* r_{1j}^* + h_{j1}^* r_{2j} + h_{j4}^* r_{3j} - h_{j3}^* r_{4j}^* \\
= S_1(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2) \tag{2.27}
\]

\[
Y_2 = -h_{j4}^* r_{1j}^* + h_{j3}^* r_{2j}^* - h_{j2}^* r_{3j} + h_{j1}^* r_{4j}^* \\
= S_2(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2) \tag{2.28}
\]

### 2.4.6 Code-6

The code-6 is represented by the equation 2.29 and it corresponds to interlacing spatio-temporal of two codes of Alamouti whose supports are disjoined. The complexity is as follows,
Study of MIMO, orthogonal codes and core operator architecture design for ML decoder

– \( C_c = 4 \)
– \( C_e = 2 \)

\[
\begin{pmatrix}
S_0 & 0 & 0 & -S_3^* \\
0 & S_1^* & S_2^* & 0 \\
0 & -S_2 & S_1 & 0 \\
S_3 & 0 & 0 & S_0^*
\end{pmatrix}
\] (2.29)

The decision variables are given by the equations 2.30, 2.31, 2.32 and 2.33

\[
Y_0 = h_{j1}^* r_{1j} + h_{j4}^* r_{4j} \\
= S_0(|h_{j1}|^2 + |h_{j4}|^2) \tag{2.30}
\]

\[
Y_3 = -h_{j4}^* r_{1j} + h_{j1}^* r_{4j} \\
= S_3(|h_{j1}|^2 + |h_{j4}|^2) \tag{2.31}
\]

\[
Y_1 = h_{j2}^* r_{2j} + h_{j3}^* r_{3j} \\
= S_1(|h_{j2}|^2 + |h_{j3}|^2) \tag{2.32}
\]

\[
Y_2 = h_{j3}^* r_{2j} - h_{j2}^* r_{4j} \\
= S_2(|h_{j2}|^2 + |h_{j3}|^2) \tag{2.33}
\]

### 2.4.7 Code-7

The code-7 is represented by the equation 2.34 and the complexity is as follows

\[
20
\]
The decision variables are given by the equations 2.35, 2.36, 2.37 and 2.38
If the demodulator is satisfied with these variables, the complexity of transmission $C_e$ is 2. If the demodulator implements the linear combinations necessary to immediate calculations of the variables of decision for $S_0$, $S_1$, $S_2$ and $S_3$, the complexity of transmission is then 4. This code does not respect the equations given by [13].

\begin{align}
Y_{S_0+S_3} & = h_{j1}^* r_{1j} + h_{j4}^* r_{4j} \\
& = (S_0 + S_3)(|h_{j1}|^2 + |h_{j4}|^2) \quad (2.35) \\
Y_{S_0-S_3} & = h_{j2}^* r_{2j} + h_{j3}^* r_{3j} \\
& = (S_0 - S_3)(|h_{j2}|^2 + |h_{j3}|^2) \quad (2.36) \\
Y_{S_1+S_2} & = h_{j3}^* r_{2j} - h_{j2}^* r_{4j} \\
& = (S_1 + S_2)(|h_{j2}|^2 + |h_{j3}|^2) \quad (2.37) \\
Y_{S_1-S_2} & = -h_{j4}^* r_{1j} + h_{j1}^* r_{4j} \\
& = (S_1 - S_2)(|h_{j1}|^2 + |h_{j4}|^2) \quad (2.38)
\end{align}
2.4.8 Code-8

The code-8 is represented by the equation 2.39 and the complexity is as follows,

\(- \text{Cc} = 4\)
\(- \text{Ce} = 4\)

\[
\begin{pmatrix}
S_0 & S_1 & S_2 & S_3 \\
-S_1 & S_0 & -S_3 & S_2 \\
-S_2 & S_3 & S_0 & -S_1 \\
-S_3 & -S_2 & S_1 & S_0 \\
S_0^* & S_1^* & S_2^* & S_3^* \\
-S_1^* & S_0^* & -S_3^* & S_2^* \\
-S_2^* & S_3^* & S_0^* & -S_1^* \\
-S_3^* & -S_2^* & S_1^* & S_0^*
\end{pmatrix}
\] (2.39)

The decision variables are given by the equations 2.40, 2.41, 2.42 and 2.43

\[
Y_0 = h_{j1}^* r_{ij} + h_{j2}^* r_{2j} + h_{j3}^* r_{3j} + h_{j4}^* r_{4j} + h_{j1} r_{5j}^* + h_{j2} r_{6j}^* + h_{j3} r_{7j}^* + h_{j4} r_{8j}^*
= 2S_0(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2)
\] (2.40)

\[
Y_1 = h_{j2}^* r_{ij} - h_{j1}^* r_{2j} - h_{j4}^* r_{3j} + h_{j3}^* r_{4j} + h_{j2} r_{5j}^* - h_{j1} r_{6j}^* - h_{j4} r_{7j}^* + h_{j3} r_{8j}^*
= 2S_1(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2)
\] (2.41)

\[
Y_2 = h_{j3}^* r_{ij} + h_{j4}^* r_{2j} - h_{j1}^* r_{3j} - h_{j2}^* r_{4j} + h_{j3} r_{5j}^* + h_{j4} r_{6j}^* - h_{j1} r_{7j}^* - h_{j2} r_{8j}^*
= 2S_2(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2)
\] (2.42)

\[
Y_3 = h_{j4}^* r_{ij} - h_{j3}^* r_{2j} - h_{j2}^* r_{3j} - h_{j1}^* r_{4j} + h_{j4} r_{5j}^* - h_{j3} r_{6j}^* - h_{j2} r_{7j}^* - h_{j1} r_{8j}^*
= 2S_3(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2)
\] (2.43)
2.4.9 Code-9

The decision variables of the code 9 is represented by the equation 2.44, 2.45 and 2.46 below which has the complexity as,

\[ Y_0 = h_{j1}^* r_{1j} + h_{j2}^* r_{2j}^* + \left( \frac{h_{j3}^* - h_{j4}^*}{2} r_{3j} - \frac{h_{j3} + h_{j4}}{2} r_{3j}^* \right) + \left( \frac{h_{j3}^* - h_{j4}^*}{2} r_{4j} - \frac{h_{j3} + h_{j4}}{2} r_{4j}^* \right) \]

\[ = S_0(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2) \]

\[ Y_1 = h_{j2}^* r_{1j} - h_{j1}^* r_{2j}^* + \left( \frac{h_{j3}^* - h_{j4}^*}{2} r_{3j} - \frac{h_{j3} + h_{j4}}{2} r_{3j}^* \right) + \left( \frac{h_{j3}^* - h_{j4}^*}{2} r_{4j} - \frac{h_{j3} + h_{j4}}{2} r_{4j}^* \right) \]

\[ = S_1(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2) \]

\[ Y_2 = r_{1j}(h_{j3}^* + h_{j4}^*) + r_{2j}(h_{j3}^* - h_{j4}^*) + r_{3j}(h_{j1} + h_{j2}) + r_{4j}(h_{j1} - h_{j2}) \]

\[ = \sqrt{2}S_2(|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2) \]  

(2.44)

(2.45)

(2.46)

2.4.10 Code-10

The code-10 is represented by the equation 2.47 and the complexity is as follows,

- \( C_c = 3 \)
- \( C_e = 4 \)
The decision variables are given by the equations 2.48, 2.49, 2.50 and 2.51

\[
\begin{pmatrix}
S_0 & S_1 & S_2 & S_3 \\
-S_1^* & S_0^* & -S_3^* & S_2^* \\
-S_2 & S_3 & S_0 & -S_1 \\
-S_3^* & -S_2^* & S_1^* & S_0^*
\end{pmatrix}
\]  
\hspace{1cm} (2.47)

\[
Y_0 = h_{j1}^* r_{1j} + h_{j2}^* r_{2j}^* + h_{j3}^* r_{3j} + h_{j4}^* r_{4j}^*
\]
\[
= S_0 (|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2) 
\]  
\hspace{1cm} (2.48)

\[
Y_1 = h_{j2}^* r_{1j} - h_{j1}^* r_{2j}^* - h_{j4}^* r_{3j} + h_{j3}^* r_{4j}^*
\]
\[
= S_1 (|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2) 
\]  
\hspace{1cm} (2.49)

\[
Y_2 = h_{j3}^* r_{1j} + h_{j4}^* r_{2j}^* + h_{j1}^* r_{3j} - h_{j2}^* r_{4j}^*
\]
\[
= S_2 (|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2) 
\]  
\hspace{1cm} (2.50)

\[
Y_3 = h_{j4}^* r_{1j} - h_{j3}^* r_{2j}^* + h_{j2}^* r_{3j} - h_{j1}^* r_{4j}^*
\]
\[
= S_3 (|h_{j1}|^2 + |h_{j2}|^2 + |h_{j3}|^2 + |h_{j4}|^2) 
\]  
\hspace{1cm} (2.51)

The next step consists of designing the core operator of the decoder to decode these orthogonal codes in the receiver end which is dealt in the next chapter.
Study of MIMO, orthogonal codes and core operator architecture design for ML decoder
3 Architecture of the core operator

3.1 Proposal of architecture

After the study of ten orthogonal codes, this chapter deals with the design of the architecture for the core operator of the decoder at the receiver end. In order to design the core operator of the decoder, the generalized architecture has to be considered. From the decision variables of the ten orthogonal codes studied in the last chapter, a set of common equations has been framed, which is shown below in equation 3.1 below

\[
\begin{align*}
- y &= y' \pm \Re(h_1^* r) \pm \Im(h_2^* r); \\
- y &= y' \pm \Re(h_3^* r); \\
- y &= y' \pm \Im(h_2^* r); \\
- h_3 &= (h_1 \pm h_2); \quad y = y' \pm \Re(h_3^* r) \pm \Im(h_3^* r).
\end{align*}
\]  

(3.1)

The derived set of equations from the decision variables has to be used in the decoder of the receiver; the core operator part plays a major role in the decoder module. This chapter deals with the design of the architecture of the core operator. Figure 3.1 below gives an idea about the inputs and the outputs of the block. The inputs for this block are h1, h2, r, yin, ctr, and global inputs such as clk and rst. The output from this block will be yout.
3.2 Input and Output Definitions

The input h1 and h2 (two coefficients of channels) are complex inputs, which has real and imaginary parts. (These inputs vary depending on the 10 orthogonal codes). Next considering the ‘r’ input (the received symbol), which is also a complex input that varies from one code to other. The ctr input is the control input that has to be given to the core operator block in order to perform different operation based on the architecture. The ctr input is obtained from an internal signal source, which is a result of a decoder output. Yin - input obtained at the final stage and its nothing but the output yout, from the previous cycle. The yout gives the final output for the core operator module. As a default, clk and rst are used to bring into the proper flow in the module.

Fig 3.1: Black box view for the core operator of the MIMO decoder
3.3 Operations inside the black box

The Black box should compute the following equations in order to bring into the operation of the core operator.

\[
\begin{align*}
  y &= y' \pm \Re(h_1^*r) \pm \Im(h_2^*r); \\
  y &= y' \pm \Re(h_1^*r); \\
  y &= y' \pm \Im(h_2^*r); \\
  h_3 &= (h_1 \pm h_2); \\
  y &= y' \pm \Re(h_3^*r) \pm \Im(h_3^*r).
\end{align*}
\]

This set of above defined equations can be separately written as 16 different equations, which will be more explained in the later part of the document. So in order to implement the above set of equations an architecture has to be designed. The proposed architecture for computing the above set of equations is shown in figure 3.2 and it has the inputs as described in the previous section.
Figure 3.2: Architecture of the core operator of the MIMO decoder
3.4 Internals of the architecture

Now considering the internals of the architecture, two 2*1 multiplexers say mux1 and mux2, receives the inputs h1 and h2 and the other input to the mux comes as a result of addition or subtraction of h1 and h2. The addition or subtraction of h1 and h2 can be controlled by a control signal ‘a’.

After receiving the input signals, the multiplexers depending on their respective control signals ‘b’ and ‘c’ decided on its output. In this section, while coding it has to be kept in mind that the size of the inputs and the outputs are not the same always. Once the output from the mux is obtained its fed into the next block which is a real and an imaginary multiplier. The other input for the multipliers is ‘r’. The actual set of operations that is performed by the real and the imaginary multiplier can be explained with the help of following set of equations

\[(Re1+jIm1)*(Re2+jIm2) = (Re1*Re2 - Im1*Im2)+j(Re1*Im2+Im1*Re2)\]  
(3.2)

\[Re=(Re1*Re2 - Im1*Im2)\]  
(3.3)

\[Im=(Re1*Im2 + Im1*Re2)\]  
(3.4)

So the output from the real multiplier will be (Re1*Re2 - Im1*Im2) and the output from the imaginary multiplier is nothing but (Re1*Im2 + Im1*Re2)

The outputs from the real and the imaginary multipliers are fed into the multiplexers mux3 and mux4 along with the other input ‘0’. The control
signals ‘d’ and ‘e’ decides on the output of these multiplexers. Next we get the input y’ which has to be added are subtracted with the outputs of the mux3 and mux4. The control signals ‘f’ and ‘g’ can be used to decide on the addition or subtraction operation at the stage of the architecture. The final output obtained is ‘y’ from the architecture.

### 3.5 Elaboration of the decision variable equations

As explained from the above section a total of 7 control signals namely a,b,c,d,e,f and g are required to control the various operations of the architecture. Instead of getting 7 input signals, we use a decoder, which has got 4 inputs to decode the all-possible combinations of 16 equations to be computed.

\[
y = y' + \text{Re}(h_1^* r) + \text{Im}(h_2^* r) \tag{3.5}
\]

\[
y = y' + \text{Re}(h_1^* r) - \text{Im}(h_2^* r) \tag{3.6}
\]

\[
y = y' - \text{Re}(h_1^* r) + \text{Im}(h_2^* r) \tag{3.7}
\]

\[
y = y' - \text{Re}(h_1^* r) - \text{Im}(h_2^* r) \tag{3.8}
\]

\[
y = y' + \text{Re}(h_1^* r) \tag{3.9}
\]

\[
y' - \text{Re}(h_1^* r) \tag{3.10}
\]

\[
y = y' + \text{Im}(h_2^* r) \tag{3.11}
\]
\[ y = y' - \text{Im} (h_2^* r) \] (3.12)

\[ y = y' + \text{Re}(h_3^* r) + \text{Im} (h_3^* r), \]
where \( h_3 = h_1 + h_2 \) for both Re and Im

\[ y = y' + \text{Re}(h_3^* r) + \text{Im} (h_3^* r), \] (3.13)

\[ y = y' + \text{Re}(h_3^* r) + \text{Im} (h_3^* r), \]
where \( h_3 = h_1 - h_2 \) for both Re and Im

\[ y = y' + \text{Re}(h_3^* r) - \text{Im} (h_3^* r), \] (3.14)

\[ y = y' + \text{Re}(h_3^* r) - \text{Im} (h_3^* r), \]
where \( h_3 = h_1 + h_2 \) for both Re and Im

\[ y = y' + \text{Re}(h_3^* r) - \text{Im} (h_3^* r), \] (3.15)

\[ y = y' + \text{Re}(h_3^* r) - \text{Im} (h_3^* r), \]
where \( h_3 = h_1 - h_2 \) for both Re and Im

\[ y = y' - \text{Re}(h_3^* r) + \text{Im} (h_3^* r), \] (3.16)

\[ y = y' - \text{Re}(h_3^* r) + \text{Im} (h_3^* r), \]
where \( h_3 = h_1 + h_2 \) for both Re and Im

\[ y = y' - \text{Re}(h_3^* r) + \text{Im} (h_3^* r), \] (3.17)

\[ y = y' - \text{Re}(h_3^* r) + \text{Im} (h_3^* r), \]
where \( h_3 = h_1 - h_2 \) for both Re and Im

\[ y = y' - \text{Re}(h_3^* r) - \text{Im} (h_3^* r), \] (3.18)

\[ y = y' - \text{Re}(h_3^* r) - \text{Im} (h_3^* r), \]
where \( h_3 = h_1 + h_2 \) for both Re and Im

\[ y = y' - \text{Re}(h_3^* r) - \text{Im} (h_3^* r), \] (3.19)

\[ y = y' - \text{Re}(h_3^* r) - \text{Im} (h_3^* r), \]
where \( h_3 = h_1 - h_2 \) for both Re and Im

\[ y = y' - \text{Re}(h_3^* r) - \text{Im} (h_3^* r), \] (3.20)

where \( h_3 = h_1 - h_2 \) for both Re and Im
3.6 Decoding of the control signals

From the above set of equations we can say that it is required to compute 16 equations in the given architecture. The block diagram of the core operator including the decoder is shown in figure 3.3 below. Now with respect to the set of equations a computation table is built which is shown using the table 3.1.
### Table 3.1 Decoder inputs and outputs for the black box of the core operator

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
<th>Eqn number</th>
</tr>
</thead>
<tbody>
<tr>
<td>I0 I1 I2 I3 a b c d e f g</td>
<td>0 0 0 0 0 0 0 0 1 1</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>0 0 0 1 0 0 0 0 0 1 0</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>0 0 1 0 0 0 0 0 0 0 1</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>0 0 1 1 0 0 0 0 0 0 0</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>0 1 0 0 0 0 0 0 1 1 0</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>0 1 0 1 0 0 0 0 1 0 0</td>
<td>3.10</td>
</tr>
<tr>
<td></td>
<td>0 1 1 0 0 0 0 1 0 0 1</td>
<td>3.11</td>
</tr>
<tr>
<td></td>
<td>0 1 1 1 0 0 0 1 0 0 0</td>
<td>3.12</td>
</tr>
<tr>
<td></td>
<td>1 0 0 0 1 1 1 0 0 1 1</td>
<td>3.13</td>
</tr>
<tr>
<td></td>
<td>1 0 0 1 0 1 1 0 0 1 1</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>1 0 1 0 1 1 1 0 0 1 0</td>
<td>3.15</td>
</tr>
<tr>
<td></td>
<td>1 0 1 1 0 1 1 0 0 1 0</td>
<td>3.16</td>
</tr>
<tr>
<td></td>
<td>1 1 0 0 1 1 1 0 0 0 1</td>
<td>3.17</td>
</tr>
<tr>
<td></td>
<td>1 1 0 1 0 1 1 0 0 0 1</td>
<td>3.18</td>
</tr>
<tr>
<td></td>
<td>1 1 1 0 1 1 1 0 0 0 0</td>
<td>3.19</td>
</tr>
<tr>
<td></td>
<td>1 1 1 1 0 1 1 0 0 0 0</td>
<td>3.20</td>
</tr>
</tbody>
</table>
Figure 3.4 Architecture of the core operator with the Control signals
### Table 3.2 Control signals and its purpose

<table>
<thead>
<tr>
<th>Control signals</th>
<th>Action / operation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>a</code></td>
<td>performs addition if its <code>0</code></td>
<td>This signal is responsible to produce the output h3 by computation from the inputs h1 and h2 and acts as one of the input for mux1 and mux2</td>
</tr>
<tr>
<td></td>
<td>performs subtraction if its <code>1</code></td>
<td></td>
</tr>
<tr>
<td><code>b</code></td>
<td>Input h1 is selected by the mux1 if its <code>0</code></td>
<td>The inputs namely h3 and h1 are obtained by the mux1 and depending on this control signal the output is choosen.</td>
</tr>
<tr>
<td></td>
<td>Input h3 is selected by the mux1 if its <code>1</code></td>
<td></td>
</tr>
<tr>
<td><code>c</code></td>
<td>Input h2 is selected by the mux2 if its <code>0</code></td>
<td>The inputs namely h3 and h2 are obtained by the mux1 and depending on this control signal the output is choosen.</td>
</tr>
<tr>
<td></td>
<td>Input h3 is selected by the mux2 if its <code>1</code></td>
<td></td>
</tr>
<tr>
<td><code>d</code></td>
<td>Input from the real multiplier is selected by the mux3 if its <code>0</code></td>
<td>Either the input from the real multiplier or input <code>0</code> is choosen.</td>
</tr>
<tr>
<td></td>
<td>Input <code>0</code> is selected if its <code>1</code></td>
<td></td>
</tr>
<tr>
<td><code>e</code></td>
<td>Input from the imaginary multiplier is selected by the mux4 if its <code>0</code></td>
<td>Either the input from the imaginary multiplier or input <code>0</code> is choosen.</td>
</tr>
<tr>
<td></td>
<td>Input <code>0</code> is selected if its <code>1</code></td>
<td></td>
</tr>
<tr>
<td><code>f</code></td>
<td>The value from the mux3 is added with input y' if this control signal is <code>1</code></td>
<td>The addition or subtraction in this stage is based on this control signal</td>
</tr>
<tr>
<td><code>g</code></td>
<td>The value from the mux4 is added with input y' if this control signal is <code>1</code></td>
<td>The addition or subtraction in this stage is based on this control signal</td>
</tr>
</tbody>
</table>

**The explanation for control signals:**

- The control signals `a` to `g` are used to manage the flow of data in the system. Each signal has a specific purpose and action depending on its value.

- **Control signals `a`**
  - Performs addition if its value is `0`.
  - Performs subtraction if its value is `1`.

- **Control signals `b`**
  - Input h1 is selected by the mux1 if its value is `0`.
  - Input h3 is selected by the mux1 if its value is `1`.

- **Control signals `c`**
  - Input h2 is selected by the mux2 if its value is `0`.
  - Input h3 is selected by the mux2 if its value is `1`.

- **Control signals `d`**
  - Input from the real multiplier is selected by the mux3 if its value is `0`.
  - Input `0` is selected if its value is `1`.

- **Control signals `e`**
  - Input from the imaginary multiplier is selected by the mux4 if its value is `0`.
  - Input `0` is selected if its value is `1`.

- **Control signals `f`**
  - The value from the mux3 is added with input y' if this control signal is `1`.

- **Control signals `g`**
  - The value from the mux4 is added with input y' if this control signal is `1`.
<table>
<thead>
<tr>
<th>Signals</th>
<th>Comments</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>h1</td>
<td>One of the input signal to mux1. Its a complex number</td>
<td>N, P</td>
</tr>
<tr>
<td>h2</td>
<td>One of the input signal to mux2. Its a complex number</td>
<td>N, P</td>
</tr>
<tr>
<td>h3</td>
<td>This signal comes as a result of addition or subtraction of the signals h1 and h2 and is fed as another input for mux1 and mux2</td>
<td>N + 1, P</td>
</tr>
<tr>
<td>h4</td>
<td>This signal is the output from the mux1</td>
<td>N + 1, P</td>
</tr>
<tr>
<td>h5</td>
<td>This signal is the output from the mux2</td>
<td>N + 1, P</td>
</tr>
<tr>
<td>r</td>
<td>This is one of the input signal to the architecture and a complex input</td>
<td>N, P</td>
</tr>
<tr>
<td>h6</td>
<td>The output of the real multiplier</td>
<td>2(N + 1) +1, 2P</td>
</tr>
<tr>
<td>h7</td>
<td>The output of the imaginary multiplier</td>
<td>2(N + 1) +1, 2P</td>
</tr>
<tr>
<td>y'</td>
<td>The main input which is nothing but a form of previous output</td>
<td>N + 2, P</td>
</tr>
<tr>
<td>h8</td>
<td>The output from mux3</td>
<td>2(N + 1) +2, 2P</td>
</tr>
<tr>
<td>h9</td>
<td>The output from mux4</td>
<td>2(N + 1) +3, 2P</td>
</tr>
<tr>
<td>Y</td>
<td>The final output of the core operator</td>
<td>N + 2, P</td>
</tr>
</tbody>
</table>

Table 3.3 Internal signals and sizes
As described in the earlier section there are 7 control signals being used to control the flow of the architecture. The control signals acts on adder/subtractor module and it performs addition if its ‘0’ and its performs subtraction is its ‘1’. Similarly as described in the table 3.2 each and every control signals performs its operation of different modules of the architecture.

Now lets consider the internal signals and their sizes, which are flowing inside the architecture. The N represents the number of bits for the real part and P represents the number of bits for the imaginary part. The values for N and P can be adjusted by modifying it in the implementation phase, so that it can be used in a generalized way. This signals and its sizes are mentioned and explained in Table 3.3.

This concludes the design architectural design of the core operator for the decoder module.
4 Conclusion and Future work

As the research in this area is at tremendous growth rate with lot of challenges there is a high scope of development in this domain. The design of MIMO channels, decoders, and architectural design of different modules both in the transmission and reception is a potential area for future work. There is also a lot of commercial work going on in designing MIMO based devices and to bring them into standardization. There is also a lot of research going on in the accurate channel estimation, Feedback channel information, Capacity-achieving constellation designs and many more. There are also lot of challenges in terms of Coding, Power control, Feedback and Complexity which has to be overcome in the future designs.

Considering this project in specific, the core operator can be embedded in the entire decoder architecture in the future work and addition of dual port memories for storing and manipulating H and r values can be done along with the memory mapping and implementation. On completion of that, the decoder can be well optimized as a ML decoder and can be used in the reception end. The decoder can also be designed in other possible ways based on the tradeoff between the speed and the area.
Reference


Appendix

Glossary of Terms & Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIMO</td>
<td>Multi Input Multi Output</td>
</tr>
<tr>
<td>STBC</td>
<td>Space Time Block Codes</td>
</tr>
<tr>
<td>SISO</td>
<td>Single Input Single Output</td>
</tr>
<tr>
<td>MISO</td>
<td>Multi Input Single Output</td>
</tr>
<tr>
<td>SIMO</td>
<td>Single Input Single Output</td>
</tr>
<tr>
<td>ML</td>
<td>Maximum Likelihood</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>HDTV</td>
<td>High-definition television</td>
</tr>
<tr>
<td>STTC</td>
<td>space-time trellis code</td>
</tr>
<tr>
<td>OSTBC</td>
<td>Orthogonal Space Time Block Codes</td>
</tr>
<tr>
<td>CSI</td>
<td>Channel State Information</td>
</tr>
</tbody>
</table>
På svenska

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