Performance Evaluation of Spatial Multiplexing MIMO Systems with Various Detection Schemes

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ABSTRACT

Spatial Multiplexing (SM) over multiple-input multiple output (MIMO) channels significantly improves the data rates over wireless channels. The challenge is to design low complexity and high performance algorithms that capable of accurately detecting the transmitted signals. In this paper, the general model of MIMO communication system was introduced in addition to several MIMO Spatial Multiplexing (SM) detection techniques. The Bit Error Rate (BER) performance and computational complexity of Minimum Mean Square Error (MMSE), Zero Forcing (ZF), and Maximum Likelihood (ML) detection schemes have been analyzed and compared to each other using Matlab R2009b. Results of simulation illustrates that their performances of MMSE and ZF detectors are close together and need more than 14 dB of Signal to Noise Ratio (SNR) to achieve 10^{-4} BER. On the other hand ML detector shows better results than MMSE and ZF detectors but the complexity and the delay are large. Been proposed to install the number of transmitter antennas fixed on 2 and change receiving antennas 2, 3, and 4. Results showed that the present proposal came close to the results of the previous model, but less complexity.

Keywords: – MIMO, SM, ZF, ML.

تقييم اداء أنظمة الكشف لمنظومة الإدخال والإخراج المتعدد الإرسال المتعددة المكانية

الخلاصة

استخدام نظام متعدد المكانية (SM) مع نظام الإدخال والإخراج المتعدد (MIMO) ينتج عنه تحسن كبير في نقل معدل البيانات عبر القنوات اللاسلكية. التحدي الكبير هو في تصميم منظومة ذات تعقيد اقل واداء افضل في كشف موثوق عن الاشارات المرسلة. في هذا البحث تم تطبيق نظام (MIMO) مع (SM) باستخدام تقنيات كشف متعددة. معدل البيانات الخاطئة (BER) والتعقيد في التركيب لتقنيات الكشف نوع الصفر الاجباري (ZF) و الحد الادنى لمربع متوسط الخطأ (MMSE) وكذلك المجاورالاقرب (ML) تم تحليلها باستخدام الماتلاب. نتائج المحاكاة اوضحت بان اداء كل من (ZF) و (MMSE) متقارب ويحتاج الى نسبة اشارة الى الضوضاء (SNR) بمقدار 14 ديسبل للحصول على 10^{-4} (BER). ومن ناحية اخرى فان الكاشف نوع (ML) اظهر نتائج افضل من الكواشف (MMSE) و (ZF) لكن بتعقيد وتاخير زمني اكبر. وقد تم اقتراح تركيب يتم فيه تثبيت عدد هوائيات الارسال مع تغيير عدد هوائيات الاستقبال. النتائج بينت بان اداء التركيب المقترح يقترب من الموديل السابق ولكن بتعقيد اقل.

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INTRODUCTION

Multiple-input multiple-output (MIMO) systems offer both high data rates and high link reliability for mobile wireless communications due to the inherent space diversity. Spatial multiplexing (SM) MIMO systems provide higher data rates as each transmit antenna emits an independent information symbol in different time slots, i.e with M_t (where M_t is the number of transmitted antennas), the data rate can be increased by a factor of M_t. On the other hand, the achievable diversity order (negative exponent of the error rate at high SNR) in SM-MIMO depends on the detection (or equalization) technique incorp-orated at the MIMO receiver [1]. Conseque-ntly, efficient signal detection algorithms for spatial multiplexing MIMO systems have attracted much interest. A prime example is the Vertical Bell Laboratories Layered Spa-ce Time (V-BLAST) detector [2]. However, the performance of the VBLAST detection scheme is limited due to imperfect interfe-rence cancellation and insufficient receives diversity [3].

The optimal detector that minimizes the average error probability is the Maxim-um Likelihood (ML) detector [1]. However, the ML detector practically infeasible as its computational complexity is exponential. Different algorithms generally known as sphere decoders have been developed to achieve near ML performance with polynomial complexity [4]. On the other end of the complexity spectrum the equalizer based MIMO detection schemes can be found. These include Zero-Forcing (ZF) detector [5] and Minimum-Mean-Square Error (MMSE) detector [6]. The ZF-detector and the MMSE detector have the minimal computational burden as they require only matrix operations, e.g. pseudo-inverse. However, the error performance of both ZF and MMSE detectors are significantly lower than the optimal ML detector. Note that both ZF-detector and MMSE-detector have a diversity order of $N_r - M_t + 1$, while the optimal ML-detector has a diversity order of N_r, where N_r is the number of receive antennas [7].

In this research is to study and analyze the performance of the SM and a simulation using Matlab R2009b for MMSE, ZF, and ML detectors for the purpose of highlighting the advantages and disadvantages of this system and compare the performance of these detectors and then attempt to submit proposals for the development of SM for wireless communication fading circumst-ances.

MIMO SYSTEM

Fig.1 illustrates the system architecture used for MIMO wireless communications with M_t number of transmit antennas and N_r number of receive antennas. MIMO systems use multiple sources and multiple receivers to improve communication performance. Allowing for higher spectral efficiency, MIMO offers significant increases in data throughput, link reliability or diversity without additional bandwidth or transmit power [8].

Transmit diversity improves the signal quality and achieves a higher SNR ratio at the receiver side; it involves transm-itting data stream through multiple antennas and receiving by single antenna or more. Transmit diversity can effectively mitigate multipath fading effects as multiple antennas afford a receiver several observ-ations of the same data stream. Receive diversity are widely used in wireless communication systems; it can be achieved by receiving redundant copies of the same signal. The idea behind receive diversity is that each antenna at the receive end can observe an independent copy of the same signal. Therefore the probability that all signals are in deep fade simultaneously is significantly reduced [9].

The channel matrix $M_t \times N_r$ is denote as:

$$H = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1M_t} \\ h_{21} & h_{22} & \dots & h_{2M_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_{r1}} & h_{N_{r2}} & & h_{rM_t} \end{bmatrix} \quad \dots \dots\dots. (1)$$

Whose entries *hij* are attenuations from the *jth* transmit element to the *ith* receive element.

It has been demonstrated in [10] that MIMO systems provide tremendous capacity. When Channel State Information (CSI) is not available at the transmitter, the capacity of a MIMO system expressed in bits per second per hertz (bps/Hz) can be written as:

$$C = log_2 \left[det \left(I_{Nr} + \frac{\rho}{M_t} . H . H^T \right) \right] \frac{bps}{Hz} \dots . (2)$$

Where I_{Nr} is the identity matrix of size $N_r \times N_r$, H is the channel matrix of size $N_r \times M_t$ with H^T being its transpose conjugate, and ρ gives the average (SNR) per receiver branch independent of the number of transmitting antennas M_t.

SPATIAL MULTIPLEXING

In SM, a high-rate signal is split into several low-rate signals such that each can be accommodated within the allocated bandwidth. Multiple antennas receive these signals from different directions-of-arrival. The receiver, having knowledge of the channel, exploits the directions-of-arrival differences to separate the received signals into the individually transmitted signals. Demodulation results in the original sub-streams that can be combined to yield the original bit stream. The end goal of using SM is to increase the throughput of the network at no additional transmit power. For the 2×2

MIMO system, the SM transmitted sequence over two symbol intervals is illustrated in Fig. 2 [11].

The receiver, having knowledge of the channel, can discriminate between and extract both signals. There are three main types of receivers for spatial multiplexing systems: the maximum likelihood receiver, the linear receiver, and the successive interference cancellation receiver [12]. The linear receivers have a relatively low decoding complexity when compared to the Maximum-Likelihood (ML) or the succe-ssive interference receivers [13].

DETECTOR TYPES

Zero-Forcing

Zero-Forcing (ZF) technique is the simplest MIMO detection technique, which was proposed in [14]. Where filtering matrix is constructed using the ZF performance based criterion. The drawback of ZF scheme is the susceptible noise enhancement and loss of diversity order due to linear filtering [15]. ZF can be implemented by using the inverse of the channel matrix H to produce the estimate of transmitted vector $\breve{x}$ [16].

$$\breve{x} = H^{*}y = H^{*}(Hx + n) = x + H^{*}n \ldots\ldots (3)$$

Where $(.)^{*}$ denotes the pseudo-inverse. With the addition of the noise vector, ZF estimate, i.e. $\breve{x}$, consists of the decoded vector x plus a combination of the inverted channel matrix and the unknown noise vector. Because the pseudo-inverse of the channel matrix may have high power when the channel matrix is ill-conditioned, the noise variance is consequently increased and the performance is degraded. To alleviate for the noise enhancement introduced by the ZF detector, the MMSE detector was proposed, where the noise variance is considered in the construction of the filtering matrix [16].

Minimum Mean Square Error

Minimum Mean Square Error (MMSE) approach alleviates the noise enhancement problem by taking into consideration the noise power when constructing the filtering matrix using the MMSE performance-base criterion. The vector estimates produced by an MMSE filtering matrix becomes [17]:

$$\breve{x} = [\{(H^{H}H + (\sigma^{2}I))^{-1}\}H^{H}] \qquad \ldots.. (4)$$

Where $(H)^{H}$ is the Hermitian transpose of H and σ^{2} is the noise variance. The added term ($1/SNR = \sigma^{2}$), in the case of unit transmit power) offers a trade-off between the residual interference and the noise enhancement. Namely, as the SNR grows large, the

MMSE detector converges to the ZF detector, but at low SNR it prevents the worst Eigen values from being inverted. At low SNR, MMSE becomes Matched Filter [17]:
$[\{(H^H H(\sigma^2 I))^{-1}\}H^H]\,\sigma^2 H^H$……(5)
At high SNR, MMSE becomes ZF:

$$\left\{\left(H^H H + (\sigma^2 I)\right)^{-1}\right\} H^H \approx (H^H H)^{-1} \text{………(6)}$$

Maximum-Likelihood decoder (MLD)

MLD is achieved in a simple way through decoupling of the signals transmitted from different antennas rather than joint detection. Alamouti scheme is optimum in the ML sense and results in a minimum Euclidean distance per-symbol decision rule:

$$\breve{x} = min\|y_i - x_i\|^2 \qquad \text{………..(7)}$$

This in turn minimizes the error probability. ML decision algorithm is used under conditions of uncertainty. The ML decision maker is meant to ignore all possible events except the one most likely to occur, and should select the course of action that produces the best possible result in the given circumstances [13].

Although MLD achieves the best performance and diversity order, it requires a brute-force search which has an expon-ential complexity in the number of transmit antennas and constellation set size. For example, if the modulation scheme is 64-QAM and 4 transmit antenna, a total of 64^4 = 16777216 comparisons per symbol are required to be performed for each transm-itted symbol. Thus, for high problem size, i.e. high modulation order and high transmit antenna (M_t), MLD becomes infeasible [16].

SM-MIMO CHANNEL MODEL

Consider a transmitted vector $x = \left[x_1, x_2, \cdots, x_{N_t}\right]^T$ whose elements are drawn independently from a complex cons-tellation set *m* , e.g. Quadrature Amplitude Modulation (QAM) constell-ation. The vector is then transmitted via a MIMO channel characterized by the channel matrix *H*. The channel matrix contains the complex path gains $[H]_{ij}$ between every transmit and receive antenna pair. It has been adopted an uncorrelated Rayleigh flat-fading channel model and, consequently, these coefficients are independent ident-ically distributed complex Gaussian random variables with zero mean and unit variance, i.e.,$[H]_{ij} \approx CN(0,1)$.

The received vector $r = \left[r_1, r_2, \cdots, r_{N_r}\right]^T$ can then be given as following,

$$r = Hx + n \qquad \text{……………..(8)}$$

Where the elements of the vector $n = \left[n_1, n_2, \cdots, n_{N_r}\right]^T$ are drawn from independent and identically distributed circular symmetric Gaussian random variables.

SIMULATION AND RESULTS

In this section will study and analyze the performance of spatial multiplexing system with MMSE, ZF, and ML decoders. Suppose that the number of transmitter and receiver antennas will be 2×2, 3×3, and 4×4 for each type of decoder. For the purpose of standing over the possibility of increasing the data transfer rate in this system QPSK, 8-PSK, and 16-PSK has been evaluated for each.

MMSE and ZF Decoders

First step of simulation is done for MMSE and ZF without ML. Fig. 3 shows performance estimation of these two detectors, the number of antennas used is $(M_t, N_r) = (2, 2)$ system with QPSK, 8-PSK and 16-PSK modulation. The SNR, ranges between 4 dB and 28 dB in step of 2 dB. In this example MMSE curve performs better than ZF by about *2.5 dB* at an error rate of 10^{-5} for QPSK. But at 16-PSK, their performances are identically, as well as with 8-PSK level be close together. This means that the MMSE detector is more meaningful when the low level of modulation.

The reason for this as it is known that the rate of error increases with high levels of modulation and as described in subsection 4-1, because the pseudo-inverse of the channel matrix may have high power when the channel matrix is ill-conditioned, the noise variance is consequently increased and the performance is degraded. For more detail for this point see [16].

Now for $(M_t, N_r) = (3, 3)$ system perform-ance has become the best for all levels of modulation as is clear from Fig. 4. It is noted here that the increase in the number of antennas from *2 × 2 to 3 × 3*, the performance of MMSE detector is improving by *1.5* to *3 dB* while the ZF is improved by *2 to 3 dB*. But it must be noted here that the latter is less complicated than MMSE. Also, both decoders need more than *15 dB* to reach acceptable error rate (10^{-4}) for various level of constellations.

MLD

As for the MLD with QPSK it is also clear from Fig. 5, it improves dramatically with the increase in the number of antennas. This decoder needs *15 dB* to reach BER of 10^{-4} in the event that the number of antennas is *2 × 2*. But upwards to the *3 × 3*, it needs only to *10 dB* to reach the same BER, which mean a profit of *10 dB*. Thus, whenever the number of antennas increases, the performance improvement will be better but the problem is the large increase in complexity as indicated in subsection 4-3.

Then re-test of this decoder to a higher level of modulation (8-PSK) has been to get the results shown in Fig. 6, which indicates that the performance fell signif-icantly with the high level of modulation. In this experiment, if the number of antennas is *(4 × 4)*, this detector needs to *14 dB* to get BER of 10^{-4}, but in comparison with Fig. 5, it is to just less than *8 dB* to reach the same BER. In addition of large delay time which means that it is very difficult to use this decoder for high level of constellation in some application with more multiple antennas, although it is better detector for spatial multiplexer.

Proposed Scheme

Of previous results can be concluded that the MLD is the best but the problem is the increased complexity and time-delay with the increase in the number of antennas as well as the high level of constellation in the knowledge that the increase in the number of antennas results as indicated in the above cause a significant improvement as the high level of constellation is required for increasing the rate data transfer.

After checking found that the increase in the number of transmitter antennas increases the performance impro-ved with increasing complexity and time-delay either increase the receiving antennas to improve performance without the comple-xity. Thus the proposal is to increase the number of receiving antennas while reduc-ing the number of transmitted antennas.

In the following experiment was installed the number of transmitter antennas to $M_t = 2$ and increase receiving antennas $N_r=2, 3,$ *and 4*. The results in Fig. 7 showed that good performance for the new parameters, it can obtain 10^{-5} BER at 12 dB of SNR for number of antennas *(2 × 4)* while getting same BER at 10.5 dB for *(4×4)* antennas but reducing the complexity and delay time. For the purpose of comparison with Fig. 5, and according to [16] the detector will work 256 process of comparing for each transmitted symbol in case of $(M_t, N_r) = (4, 4)$, while decreasing this number to 4 with the model proposed in the results that appeared

CONCLUSIONS

In this paper the performance of the spatial multiplexing has been analyzed using MMSE, ZF and ML detectors. Results showed that the MMSE performs better than ZF by about *2.5 dB* at an error rate of 10^{-5} for QPSK for number of antennas *(2×2)*, but the higher the level of modulation their performance to be closed together so that it became identical at 16-PSK because the performance is degraded with ill conditioned channel matrix. But ZF is the simplest in terms of the complexity of the installation. On the other hand the performance of MMSE and ZF improved by *3 dB* for QPSK when increasing the number of antennas to *(3×3)*. From this it can be concluded that both have a weak performance in Rayleigh fading channel as each required *14 dB*, at least for the error rate of 10^{-4} in all cases.

The simulation results indicated that MLD is better than the MMSE and ZF types, but suffers from a significant increase in the complexity and the fact that the problem increases with increasing the number of transmitter antennas with high level of modulation, as explained in subse-ction 4-3. The proposal is to install the num-ber of transmitter antennas on 2 while incre-asing in the number of receiving antennas 2, 3, and 4. The results showed that the perfor-mance of MLD with $(M_t, N_r)= (2, 4)$ is delayed by *1.5 dB* from the regular system with $(M_t, N_r)= (2, 4)$, which can be considered a close relative to the minimize the size of the complex and time-delay.

REFERENCES

[1] Artes, H. D. Seethaler, and F. Hlaw-atsch, “Efficient detection algorithms for MIMO channels: A geometrical approach to approximate ML dete-ction”, *IEEE Transactions on Signal Processing*, Vol. 51, No. 11, pp. 2808-2820, November 2003.

[2] Golden, G. D. G. J. Foschini, R. A. Valenzuela, and P. W. Wolniansky, “Detection algorithm and initial laboratory results using V-BLAST space time communication archite-cture,” *Electron. Lett.*, vol. 35, no. 1, pp. 14–15, Jan. 1999.

[3]Adnan Ahmed Khan1, Sajid Bashir, Muhammad Naeem, Syed Ismail Shah and Xiaodong Li, “Symbol dete-ction in spatial multiplexing system using particle swarm optima-zation meta-heuristics”, *Int. J. Comm-un. Syst.* 2008.

[4] Viterbo, E. and J. Boutros, “A universal lattice code decoder for fading channels”, *IEEE Transactions on Information Theory*, Vol. 45, No. 5, pp. 1639-1642, July 1999.

[5] Pammer,V. Y. Delignon, W. Sawaya, and D. Boulinguez, “A low compl-exity suboptimal MIMO receiver: T he combined ZF-MLD algorithm”, *IEEE PIMRC’03*, Vol 3, pp. 2271 -2275, September 2003.

[6] Rugini, L. P. Banelli, and G. B. Giannakis, “MMSE-based local ML detection of linearly precoded OFDM signals”, *IEEE ICC’04*, Vol. 6, pp. 3270-3275, June 2004.

[7] Athaudage, R. N. M. Zhang, A. D. S. Jayalath, and T. D. Abhayapala, “ Classifier Based Low-Complexity C MIMO Detection for Spatial Multip-lexing Systems”, *Special Research Center for Ultra-Broadband Inform-ation Networks, IEEE,* 978-1-4244-2038-4/08, 2008.

[8] Paulraj, A. R. Nabar, and D. Gore,” *Introduction to space-time wireless commu-nications”*, Cambridge Univ-ersity Press, New York, NY, USA, 2008.

[9]Jeffrey G.Andrews, Arunabha Ghosh, and Rais Mohamed,” *Fundamentals of WiMAX: Understanding Broad-band Wireless Networking*”, Prentice Hall, 2007.

[10]George,V. Tsoulos “MIMO SYSTEM ECHNOLOGYFOR WIRELESS MMUNICATIONs” CRC Press Taylor & Francis Group, 2006.

[11]design for the global multi-chip fast-net interconnection module”, *The 14th Annual Meeting of the IEEE , USA, pp* 814 - 815 vol.2, 2001.

[12] Lozano and N. Jindal, A. “Transmit *on Wireless Communications, IEEE* VOL. 9, NO. 1, 2010.

[13] Paulraj,A. R. Nabar, and D. Gore, *"Introduction to space-time wireless commu-Nications"*, Cambridge Univ-ersity Press, New York, NY, USA, 2008.

[14] Foschini,G. J. "Layered space-time architecture for wireless commu- nication in a fading environment when using multi-element antennas, " *Bell Labs Tech*. J., vol. 1, no. 2, pp. 41-59, 1996.
[15] Bolcskei,H. D. Gesbert, C. Papadias, and A. J. van der Veen, Eds., *"Space-*

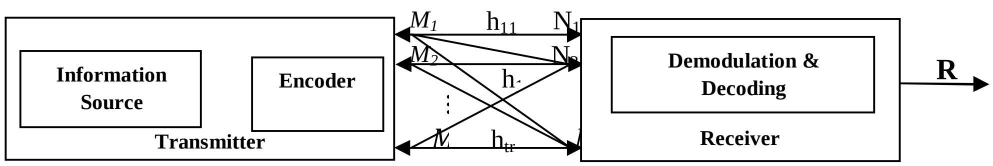

Figure (1): MIMO Communication System Block Diagram

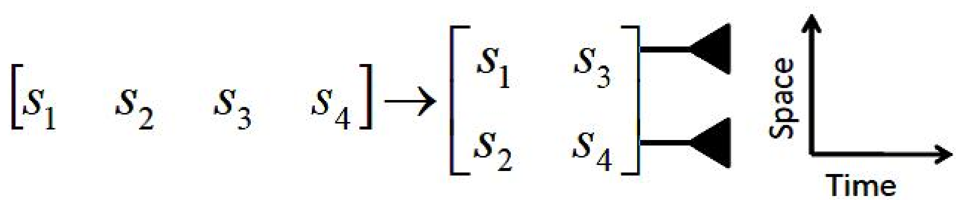

Figure (2): Schematic Representation of Spatial Multiplexing Encoding

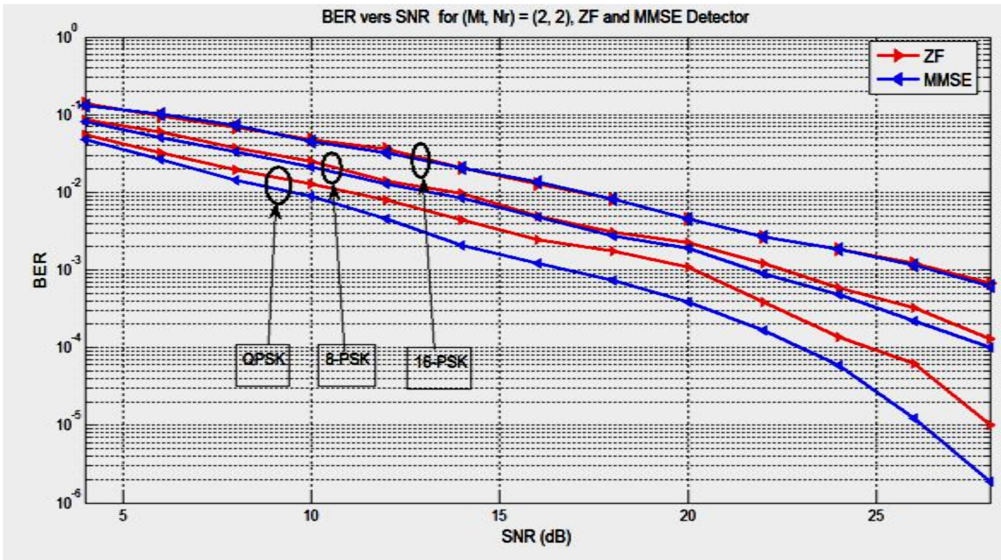

Figure (3) performance of (2 × 2) Spatial Multiplexing with ZF and MMSE Detector

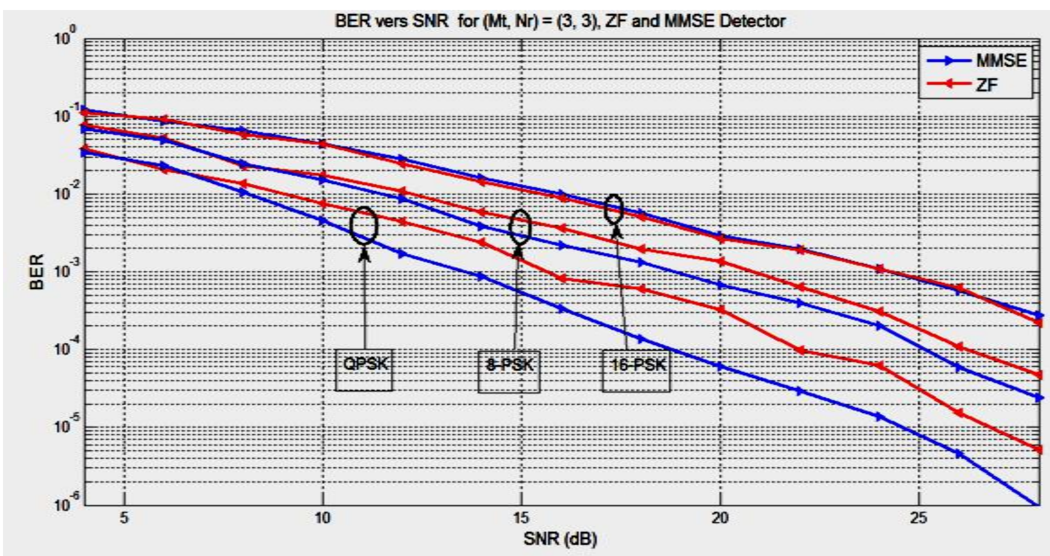

Figure (4) performance of (3 × 3) Spatial Multiplexing with ZF and MMSE Detector

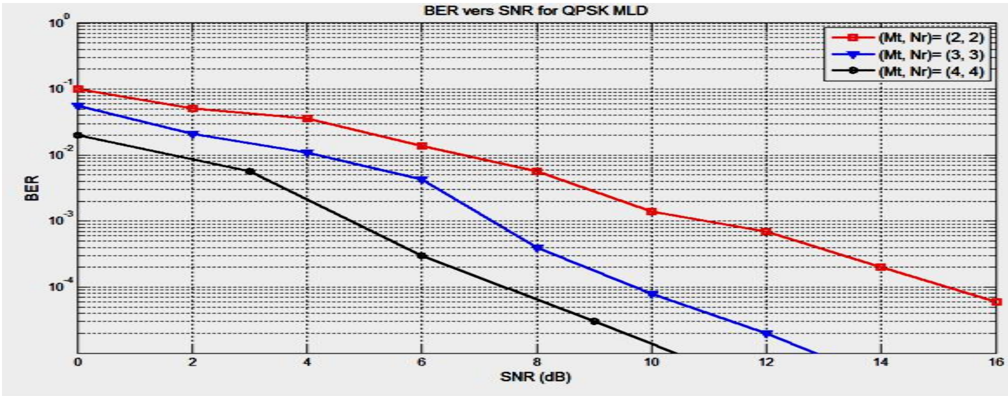

Figure (5) Performance of SM with various numbers of antennas for QPSK-MLD

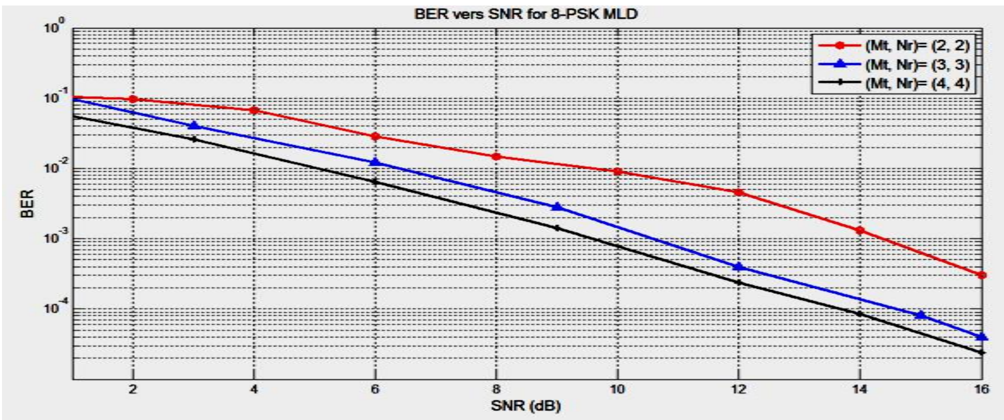

Figure (6) Performance of SM with various numbers of antennas for 8-PSK-MLD

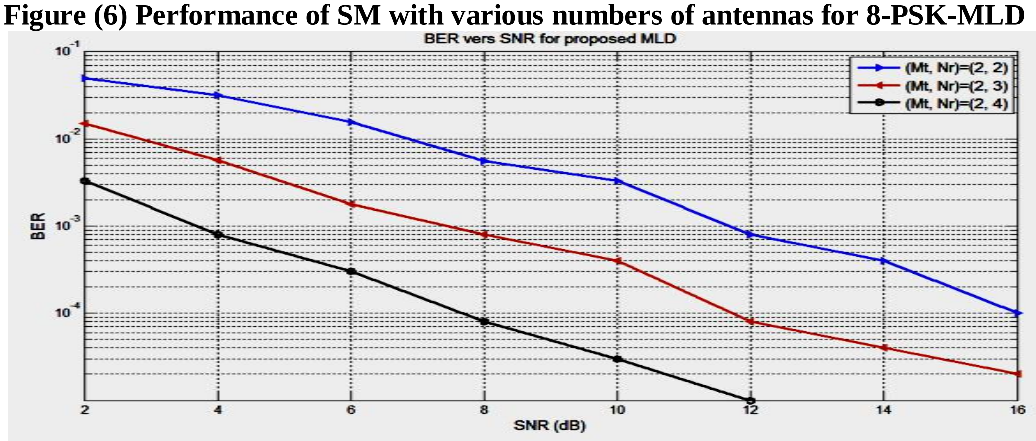

Figure (7) the performance of MLD with proposed numbers of antennas