Performance Evaluation of Signal Detection Techniques for Spatially Multiplexed MIMO Systems

Abdulati Abdullah, Adel.A.M.Abosdel, Nagmden Miled Naser, Aeshah Mohammed

Faculty of Engineering
Azzaytuna University

الملخص

النمو الهائل في الاتصالات اللاسلكية أصبح واضح، خصوصا في التركيز على الشبكة المحلية اللاسلكية واسعة النطاق والهواتف المحمولة. لتلبية طلب الوصول بشكل أسرع للتقنيات اللاسلكية، هناك حاجة للتغيير من أنظمة الهوائي التقليدية ذات المداخلات الفردية والمخرجات الفردية (SISO). لذلك، تم إحراز تقدم كبير في الآونة الأخيرة في تطوير الأنظمة التي تستخدم هوائيات متعددة في المرسل والمستقبل لتحقيق أداء أفضل. أنظمة الاتصالات (MIMO) تستخدم هوائيات متعددة في كل من طرفي المرسل والمستقبل لتحقيق كفاءة طيفية عالية. ومع ذلك ، فإن تنفيذ أنظمة MIMO يأتي على حساب زيادة التعقيد في تصميم المستقبل. يشكل اكتشاف متجه الرموز المأخوذة من أبجدية محدودة عند إرسالها عبر نظام MIMO مهمة تنفيذ صعبة. الهدف من هذه الورقة هو استخدام تقنيات الكشف المختلفة مثل تقنيات الكشف الخطي وخوارزمية فك التشفير (SD). كما تناقش هذه الورقة تقييم الأداء وجوانب التنفيذ لهذه التقنيات كوسيلة لكشف فعالية أنظمة MIMO. تم استخدام برنامج المحاكاة الماتلاب لتصميم وتقييم النتائج.

ABSTRACT

A considerable enhancement has been experienced in the field of broadband wireless techniques. For that reason, it is not efficient to deploy the single-input single output (SISO) scenario for meeting the demand of higher data rate acceleration any more.Thus, a majorsystem development has been to use multiple antennas at both sides the transmitter and receiver to attain better performance based on bit error rate measurement. Multiple-input-multiple-output (MIMO) deploys multiple antennas at both ends to achieve high power and spectral efficiency.However,MIMO system comes at the cost of complexity at the recovery side. The objective of this paper is to includeand evaluate various techniques of signal detections, for example; linear detection techniques and sphere decoding (SD) algorithm.Sphere detection has demonstrated an efficient means to detect the spatially multiplexed symbols. The implementation is done in MATLAB Simulation.

Key-Words:MIMO systems, spatial multiplexing, antenna selection, multiple-input multiple-output MIMO Systems and detection techniques.

1- Introduction

The development of wireless communication systems has been rapid during the last two decades. The data rates as well as the quality of service (QoS) requirements are continuously growing to enable a rich user experience in wireless communication services. This will require high capacity and flexibility from future wireless communication systems and networks giving that regulation and other factors render the radio frequency (RF) spectrum a scarce and valuable resource [D. Haider, S. A. Shah , S. I. Shah and U. Iftikhar,]. Therefore, the physical layer of future wireless communication networks must be capable of providing an ever-increasing capacity in terms of high spectral efficiency, higher data rates and larger numbers of simultaneous users. Advanced technologies such as the use of multiple antennas both at the transmitter and receiver enable very efficient utilization of the spectrum [D. Haider, S. A. Shah , S. I. Shah and U. Iftikhar, &L. Zheng and D. N. C. Tse.]. The use of multiple antennas both in the transmitter and receiver results in a so-called multiple input-multiple-output (MIMO) radio channel as opposed to the conventional single-input-single-output (SISO) radio channel. MIMO in combination with orthogonal frequency-division multiplexing (OFDM) (MIMO–OFDM) have been identified as a promising approach for high spectral efficiency wideband systems [P. Pathak and R. Pandey,]. The increasing data rates and higher capacity requirements call for improved receiver implementations and architectural design. The more stringent performance requirements call for further research on architectures and implementation of baseband receiver algorithms as well. The solution for the implementation is a trade-off between hardware complexity and operational performance. Thereby to achieve high data rate communication, the system has to overcome problems such as additive noise and channel fading. One way is to make several replicas of the signal available to the receiver with the hope that at least some of them are not severely attenuated. This technique is called diversity [L. Zheng and D. N. C. Tse]. Examples of diversity techniques include time diversity, frequency diversity and space diversity. As the available bandwidth is finite, space diversity schemes seem promising, since they do not involve any loss of bandwidth . Such a multiple-input-multiple-output (MIMO) system promises significant improvements in terms of spectral efficiency, link reliability and improves the system capacity compared to conventional systems [B. M. Hochwald and T. L. Marzetta].

The benefits of MIMO technology that help achieve such significant performance gains are array gain, spatial diversity gain, spatial multiplexing gain and interference reduction [P. Pathak and R. Pandey& B. M. Hochwald and T. L. Marzetta]. Array gain is the increase in receive SNR that results from a coherent combining effect of the wireless signals at a receiver. The coherent combining may be realized through spatial processing at the receive antenna array and/or spatial pre-processing at the transmit antenna array. Array gain improves resistance to noise, thereby improving the coverage and the range of a wireless network [Younis, Abdelhamid]. However, the signal level at a receiver in a wireless system fluctuates or fades. Spatial diversity gain mitigates fading and is realized by providing the receiver with multiple (ideally independent) copies of the transmitted signal in space, frequency or time.

2- Principle of Spatially multiplexed MIMO System

The main concerns of wireless communications are to achieve the higher data rate and to increase the spectral and the energy efficiency, the multiple antennas technology which is also known as the MIMO technology has been widely used by advanced wireless communication systems.The MIMO is a key of critical technologies that is used in 3G/4G wireless communication system. It enables transmission of higher rate over wireless channel. Since, multiple input refers to multiple transmit antennas, while multiple output refers to multiple receive antennas. There is a fading channelcoefficient between each pair of transmitting and receiving antenna. In particular, a MIMO is a collection or combination of large number of fading channels as shown in figure 1 [D. Haider, S. A. Shah , S. I. Shah and U. Iftikhar, & L. Zheng and D. N. C. Tse.]. Figure 1Typical model of MIMO system

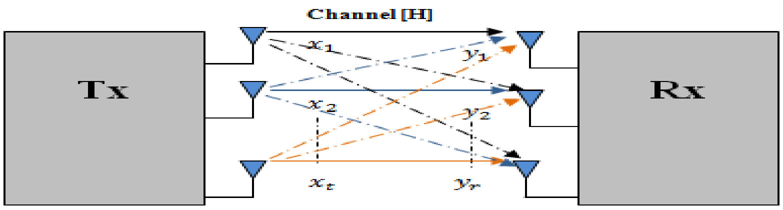

Figure 1Typical model of MIMO system

Therefore, such multiple antennas lead to diversity and resulting in an increase in reliability and data rate, which is possible by transmitting several information streams in parallel as shown in figure 2. This property which is a very key property in MIMO system is known as a spatial multiplexing (SMX) [L. Zheng and D. N. C. Tse].

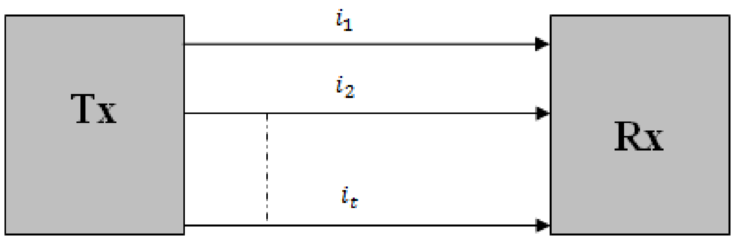

Figure2 Transmit multiple information streams in parallel

Thistechnique uses space division multiplexing (SDM) to simultaneously send more parallel stream of information instead of using time or frequency [Sun, Shu, et al]. MIMO techniques can generally be classified in terms of two categories such as multiplexing gain, which is obtained over the spatial multiplexing, where several independent streams are conveyed through different antennas at identical time instant. Also, The Bell labs layered space-time architecture (BLAST) is an example of the spatial multiplexing (SMX). It can support an extremely high data rate under promising channel environments[Sun, Shu, et al]. Therefore, The SMX modulation algorithm can be summarized by:

1. The incoming data bits are divided into a number of sub–streams, equal to the number of transmit antennas. Each sub–stream contains the data bits to be transmitted to a single transmit antenna.

2. Each sub–stream is modulated using any conventional modulation scheme such as binary phase shift keying (BPSK) modulation or quadrature amplitude modulation (QAM).

3. The sub–streams are then transmitted simultaneously from the existing transmit antennas. Thus a spectral efficiency that increases linearly with the number of transmit antennas is achieved.

Thus, SMX may not always be practically feasible especially in modern wireless communications where energy efficiency is of great concern. Therefore, solutions need to be found that strike an elegant trade-off between computational complexity, energy efficiency, and spatial multiplexing gain [Sun, Shu, et al]. The second widely used category of MIMO technologies is the space-time-coding (STC) which improves the reliability of the system by maximizing the spatial diversity. The Altamonte scheme is a typical example of this category. For the STC technology, redundant data are transmitted through different antennas in order to improve the system's reliability. However, the major problem of STC technology is the limited spectral efficiency, where even for a full diversity STC system, the maximum spectral efficiency is only one symbol per time instant. Next chapter will illustrate in depth the principals of Altamonte STB coding [Sun, Shu, et al].

3- Model of MIMO System

Consider a transmitter with t transmit antennas and a receiver with r receive antennas as demonstrated in Fig.1. That is t symbols can be transmitted on t transmit antennas, similarly for r received symbols, where the symbols can be stated as a vector.

$$\hat{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_t \end{bmatrix} \text{and} \hat{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_r \end{bmatrix} \quad (1)$$

Therefore,

$\hat{y}_{rx1} = H\hat{x}_{tx1} + \hat{n}_{rx1}(2)$

Where $H$is channel coefficient matrix that is equal to $t * r$ and $\hat{n}$ is noise vector.

$$H = \begin{bmatrix} \mathrm{h}_{11} & \cdots & \mathrm{h}_{1t} \\ \vdots & \ddots & \vdots \\ \mathrm{h}_{r1} & \cdots & \mathrm{h}_{rt} \end{bmatrix}$$

For h_{11}denotes the channel coefficient of first transmit antenna and first receive antenna. Final formula of MIMO system is

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_r \end{bmatrix} = \begin{bmatrix} \mathrm{h}_{11} & \cdots & \mathrm{h}_{1t} \\ \mathrm{h}_{21} & & \mathrm{h}_{2t} \\ \vdots & \ddots & \vdots \\ \mathrm{h}_{r1} & \cdots & \mathrm{h}_{rt} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_t \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_r \end{bmatrix} \quad (3)$$

System that use only multiple receive antennas, this system is known as single input- multiple output (SIMO), that is generally used to obtain receive diversity by techniques as selection combining, maximal ratio combining or equal gain combining.

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_r \end{bmatrix} = \begin{bmatrix} \mathrm{h}_{11} \\ \mathrm{h}_{21} \\ \vdots \\ \mathrm{h}_{r1} \end{bmatrix} x_1 + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_r \end{bmatrix} \quad (4)$$

The simplest receive diversity technique is selecting the branch with the highest SNR as the output signal which is called selection combining. Whereas, Maximal ratio combining aims at maximizing SNR by multiplying the branches with weighting factors and making phase and gain adjustment. However, SNR is not always known on each branch, so the adjustment is done only according to the phase. This technique is named as equal gain combining [Sun, Shu, et al]. For $r = 1$, to have multiple transmit antennas broadcasting their information to a single receive antenna, this technique is known as (MISO) system. It is commonly used to obtain transmit diversity by using techniques as space time coding, space frequency coding, etc.

Or, it can be rewritten as

$y_1 = \hat{\mathrm{h}}^{\mathrm{H}}\hat{\mathrm{x}} + \mathrm{n}_1$ (6)

Since $\hat{\mathrm{h}}^{\mathrm{H}}$is known as the channel vector hermitian.

For $\hat{h}=\begin{bmatrix} \mathrm{h}_{11}{}^* \\ \mathrm{h}_{21}{}^* \\ \vdots \\ \mathrm{h}_{r1}{}^* \end{bmatrix}$ then $\hat{\mathrm{h}}^{\mathrm{H}} = [\mathrm{h}_{11} \quad \mathrm{h}_{12} \ldots \quad \mathrm{h}_{1t}]$

In space time coding, the spacing between transmit antennas are set sufficiently apart that the channel path gains for different transmit antennas are uncorrelated. The modified replicas of the symbols transmitted from antennas are sent over different time slots to obtain diversity. Space frequency coding is similar to space time coding but diversity is obtained by using different carriers instead of time slots [Saygili, Halil].The most special case when the system is reduced to the standard scenario of Rayleigh fading channel by having a single transmit and receive antenna, this system is termed as (SISO) system.The modeling formula of this case is

$$y = hx + w \quad (7)$$

For example, consider having 3x2 MIMO system, meaning r=3 and t=2, the channel matrix consists of six fading coefficients, two symbols are transmitted on the first and second antennas and three dimensional receive vectors are formed as,

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} \mathrm{h}_{11} & \mathrm{h}_{12} \\ \mathrm{h}_{21} & \mathrm{h}_{22} \\ \mathrm{h}_{31} & \mathrm{h}_{32} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix} \tag{8}$$

For noise vector, each n_i is considered as Gaussian noise with zero mean (μ) and variance σ^2, therefore, the expectation of this model is zero, while the second moment (total power) is equal to σ^2 . Assuming different noise elements n_i are independent identically distributed that is

$$E\{n_i n_j^*\} = \begin{cases} \mathrm{E}\{|n_i|^2\} = \sigma^2 i = j \\ E\{n_i\}E\{n_j^*\} = 0 \qquad i \neq j \end{cases} (9)$$

For covariance matrix,

$$E\{\hat{n}\hat{n}^H\} = \mathrm{E}\left\{ \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_r \end{bmatrix} [n_1^* \quad n_2^* \dots \quad n_r^*] \right\} \; (10)$$

$$= \mathrm{E}\left\{ \begin{bmatrix} |n_{11}|^2 & n_1 n_2^* & \dots & n_1 n_r^* \\ n_2 n_1^* & |n_{22}|^2 & & n_2 n_r^* \\ \vdots & & \ddots & \vdots \\ n_{r-1} n_1^* & n_{r-1} n_2^* & \dots & n_{r-1} n_r^* \\ n_r n_1^* & n_r n_2^* & & |n_{rr}|^2 \end{bmatrix} \right\}$$

$$= \begin{bmatrix} \sigma^2 & 0 & \dots & 0 & 0 \\ 0 & \sigma^2 & & 0 & 0 \\ \vdots & & \ddots & \vdots & \\ 0 & 0 & \dots & \sigma^2 & 0 \\ 0 & 0 & & 0 & \sigma^2 \end{bmatrix} = \sigma^2 \,\mathrm{I} \;\; (11)$$

Where $E\{n_i\}E\{n_j{}^*\} = 0$ for $i \neq j$ due to the orthogonally and I is the identity matrix.

Unlike other wireless communication systems, multiple-input multiple-output (MIMO) systems take advantage of the randomness introduced by scattering and multipath components to improve the spectral efficiency. MIMO systems basically serve two purposes: providing multiplexing gain by parallel transmission of independent streams of data and providing diversity gain by receiving multiple copies of independently faded data streams. So, MIMO systems are capable of achieving multiplexing gains as well as diversity gains. But both these gains cannot increase to infinity [B. Kumbhaniand R. S. Kshetrimayum]. For an $\mathbf{N_t \times N_r}$MIMO system the maximum diversity gain that can be a maximum multiplexing gain that can be achieved is min(Nt,Nr). Both thegains cannot be maximum at an instant. So, there exists a trade-off between diversity gain and multiplexing gain [B. Kumbhaniand R. S. Kshetrimayum].MIMO systems are known for improving the data rates by parallel transmission of an independent stream of digitally modulated symbols. Obviously, this augments to the total transmission rate. At the same time, MIMO systems offer diversity gain. The diversity gain is achieved as a result of multiple antennas at the receiver when multiplexing is used for transmission. In many cases, diversity is achieved at the cost of multiplexing. Diversity gain and multiplexing gain both cannot increase simultaneously [B. Kumbhaniand R. S. Kshetrimayum]. To achieve one, we need to compromise the other. So, there is a trade-off between diversity gain and multiplexing gain. MIMO systems can be used only for achieving diversity. In that case, all the antennas at the transmitter are used to transmit the same symbol from the incoming bit/symbol sequence. In the case of MIMO systems used only for multiplexing, incoming stream of information is converted into parallel bit/symbol sequences and each of these parallel sequences are transmittedsimultaneously from multiple antennas available at the transmitter. For multiplexing, it can be shown that 8×8 MIMO systems can achieve capacity as high as 40 times than that of single-input single-output (SISO) systems under certain conditions [B. Kumbhani and R. S. Kshetrimayum]. For the case of multiplexing, the channel capacity per unit channel bandwidth for MIMO systems at high signal-to-noise ratio(SNR) conditions can be given as [B. Kumbhani and R. S. Kshetrimayum]

$$C \approx min(N_t, N_r)\, log_2\, (SNR) \quad (12)$$

The multiplexing gain is limited by the minimum of the number of antennas at transmitter and the number of antennas at the receiver. This is because it is considered that there are non-interfering parallel links in multiplexing. This establishes that number of parallel links cannot be more than the minimum number of antennas on either side. The spatial multiplexing gain can be defined as

$$r = \lim_{SNR \to \infty} \frac{C}{log_2\,(SNR)} \quad (13)$$

wherer **r** is the spatial multiplexing gain. This shows that for any MIMO system, the maximum spatial multiplexing gain is $min(N_t, N_r)$. In the same way, [B. Kumbhaniand R. S. Kshetrimayum] defines the diversity gain in the following way:

$$d = \lim_{SNR \to \infty} - \frac{\log\,(BER)}{log\,(SNR)} \quad (14)$$

where**d** is the diversity gain. In other words, the diversity order of a communication system is said to be d if the bit error rate (BER) of the system varies as inverse of SNR^d in the high SNR regime. Here, we also recall that diversity order is alternatively defined as the number of independent paths from transmitter to receiver. In the case of receiver diversity systems such as selection combining or maximal ratio combining, we get the same diversity order as the number of antennas available at the receiver. In the case of MIMO systems, the maximum number of independent paths from transmitter to receiver is the same as the product of number of antennas at transmitter and at receiver. So, the maximum diversity order that can be achieved by any MIMO system is $\boldsymbol{N_t N_r}$.So, the diversity multiplexing trade-off can be given as:

$$d_{opt} = (N_t - r)(N_t - r) \quad (15)$$

where$\boldsymbol{d_{opt}}$ is the optimum diversity gain when the system is used to achieve multiplexing gain of r. As stated earlier, the trade-off given in the above expression is considering the case that multiplexing gain is obtained assuming that the parallel links are non-interfering links, i.e., an antenna at transmitter side is connected to single antenna of receiver side or there is one-to-one link among the antennas at transmitter and receiver. At the same time, while calculating the diversity gain, it considers that a link is available from an antenna at the transmitter to every antenna of the receiver. However, with fully interfering MIMO channels, the channel capacity per unit bandwidth can be given by :

$$C_{MIMO} = \log_2(\det (I_{N_r} + \frac{\bar{\gamma}}{N_t} HH^H) \quad (16)$$

where$I_{N_r}$is an identity matrix of dimension $N_r \times N_r$, and $\bar{\gamma}$ is the averageSNR per receiver antenna. Again, for optimum use of resources in this case, a subset of receiver antennas can be selected for maximum channel capacity without compromising on the number of parallel data streams that can be transmitted simultaneously. This virtually means that the channel capacity of MIMO systems can scale linearly with the number of transmitting antennas. Note that the expression of MIMO channel capacity, equation (16), is valid only when spatial multiplexing is employed at the transmitter and the channels are fully interfering.Spatial multiplexing has been seen as a sophisticated technology for improving transmission rates. But for the improved transmission rates, cost has to be paid in terms of hardware and computational complexity. Parallel transmission from multiple antennas requires separate radio frequency (RF) chain for each antennaat transmitter. These RF chains consist of complex hardware comprised of A/D converters, modulators, RF amplifiers, etc. This makes the system bulky (at least for the user handset). Although, receiver diversity techniques also demand such RF chains in multiple number, mainly receiver diversity techniques are implemented at the base stations which are not mobile in nature. So, bulky hardware can be afforded at the receiver. In addition to this, spatial multiplexing systems need inter antenna synchronization. It is also considered that if the multiplexing in MIMO systems consider non-interfering channels, the multiplexing gain that can be achieved limits to ***min(N_t , N_r)*** and no gain can be achieved in the diversity order as compared to SISO systems. But, in practice, the existence of non-interfering MIMO channels is an idealistic scenario [B. Kumbhaniand R. S. Kshetrimayum] . All the practical MIMO channels are interfering in nature, i.e., a symbol/signal transmitted from an antenna at the transmitter is surely going to suffer interference from the symbols/signals being transmitted by all other antennas at the transmitter [B. Kumbhaniand R. S. Kshetrimayum] .This fact that the practical MIMO channels are interfering in nature is helpful and can be used in a way to achieve diversity even while using multiple antennas of transmitter for parallel transmission of information, i.e., multiplexing. Interfering channels or, in fact, the channel model that is under consideration to achieve the diversity order of **N_tN_r**is helpful in explaining how MIMO systems can be useful in achieving diversity and multiplexing simultaneously, provided there exists a rich scattering environment. In such a channel model, each transmitter antenna has a link to all the receiver antennas [B. Kumbhaniand R. S. Kshetrimayum] .Therefore, the system as a whole may be considered as a parallel combination of an $\mathbf{N_t}$number of $1\times\mathbf{N_r}$receiver diversity systems, i.e., each such system can achieve diversity order of $\mathbf{N_r}$separately. Now, these $1\times\mathbf{N_r}$systems are combined such that the set of receiver antennas remain the same [B. Kumbhaniand R. S. Kshetrimayum]. Each receiver antenna receives signals from all the transmitter antennas. So, received signal at each antenna is a combination of the signals being transmitted by all the transmitter antennas. Thus, each receiver antenna receives a signal that is interfered by all the transmitted symbols from each transmitter antenna at the corresponding time instant. But also, each receiver antenna receives one copy of each symbol from every transmitter antenna. Thus at the receiver, number of copies of the same signal/symbol is the same as that of the antennas at the receiver. This means that the diversity order offered by such a system is $\mathbf{N_r}$.

4- MIMO-SMx Detection Techniques: Analysis and Simulation

The performance of spatial multiplexing in MIMO system is to have several layers or independent data streams are simultaneously transmitted via different transmit antennas. Consequently, the channel capacity can be increased linearly with the number of transmit antennas N_t. On the other hand, transmit/receive diversity schemes are impressively effective in increasing the diversity gain where consequently performance is improved [Younis, Abdelhamid]. this paper t is restricted to introduce the performance of detection techniques used in spatial multiplexing (SMx) required for satisfying the conditions (capacity and error performance) of 4G technology. Spatial multiplexing detection schemes can be mainly classified to linear, nonlinear and tree search algorithm. In this section, the main concentration will be on : Zero-Forcing (ZF), Minimum Mean-Square Error (MMSE), Successive Decoding (Cancelling or Successive Cancellation) and finally Sphere (SD) decoding [Younis, Abdelhamid]. Let re-introducing the MIMO system model as shown in figure (4) , symbols are mapped in parallel to the transmit antennas as sent simultaneously.

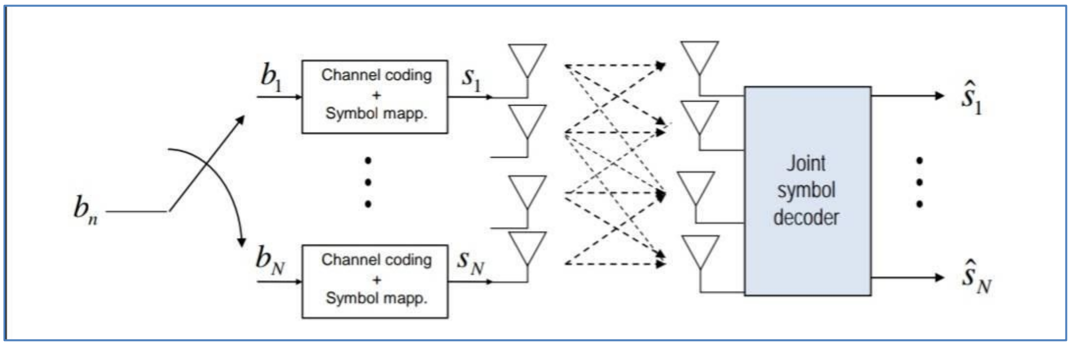

Fig 4: MIMO model system [B. Kumbhaniand R. S. Kshetrimayum]

The SMxis considered as a sufficient solution for increasing the capacity of the system with no need for additional spectral resources. The detection code with less complexity is the challengeable task in MIMO-SMx. A diversity of detection techniques can be used to remove the effect of the channel and estimate the transmitted data. Likelihood Detector (MLD) is the optimum detector technique that could efficiently recover the signal sent based on the minimum distance criterion. Although MLD supports the best performance and diversity order, it requires a high complexity brute-force search. For that reason, sub-optimal detection techniques are the potential candidates for use to solve the detection problem in MIMO systems, which are efficient regarding to performance and computational complexity. Sphere Decoding (SD) is powerful technique, which utilize restrict tree search mechanisms [Younis, Abdelhamid].

5- Linear Detection Techniques

The main goal behind employing linear detection techniques in MIM O system is to linearly filter the received signals using filter matrices, as depicted in figure 5.

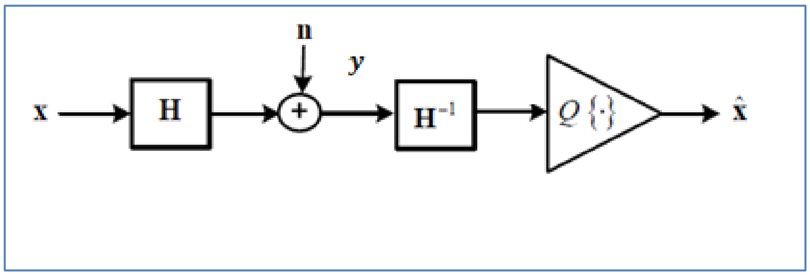

Fig 5: MIMO-SMx with linear receiver [Bohnke, R., D. Wubben, V. Khun, and K.-D. Kammeyer]

Recall equations (2) and (3) , that express the general model of MIMO system, the zero-forcing detector is given by pseudo inverse of H.

$$x_{ZF} = H^{-1}y = H^{-1}(Hx + n) = x + H^{-1}n \quad (17)$$

That is the transmit vector $x$corrupted by the transformed noise $H^{-1}n$. This component makes ZF suboptimal due to the expected huge amplifications of the noise term. The drawback of this receiver is the additive noise may strongly rise because of cancelling the signals received from the rest of transmit antennas; this may result in heavily degrading the system performance [Bohnke, R., D. Wubben, V. Khun, and K.-D. Kammeyer].The minimum mean square error (MMSE) compromises between signal interference and noise enhancement, which reduces the mean square error among the sending symbols. This results in transmitted data with a little residual noise and interference. After that data is treated in the same manner as ZF [Bohnke, R., D. Wubben, V. Khun, and K.-D. Kammeyer]

$$x_{MMSE} = (H^H H + \sigma^2 I)^{-1} H^H y \quad (18)$$

Practically, it can be complicated to attain correct factor of the noise that is essential for optimal signal detection and only a little development compared to the ZF receiver may be achieved. Therefore, MMSE is not deployed in practice. Because of the decision of each data stream is treated separately, the algorithm complexity of ZF is much less than that for Maximum likelihood Detection (MLD) receiver [B. Kumbhaniand R. S. Kshetrimayum]. To simulate linear detection techniques of MIMO system, MATLAB package is used. Figure (6) shows the bit error rate performance over Rayleigh fading channel with BPSK modulated scheme. The simulation is done for 2x2 MIMO system ($N_t = 2, and N_r = 2$) with BPSK modulation. The $\mathbf{E_b}$ / $\mathbf{N_o}$, ranges between 0 dB and 30 dB. In this case, the MMSE curve performs better than ZF by about 4 dB at an error rate of 10^{-3}. Both the ZF and MMSE detectors show a diversity order of more than $N_r - N_t + 1$ (the array and diversity gains directly depend on this term), whereas; less than N_r. The linear detection schemes are favorable in terms of computational complexity, however; their BER performance is severely degraded due to the noise enhancement in the ZF case, and when the channel matrix is not well-conditioned.

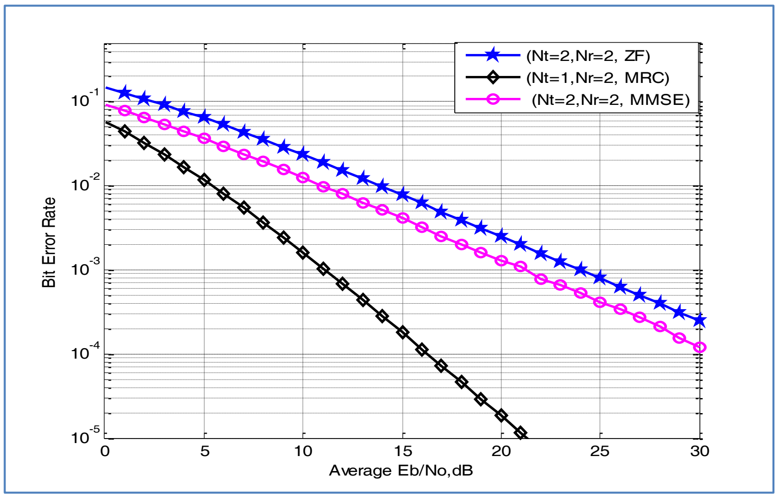

Fig 6: BER for BPSK modulation with 2x2 MIMO and linear detection equalizers.

6- Cancellation of Successive Interference

Linear detection techniques experience high degradation in diversity order, although they have simple implementation. An alternative and power approach that takes advantage of the diversity potential of the additional receive antennasis considered and named as Successive Interference Cancellation (SIC) (for instance, VBLAST decoder). V-BLAST deploys a serial decision-feedback mechanism to recover each layer separately [Gore, D., R. W. Heath Jr., and A. Paulraj]. The algorithm of VBLAST utilizes the already detected symbol x_i, provided by either ZF or MMSE filtering matrix, to produce a modified received vector with $x_i$cancelled out. Therefore, the adjusted received vector produces fewer interference and therefore the overall performance improved because of a higher diversity level. Error propagation can be a serious problem due tomiss detection of received data results in an increase in the interference when detecting subsequent layers. To minimize the impact of error propagation and optimize the VBLAST technique performance, the order of detection can boost the performance considerably. It is an optimal situation to begin with detecting the components of x that faces the least noise amplification. The algorithm is called sorted ZF-VBLAST for use of ordering [Gore, D., R. W. Heath Jr., and A. Paulraj]. Generally, the ZF-based solution is a simple solution for this situation, but not optimum as it enhances the noise. Instead, the MMSE technique is employed, which supports better performance. MMSE suppresses both the noise and interferenceparts, while the ZF algorithm nulls out only the interference components. The algorithm is called sorted MMSE-VBLAST when the ordering strategy is used. The serious disadvantage of the BLAST detection is mainly due to the computational complexity, that is because of multiple calculations of the pseudo-inverse of the channel matrix are required. Figure (7) demonstrates the performance of ZF and ZF-SIC criteria with deploying optimal ordering.

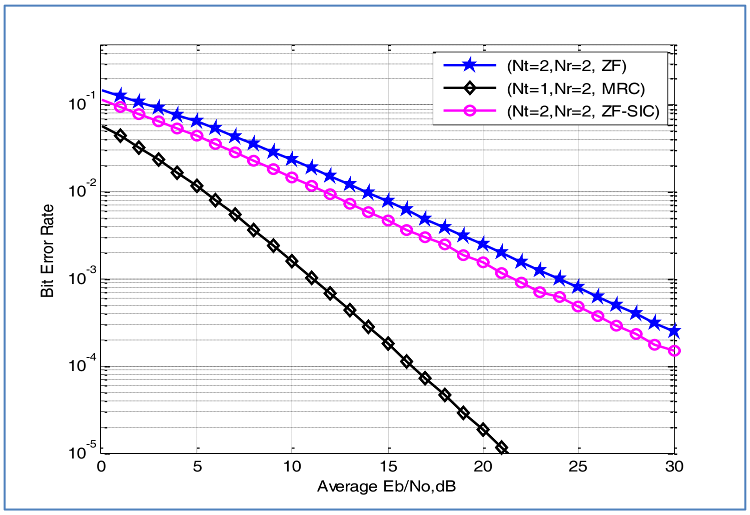

Fig 7: BER for BPSK modulation with 2x2 MIMO and ZF-SIC equalizer

It is observed that the post-detection using ordering (ZF-SIC) method achieves better performance than that for conventional ZF.This achieve the same trend for applying MMSE instead as shown in figure (8). It is clear that deploying MMSE with SIC and ordering SIC contributes to considerably improving the average of bit error rate comparing with the other conventional linear detectors that experience poor performance due to the amount of noise resulted from the amplifier applied. For example, at a target BER of 10^{-3} the difference between ZF and MMSE-SIC curves is about 5 dB and with MMSE-OSIC curve is about 14 dB. This demonstrates the impact of employing signal ordering. Note that the performance advantage of the MMSE is quite considerable in all cases. The MMSE-OSIC lags the MLD curve by about 1 dB, which implies the considerable improvement that can be met when using non-linear detection techniques instead although of receiver complexity.

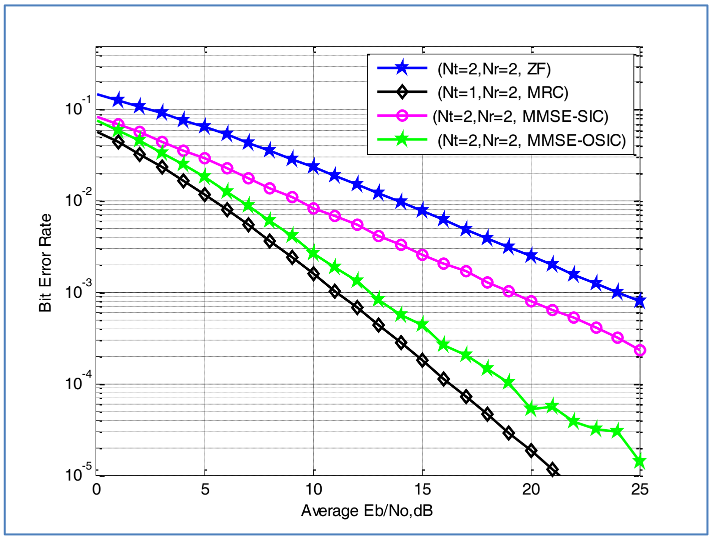

Fig 8: BER for BPSK modulation with 2x2 MIMO and MMSE-OSIC equalizer

7- Techniques of Tree-Search Detection

Sphere decoding (SD) technique is one of the tree search methods that is used to find the transmitted signal vector with minimum ML metric [Hassibi, B. and H. Vikalo]. On the other hand, it only includes a smaller set of vectors within a particluar sphere rather than all potential transmitted signal vectors. A sphere radius is adjusted first, while it increases the radius in case of no vector within a sphere, and decreases the radius in case of existinga multiple vectors within the sphere as represented in figure (9). The SD approach was achieved from the mathematical computing of shortest nonzero vector in a lattice. The SD algorithm is initiallydesignated to substantially minimize the computational complexity of signal detection in MIMO systems. In SD, the

search can be restricted to be in a circle with a radius R around the received signal y therefore;

$$x_{SD} = \arg_{min} \|y - Rx\|^2 \leq d^2 \qquad (19)$$

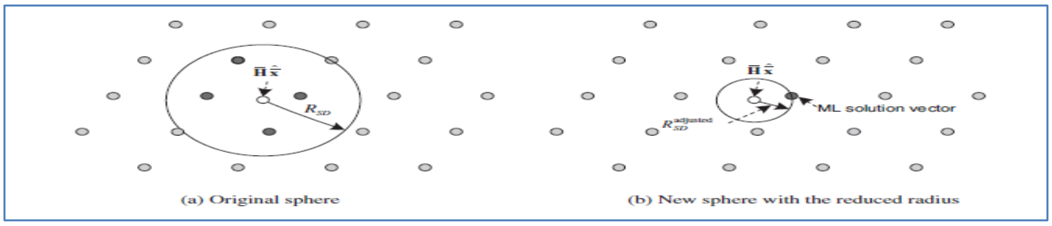

Fig 9: Illustration of the sphere decoding [B. Kumbhaniand R. S. Kshetrimayum].

First, we apply the QR decomposition to the MIMO channel matrix **H** (assumed full-rank**): H = QR**

$$\underbrace{\begin{pmatrix} H_{1,1} & H_{1,2} & \cdots & H_{1,2} \\ H_{2,1} & H_{2,2} & \ddots & H_{2,2} \\ \vdots & \vdots & \cdots & \vdots \\ H_{n,1} & H_{N,2} & & H_{N,N} \end{pmatrix}}_{H} = \underbrace{\begin{pmatrix} Q_{1,1} & Q_{1,2} & \cdots & Q_{1,2} \\ Q_{2,1} & Q_{2,2} & \ddots & Q_{2,2} \\ \vdots & \vdots & \cdots & \vdots \\ Q_{n,1} & Q_{N,2} & & Q_{N,N} \end{pmatrix}}_{Q} \underbrace{\begin{pmatrix} R_{1,1} & R_{1,2} & \cdots & R_{1,2} \\ 0 & R_{2,2} & \ddots & R_{2,2} \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & & R_{N,N} \end{pmatrix}}_{R}$$

where**Q** is an orthogonal matrix $\boldsymbol{Q}^T\boldsymbol{Q}$ = I and R is upper triangular

- Pre-multiplying the observations x by$\boldsymbol{Q}^T$, we have

$$\tilde{x} = \boldsymbol{Q}^T x = \boldsymbol{Q}^T Hs + Hn = \boldsymbol{Q}^T\boldsymbol{Q}Rs + \boldsymbol{Q}^T n = Rs + \boldsymbol{Q}^T n \qquad (20)$$

Since **Q** is orthogonal, the noise distribution does not change and therefore our problem is equivalent to that amounts to minimizing the following function

$F_k(x_n, x_{n-1}, \dots, x_k)$ *K=1,……,N*(21)

The search of the node in the final layer with the lowest accumulated cost would require, in principle, an exhaustive search with exponential complexity $|D|^N$. For the example in figure (10), it explores 2^3 = 8 paths. The main idea of sphere decoding consists of exploring only those candidate solutions or paths within a sphere of radius R centered at$\tilde{x}$, so that [B. Kumbhaniand R. S. Kshetrimayum&Hassibi, B. and H. Vikalo]:

$$\|\tilde{x} - Rx\|^2 \leq R \qquad (22)$$

the tree is explored from top to bottom, when the accumulated distance or metric at a given node exceeds the radius, there is no need to explore those nodes in lower layers. Choosing R = 6, In the sub-tree of the right side, the accumulated metric from the second layer exceeds 6. Consequently, we quit exploring all nodes below that layer (dashed lines). The problem is to choose the radius, if R is too large we may explore too many points, whereas is R is too small there might be no points inside the sphere [Hassibi, B. and H. Vikalo].

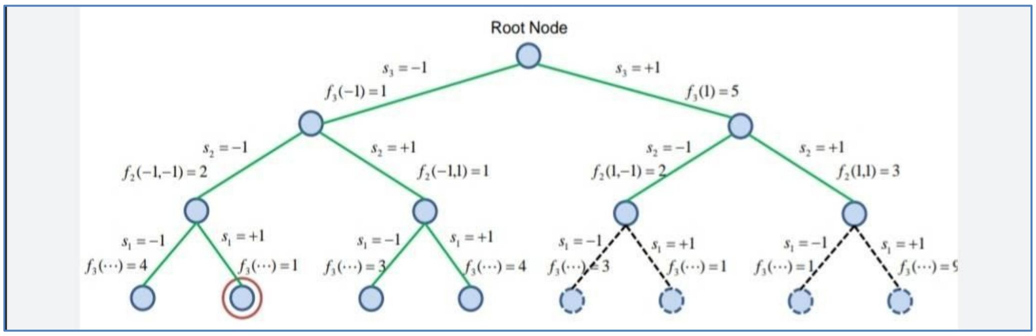

Fig 10: Illustration example of tree search in sphere decoding with R=6 [Hassibi, B. and H. Vikalo].

The point to notice is that the complexity of the sphere decoding is a random variable that depends on the MIMO channel, the noise vector, and the chosen radius. However, there is always a chance that no point is inside the chosen sphere and hence it is important to increase the radius and eventually ending up with doing an exhaustive search, so that the worst case complexity remains exponential.

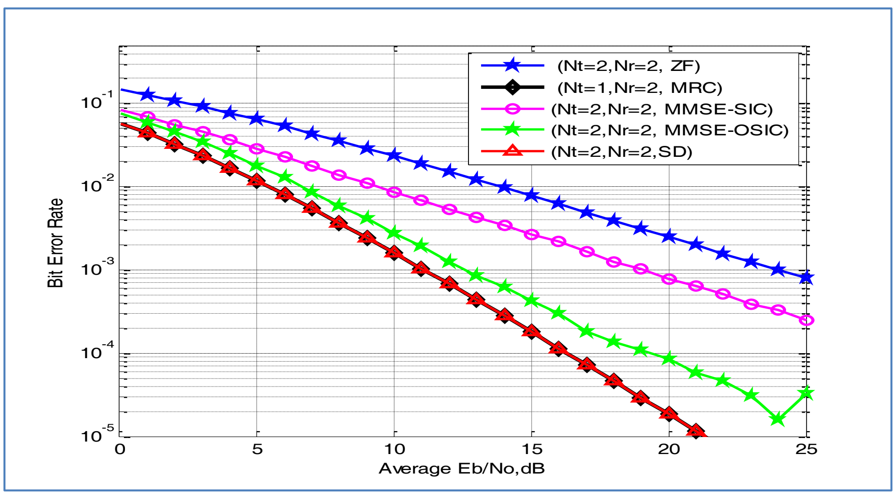

Fig 11: SD detection technique performance over other techniques.

Figure (11) shows the simulation of various detection techniques, SD achieves optimum performance when choosing the radius of the previous example and becomes identical to that for MRC, while SD search with limited radius, not as that for MRC.

Conclusion

To sum up, this project evaluates a variety of the MIMO-SMx detection schemes in terms of performance and computational complexity at the receiver side. Different performance simulations have been generated for each detection category to investigate and evaluate their BER. It has been observed that the linear detection techniques such as ZF and MMSE detection have poor performance if it is compared with MLD technique. In case of ZF equalizer, the implementation is less complicated than MLD , however due to the huge amplification in noise power required, ZF displays poorest performance . After applying the optimal ordering successive interference cancellation (OSIC) strategy involved VBLAST, the results show better performance than linear detections , although there is still kind of limitation due to error propagation. This error propagation has been alleviated by Sphere decoding (SD) algorithm. The tree search based detection techniques based on SD has achieved the identical performance that MLD achieves. For further observations, it is important to evaluate these techniques using higher order of modulation schemes with an increase in the number of transmit and receive antennas and investigate the performance of MIMO-SMx spectral efficiency. It is also worth to assess such technology over different types of fading channels.

BIBLIOGRAPHY

- D. Haider, S. A. Shah , S. I. Shah and U. Iftikhar, " MIMO network and the Alamouti, STBC (Space Time Block Coding)" American Journal of Electrical and Electronic Engineering, Vol. 5, No.1, pp 23-27, 2017.

- L. Zheng and D. N. C. Tse. Diversity and multiplexing: A fundamental tradeoff in multiple-antenna channels. IEEE Transactions on Information Theory, 49(5):1073–1096, 2003.

- P. Pathak and R. Pandey, " A novel Alamouti STBC technique for MIMO system using 16-QAM modulation and moving average filter" Journal of Engineeirng Research and Applications, Vo.4, No.8, pp.49-55, Augest 2014.

- B. M. Hochwald and T. L. Marzetta, “Unitary space-time modulation for multiple antenna communications in Rayleigh flat fading,” IEEE Transactions on Information Theory, Vol. 46, No.2, pp. 543-564, March 2000.

- Younis, Abdelhamid. "Spatial modulation: Theory to practice." (2014).

- A. Molisch and M. Win, “MIMO systems with antenna selection,” IEEE Microwave Magazine, vol. 5, no. 1, pp. 46–56, Mar. 2004.

- A. Stavridis, S. Sinanovi´c, M. D. Renzo., H. Haas, and P. Grant, "An Energy Saving Base Station Employing Spatial Modulation," in *IEEE 17th Int. Workshop on Computer AidedModeling and Design of Communication Links and Networks (CAMAD)*, Sep. 17–19 2012, pp. 231 –235.

- B. Kumbhaniand R. S. Kshetrimayum . MIMO Wireless Communications over Generalized Fading Channels. Taylor & Francis Group, LLC,2017.

- M. Di Renzo and H. Haas, "On Transmit-Diversity for Spatial Modulation MIMO: Impact of Spatial-Constellation Diagram and Shaping Filters at the Transmitter," in *IEEETrans. onVeh. Tech.*, 2013, to appear. Available: IEEE Xplore Early Access.

- N. Serafimovski, A. Younis, and H. Haas, "Spatial Modulation," Oct. 2012. [Online]. Available: http://youtu.be/cPKIbxrEDho

- G. D. Durgin, *Space-Time Wireless Channels*, ser. Prentice Hall communications engineering and emerging technologies series. Upper Saddle River, NJ : Prentice Hall PTR, c2003., 2003.

- R. Mesleh, "Spatial Modulation: A Spatial Multiplexing Technique for Efficient Wireless Data Transmission," Ph.D. dissertation, Jacobs University, Bremen, Germany, Jun. 2007.

- X. Wang and H. V. Poor, *Wireless Communication Systems: Advanced Techniques for Signal Reception*. Prentice Hall Communications Engineering and Emerging TechnologiesSeries, 2002.

- Z. R. Bharucha, "Ad Hoc Wireless Networks with Femto-Cell Deployment: A Study," Ph.D. dissertation, Univeristy of Edinburgh, 2010.

- Kumbhani, Brijesh, and Rakhesh Singh Kshetrimayum. *MIMO wireless communications over generalized fading channels*. CRC Press, 2017.

- Jafarkhani, Hamid. *Space-time coding: theory and practice*. Cambridge university press, 2005.

- Saygili, Halil. *A Comparison Of Spatial Modulation And Spatial Multiplexing Systems In Multipath Fading Channels*. Diss. Middle East Technical University, 2013.

- Jamali, Mohammad Vahid, Jawad A. Salehi, and FarhadAkhoundi. "Performance studies of underwater wireless optical communication systems with spatial diversity: MIMO scheme." *IEEE Transactions on Communications* 65.3 (2017): 1176-1192.

- Sampson, Wesley Alan, AristoteleHadjichristos, and Gurkanwal S. Sahota. "Diversity receiver for wireless communication." U.S. Patent No. 9,450,665. 20 Sep. 2016.

- Sun, Shu, et al. "MIMO for millimeter-wave wireless communications: Beamforming, spatial multiplexing, or both?." *IEEE Communications Magazine* 52.12 (2014): 110-121.

- Bohnke, R., D. Wubben, V. Khun, and K.-D. Kammeyer,(2003). "Reduced Complexity MMSE Detection for BLAST Architectures," in Proc. IEEE Global Communication Conference (Globecom'03), San Francisco, California, USA.

- Gore, D., R. W. Heath Jr., and A. Paulraj,(2002)." On performance of the zero forcing receiver in presence of transmit correlation," in Proc. Int. Symp. Inf. Theory, p. 159.

- Hassibi, B. and H. Vikalo,(2001). "On the expected complexity of sphere decoding," in Proc. Asilomar Conference on Signals, Systems and Computers, pp. 1051–1055.