ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ

ΠΟΛΥΤΕΧΝΙΚΗ ΣΧΟΛΗ

ΤΜΗΜΑ ΗΛΕΚΤΡΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ ΚΑΙ ΜΗΧΑΝΙΚΩΝ ΥΠΟΛΟΓΙΣΤΩΝ

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Διπλωματική Εργασία

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Επιβλέπων: Αργυρίου Αντώνιος

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UNIVERSITY OF THESSALY

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Spatial Modulation and Impact on Wireless Communication Privacy

Diploma Thesis

Makrygiannis Athanasios

Supervisor: Argyriou Antonios

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ΥΠΕΥΘΥΝΗ ΔΗΛΩΣΗ ΠΕΡΙ ΑΚΑΔΗΜΑΪΚΗΣ ΔΕΟΝΤΟΛΟΓΙΑΣ ΚΑΙ ΠΝΕΥΜΑΤΙΚΩΝ ΔΙΚΑΙΩΜΑΤΩΝ

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Ο Δηλών

Μακρυγιάννης Αθανάσιος

5 Αυγούστου 2020

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Makrygiannis Athanasios

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ΠΕΡΙΛΗΨΗ

Λόγω της ταχείας αύξησης τα τελευταία χρόνια της κίνησης δεδομένων που προέρχονται απο φορητές συσκευές, οι ερευνητές καλούνται να βρουν λύσεις για να διαχειριστούν αυτή τη ζήτηση. Κάθε νέα γενιά ασύρματων δικτύων έχει τον ίδιο στόχο, να εισάγει λύσεις που βελτιώνουν την επίδοση, είναι πιο αποδοτικές, είναι σε θέση να εξυπηρετούν ακόμη περισσότερους συνδρομητές και είναι εφικτές απο οικονομικής άποψης. Όλα αυτά πρέπει να επιτευχθούν και ταυτόχρονα να συμμορφωθούν με τους φυσικούς, οικονομικούς και νομικούς περιορισμούς που υφίστανται. Η πρόσφατα εγκατεστημένη πέμπτη γενιά δικτύων (5G) κατάφερε να βελτιωθεί σε κάθε πτυχή σε σύγκριση με την προηγούμενη γενιά και ήδη τα πρώτα δίκτυα έχουν αρχίσει να αναπτύσσονται. Τώρα η προσοχή για τα επόμενα χρόνια θα μετατοπιστεί ξανά στην έρευνα τεχνολογιών που θα εφαρμοστούν σε μελλοντικά πρότυπα δικτύων κινητής τηλεφωνίας. Αυτός είναι και ο στόχος αυτής της εργασίας. Ερευνούμε μια πολλά υποσχόμενη τεχνική χωρικής πολυπλεξίας που ονομάζεται Spatial Modulation (SM) η οποία εξαλείφει πολλά προβλήματα που σχετίζονται με τις MIMO διατάξεις, παρέχει υλοποιήσεις πομπού χαμηλής πολυπλοκότητας και απόδοση ισοδύναμη με σύγχρονες λύσεις. Χρησιμοποιούμε επίσης μια διαφορετική μέθοδο ανίχνευσης που βασίζεται στην αρχή Maximum Likelihood (ML) και επιτυγχάνει καλύτερα αποτελέσματα από τον αρχικό Maximal-Ratio Combining (MRC) ανιχνευτή. Χρησιμοποιούμε το Matlab για να προσομοιώσουμε την απόδοση του συστήματός μας, μετράμε το ποσοστό σφάλματος bit διαφορετικών συνδυασμών συστοιχιών κεραιών και σχημάτων διαμόρφωσης. Τα αποτελέσματα επιβεβαιώνουν την αναμενόμενη απόδοση και συμφωνούν με παρόμοιες μελέτες. Καταλήγουμε στο συμπέρασμα ότι πρόκειται για μια πολλά υποσχόμενη τεχνική που έχει περιθώρια περαιτέρω βελτίωσης και θα μπορούσε να αποτελέσει μια βιώσιμη λύση λόγω του χαμηλού κόστους σχεδίασης του πομποδέκτη. Η μελλοντική έρευνα θα μπορούσε επίσης να διερευνήσει τρόπους για να καταστήσει την αρχιτεκτονική SM πιο ασφαλή, μια σημαντική πτυχή που θα καταστήσει την τεχνολογία ακόμη πιο ανταγωνιστική στο μέλλον.

ABSTRACT

Due to the rapid increase in mobile traffic in recent years, researchers are required to find solutions to manage this demand. Every new generation of mobile networks has the same goal, introduce solutions that improve performance, are more efficient, can serve even more subscribers, and are cost-effective. All these have to be achieved and at the same time comply with the physical, financial, and legal restrictions that exist. The recently introduced fifth generation of networks managed to improve on every aspect compared to the previous generation and already the first networks have begun to appear. Now the focus for the next years will shift again into the research of technologies to be implemented into future standards of mobile networks. That is the aim of this paper. We research a promising spatial multiplexing technique called Spatial Modulation (SM) which eliminates many MIMO related problems and provides low complexity transmitter designs with equivalent performance to modern solutions. We also use a different detection method which is based on the Maximum Likelihood (ML) principle and achieves better results than the original Maximal-Ratio Combining (MRC) detector. We use Matlab to simulate the performance of our system, we measure the Bit Error Rate of different combinations of antenna configurations and modulation schemes. The results confirm the claimed performance and agree with similar studies. We conclude that it is about a promising technique that has room for further improvement and could be a viable solution due to the low cost of the transceiver design. Future research could also explore ways to make SM architecture more secure, an important aspect that will make the technology even more competitive in the future.

CONTENTS

CHAPTER 1

INTRODUCTION

The huge rise of the mobile market in the last decades spiked the number of subscribers and as a result the consumption of mobile data traffic. The projections show that this upward trend is going to continue [1], hence mobile operators need to keep finding solutions to make the most of the available spectrum. Solutions in that direction have been implemented since the introduction of the fourth generation of mobile networks (4G). Orthogonal Frequency-Division Multiple Access (OFDMA) [2], Multiple-Input and Multiple-Output (MIMO)) [3], Dynamic Channel Allocation (DCA)) [4], and Channel-Dependent Scheduling (CDS) [5] are some of the technologies that aimed to increase the spectral efficiency. In the fifth generation of networks (5G) new frequencies were introduced as well as technologies such as Massive MIMO and Beamforming to further improve on that aspect [6]. They all succeed in doing so, without missing the drawbacks, but the ever-increasing demand always dictates for better performing and more efficient solutions. That is why the last decade a family of techniques called Index Modulation (IM) caught the attention of the scientific community. They are based on the idea that a fraction of bits are not transmitted explicitly but through the realization of the channel by the receiver and the rest of the bits are transmitted through a modulated symbol. IM techniques by exploiting this novel idea manage to provide improved spectral efficiency compared to competing MIMO architectures while at the same time eliminate many of the MIMO shortcomings such as Inter-channel Interference (ICI) and Inter-antenna Synchronization (IAS). There is active ongoing research into this category of techniques and many versions have arisen from. The main schemes that emerged from spanning the IM into the time, space, frequency, and channel domains are Time Domain-Index Modulation (TD-IM), Spatial Modulation (SM), Index Modulation-Aided Orthogonal Frequency Division Multiplexing (IM-OFDM) and Media-Based Modulation (MBM) respectively [7].

This paper examines the performance of the Spatial Modulation technique which was firstly proposed by Mesleh, Haas, Ahn, and Yun [8]. This technique uses the antenna indexes as an information-carrying unit apart from the Amplitude Phase Modulation (APM) symbols. It assumes no correlation between the channel paths and Channel State Information (CSI) [9] at the receiver, two important parameters for the detection. By allowing only one antenna of the array to transmit at a time it manages to provide the transmitted symbol with a unique signature. This results from the interaction of the symbol with the channel. That way the antenna index information is added implicitly to the bits that are being transferred. The receiver will make a joint detection of the original bits by doing an exhaustive comparison of all the combinations that could have arisen with the received symbol. We base our testing on the improved Maximum likelihood (ML) detection method proposed by Jeganathans, Ghrayeb, and Szczecinski [10]. The ML detector chooses as its prediction the combination with the minimum Euclidean distance from the received symbol. All of the above are discussed in more detail during the course of the paper.

The rest of the paper is organized into four chapters which are ordered as follows. In the second chapter, we dive into a detailed presentation of the system model, focusing more on the transmitting side. In the third chapter, we shift our focus to the receiver and mainly on the detection algorithm which we accompany with a Matlab implementation to extend the understanding of the reader. In the fourth chapter, we provide detailed results of the system's performance accompanied by some useful insights from relevant papers. Finally, in the last chapter, we conclude our paper.

CHAPTER 2

SYSTEM MODEL

Before proceeding to the description of the system model, we first have to declare some notations and assumptions we have made. We assign capital letters to matrices and small letters to vectors and scalar values. The letter 'M' denotes the cardinality of the modulation scheme, M-QAM or M-PSK. N_t is the number of transmitting and N_r the number of receiving antennas, both must be a power of two integers. H is the MIMO channel matrix and it has size (N_r, N_t). h_{i,N_t} is a column vector of size (N_r, 1) containing the paths between the transmitting antenna and all the receiving ones. The channel matrix is composed of complex random variables whose real and imaginary parts are independent normally distributed random variables with zero mean and unit variance ($h_{i,j}$ ~CN (0, 1)). The added thermal noise w(k) is also a vector of random variables with size (N_r, 1), following the model of additive white Gaussian noise (AWGN), where w_i ~CN (0, No). Finally, for the estimated values and vectors, we use the tilde '~' character as an accent above the letters.

In this paper, we use a spatial multiplexing MIMO technique called Spatial Modulation (SM) which was first defined by Mesleh et al. [8]. The system model is presented in figure 2.1. There we have a vector q(k) of size N_b bits that have to be transmitted. We divide this bitstream into blocks of n=$log_2(N_t)$+log_2(M) bits. From each block, we use the first $log_2(N_t)$ bits to determine the index l of the transmitting antenna and the last log_2(M) bits for symbol encoding. For example, a system with four transmitting antennas ($N_t = 4$) and a BPSK modulation ($M = 2$) will create blocks of n=log_2(4)+log_2(2)=2+1=3 bits, the first two bits will determine the antenna index and the last one the symbol. The spectral efficiency of the used example is n=3 bits and we can affect it either by changing the number of transmitting antennas or the modulation type. In case we want to match the performance of the current system, we could use two transmitting antennas and QPSK modulation, then the spectral efficiency would also be n=log_2(2)+log_2(4)=1+2=3 bits. How bit sequences are interpreted by the transmitter and how the specifications of the system (number of antennas, modulation scheme) affect that, is presented in more detail in figure 2.2. As for the total information, the transmitted symbol will carry, these are not only the bits that modulated into the symbol but also the bits that took part in the selection of the antenna. The antenna index bits, in contrast with the symbol bits, are transferred implicitly by the effect of the channel path h_{i,N_t} on the send symbol. This effect alters, depending on the transmitting antenna and that is what SM exploits. It relies on the diversity that exists between the channel paths and uses it as a means to convey additional information. The lesser correlation these paths have, the better the chances of the detector in the receiver, to correctly determine the transmitting antenna. We will further examine this topic in chapter 3, "Main Algorithm Design".

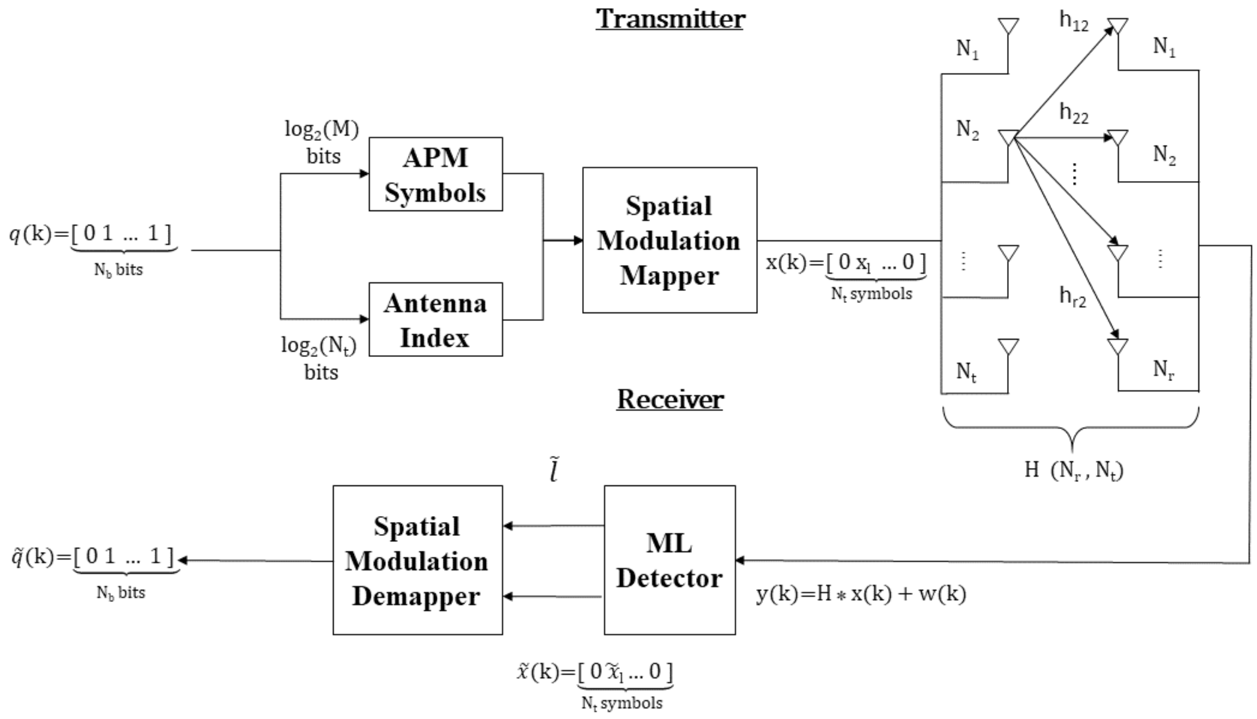
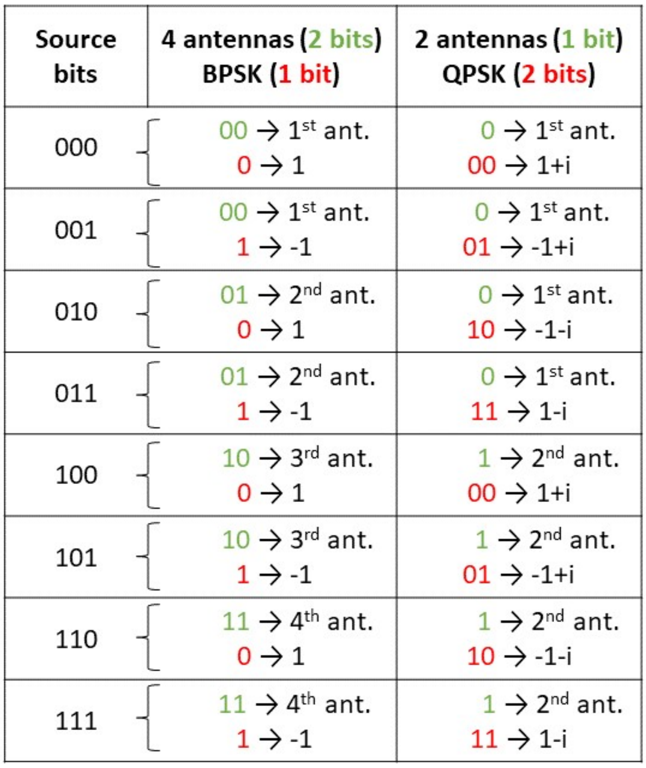


Figure 2.1: Spatial Modulation System Model

After converting the block bits appropriately, the Spatial Modulation mapper uses this information to create a vector x(k) of size (N_t, 1). It places the modulated symbol x_l in the position l that corresponds to the antenna index. Every other position on the vector will be zero, indicating that nothing will be sent from the remaining antennas. SM mapper is going to produce as many x(k) vectors as there are blocks of bits. For example, in a bitstream q(k) of size N_b=10^4 and n=3, there are going to be 3.333 blocks of bits which will pass through SM mapper and produce 3.333 x(k) vectors. In a system with four antennas and BPSK modulation, if a block has a sequence of bits "010", as we can see from the table in figure 2.2, this will result in a symbol "1" being sent from the 2^{nd} antenna. The vector produced by the SM mapper will be $x(k)$ = [0 1 0 0 $]^T$. Following the same process, every block will be converted to vector and fed to the transmitting antennas for sending.



Source bits	4 antennas (2 bits) BPSK (1 bit)	2 antennas (1 bit) QPSK (2 bits)
000	00 → 1st ant. 0 → 1	0 → 1st ant. 00 → 1+i
001	00 → 1st ant. 1 → -1	0 → 1st ant. 01 → -1+i
010	01 → 2nd ant. 0 → 1	0 → 1st ant. 10 → -1-i
011	01 → 2nd ant. 1 → -1	0 → 1st ant. 11 → 1-i
100	10 → 3rd ant. 0 → 1	1 → 2nd ant. 00 → 1+i
101	10 → 3rd ant. 1 → -1	1 → 2nd ant. 01 → -1+i
110	11 → 4th ant. 0 → 1	1 → 2nd ant. 10 → -1-i
111	11 → 4th ant. 1 → -1	1 → 2nd ant. 11 → 1-i

Figure 2.2: SM Mapping table of two different setups with spectral efficiency of 3 bits

As we previously explained, because of the zeroes in the column vector x(k), during every transmission only one antenna will participate. The sent symbol will have to traverse through a Rayleigh flat-fading channel [11]. The channel is described by a matrix H of size (N_r, N_t). Each column of H represents the paths a symbol from N_t antenna will follow to reach every antenna on the receiving end. In a case where the first antenna is transmitting and four receiving at the other side, the equivalent column vector will be $h_{i,1} = [\ h_{1,1},\ h_{2,1},\ h_{3,1},\ h_{4,1}\ ]^T$. As a result, the symbol will be multiplied with the aforementioned channel gain $h_{i,1}$, and AWGN noise will be added at the receiving end. The final form of the received signal y will be a vector of size (N_r, 1), containing N_r versions of the transmitted symbol as received by each N_r antenna. This process will be repeated until every block-vector arrives at the receiver. The received symbol can be expressed by

$$y(k) = h_{i,N_t} * x_l + w(k)$$

or more generally

$$y(k) = H * x(k) + w(k)$$

CHAPTER 3

MAIN ALGORITHM DESIGN

At the receiver, we use an optimal detector as proposed by Jeganathans et al. [10]. The detector is proven to perform better than the Maximal-ratio combining (MRC), introduced in [8]. It is based on the ML principle [12] and expects CSI in order to work. This can be done through channel estimation but in this paper we are not implementing any type, we assume perfect knowledge.

As mentioned in the previous chapter, the traversing symbol will be multiplied with every element of the h_{i,N_t} vector and AWGN noise will be added before reaching the detector. This interaction will create N_r unique variations of the transmitted symbol. For example, in a setup used before, with the first antenna transmitting and four receiving ($N_r = 4$), the resulting vector will be

$$y(k) = h_{i,1} * x_l + w(k) =$$

$$= [\ h_{1,1} * x_l + w(1),\ h_{2,1} * x_l + w(2),\ h_{3,1} * x_l + w(3),\ h_{4,1} * x_l + w(4)\ ]^T$$

The ML detector will compute the Euclidean distances between the received signal y(k) and every possible combination that could have been sent from the transmitter. These combinations could be produced by multiplying the symbols that exist in the three-dimensional constellation diagram and the h_{i,N_t} column vectors of H. The three-dimensional constellation diagram is a classic constellation diagram with an added third dimension, that of antenna index. An example of such a diagram for QPSK modulation and four transmit antennas can be seen in figure 3.3 as first presented in [13]. This computation is achievable because of CSI and knowledge of all the possible symbols that can occur based on the chosen modulation.

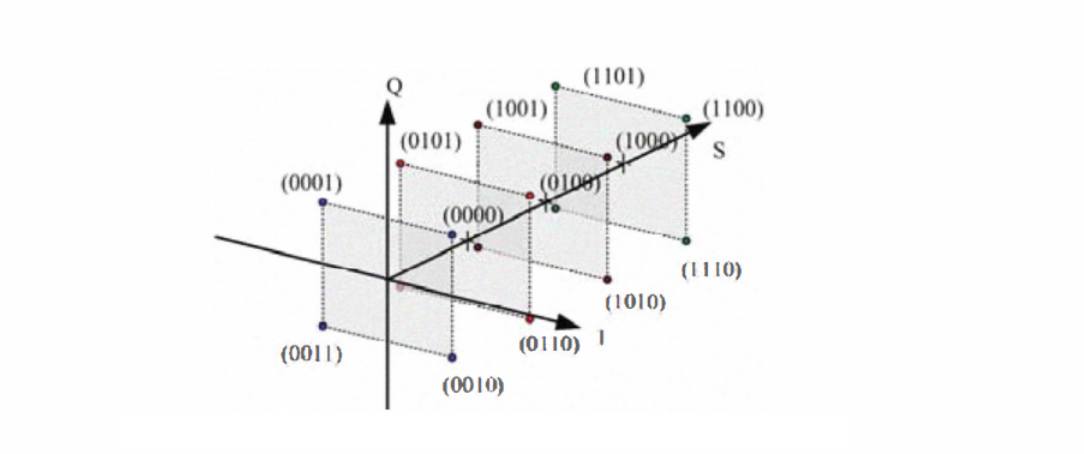


Figure 3.3: Three-dimensional Constellation diagram [13]

As we can observe, the less correlation there is between the column vectors of H, the more chances there are for the estimation to be correct. That happens because, as uncorrelation grows between h_{i,N_t} vectors, this will result in less similar outcomes, thus less likelihood for the detector to make an error. The detector after all these calculations will find the combination that has the minimum Euclidean distance from the received symbol and pick it as its prediction. It will have first to estimate $N_t * N_r * M$ distances before reaching a decision, which will inevitably increase the complexity of the algorithm. It is clear that aiming for the optimal result hits the performance of our system. Mingxi et al. in [13] proposed a new Antenna Index-List (AI-List) algorithm that aims to achieve comparable performance to ML but with less complexity.

3.0.1 Example of ML detector in Matlab

To further extend the understanding of the ML detector, we present our implementation of the algorithm in Matlab below:

```
tx_est=zeros(1,size(tx_transm,2));
x_transm_est=zeros(1,size(sym_transm,2));
for l=1:size(sym_transm,2)
    distance=zeros(Nt,length(const));
    for k=1:length(const)
        for j=1:Nt
            distance(j,k)=norm(y(:,l)-H(:,j)*const(k));
        end
        [min_value, min_row] = min(distance);
        [total_min_value, min_col] = min(min_value);
        tx_est(1,l)=min_row(min_col);
        x_transm_est(1,l)=const(min_col);
    end
end
sym_transm_est(i,:)=x_transm_est;
tx_transm_est(i,:)=tx_est;
```

We are calculating the aforementioned Euclidean distances inside three nested "for" loops. The inner one iterates for every transmitting antenna, essentially changing the column vector h_{i,N_t}, by which the symbol will be multiplied to, at every loop. The middle one loops for every possible symbol of the constellation diagram and the outer one changes the sent symbol y(k) for the process to compute every received symbol. When the inner loop finishes, we have collected the distances between y(k) and a specific symbol sent from every transmitting antenna. We find the minimum value of those distances and store it. When the middle loop finishes, we have collected the minimum values of every possible symbol and we choose as our estimation of the sent symbol, the smallest one. This process is finished when the smallest distance has been calculated for every received symbol.

The above process can be generally formulated as

$$min \| \; y(k) - h_{i,N_t} * symbols(i) \; \|$$

where $symbols(i)$ takes the value of every possible symbol existing on the three-dimensional constellation diagram. After finding the smallest distance for a received symbol, it can then extract the appropriate information about the antenna index and the sent symbol. The two predictions will be forwarded to the SM demapper for reversing the process done in the transmitter. The output of that process will be a block of bits of size n. For the estimated initial bitstream to be reconstructed, every retrieved block will have to be added to the q̃(k) vector.

CHAPTER 4

RESULTS

In our simulations, we used the Spatial Modulation technique [8] in a Rayleigh flat-fading channel with various antenna configurations. The MIMO setups used are 2x2, 4x4, 8x8, and 16x16. The SNR and channel impulse response is considered known at the receiver, no channel estimation method is used. We have AWGN with random values following the normal distribution with zero mean and noise power of No/2. We use several modulation methods both M-PSK and M-QAM. The transmit power is normalized to 1 Watt and we are applying the Monte Carlo technique by sending 10^5 randomly generated bits for each value of SNR. Before continuing, it is useful to remind that in SM the spectral efficiency depends on the combination of antennas and modulation. It can be calculated by applying the following formula, n=$log_2(N_t)$+log_2(M) where N_t is the number of transmitting antennas and M the modulation scheme being used.

In figures 4.4 and 4.5, we have on the vertical axis in logarithmic scale the Bit Error Rate of the modulation used and on the horizontal axis the Signal to Noise Ratio values in dB. We are presenting the performance of our system in a 4x4 MIMO antenna configuration using the SM technique. We can observe that the 4QAM Modulation achieves a better BER performance for SNR values from 0dB to 20dB and spectral efficiency of 4 bit/s/Hz. From 20dB to 30dB though the BER performance is the same between 4QAM and 32QAM but we prefer the latter because of the better spectral efficiency (7 bit/s/Hz).

In general, running simulations also for 2x2, 8x8 and 16x16 MIMO systems shown that, considering a static modulation scheme, increasing the number of antennas always benefits the performance of BER and the spectral efficiency. Meaning that if we can increase our transmitting and receiving antennas we would benefit in both throughput and error rate. If we can not expand our antenna array then the best performing choice, for SNR up until 5dB, is the 4QAM modulation on every configuration. After that, the more antennas you have, the earlier you can increase your modulation scheme as noise decreases. We provide a more detailed look at the aforementioned in the following figure 4.6, where located inside the parentheses is the BER results.

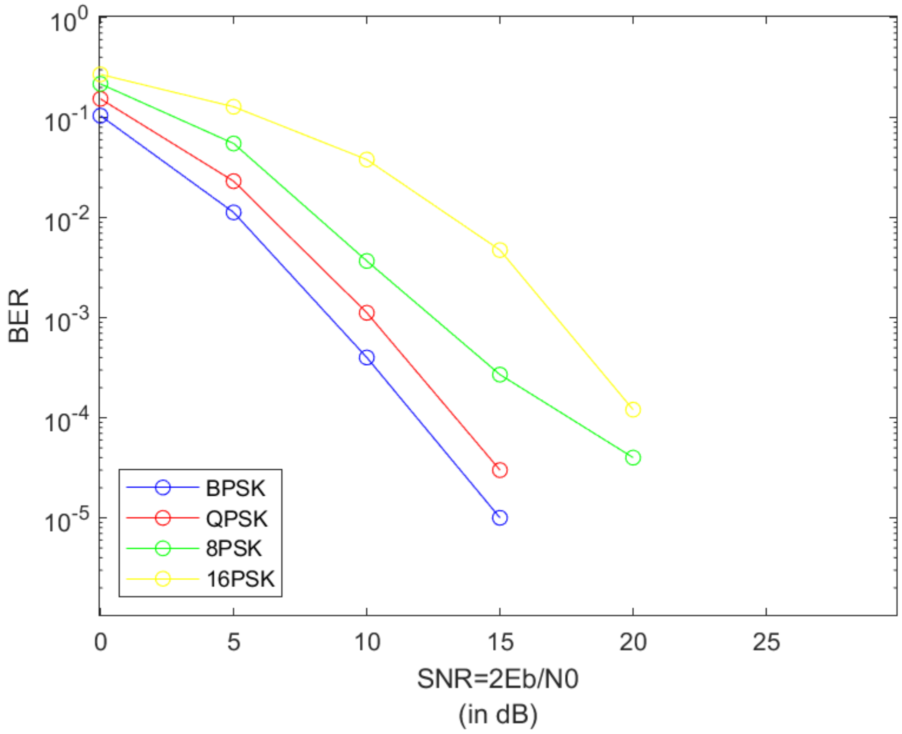


Figure 4.4: Three bits transmission in a 4x4 MIMO channel using various PSK modulations

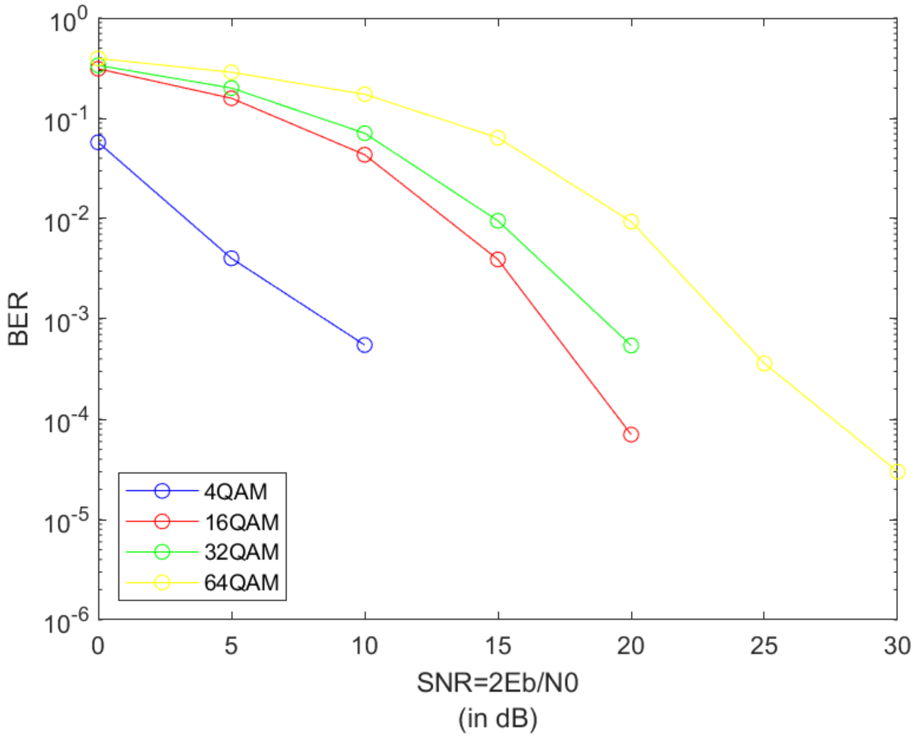
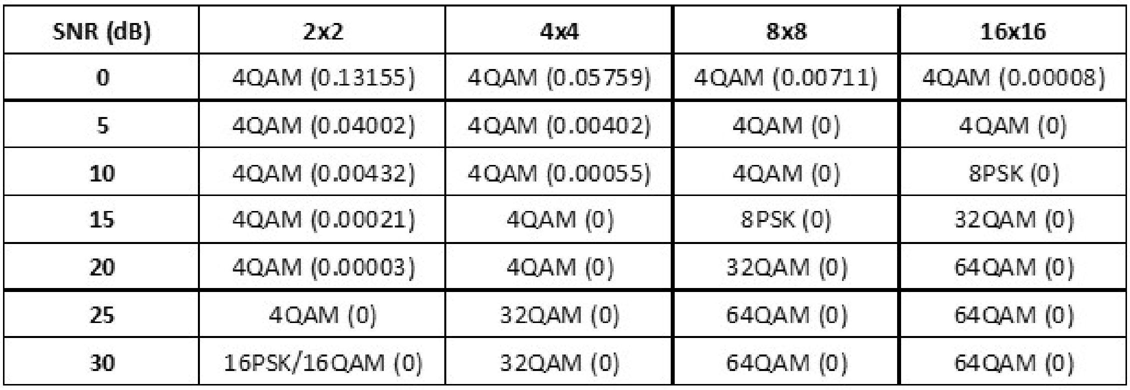


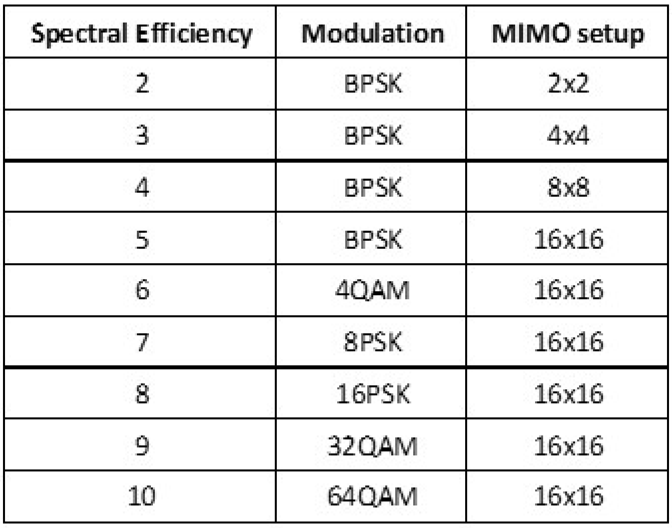
Figure 4.5: Three bits transmission in a 4x4 MIMO channel using various QAM modulations



SNR (dB)	2x2	4x4	8x8	16x16
0	4QAM (0.13155)	4QAM (0.05759)	4QAM (0.00711)	4QAM (0.00008)
5	4QAM (0.04002)	4QAM (0.00402)	4QAM (0)	4QAM (0)
10	4QAM (0.00432)	4QAM (0.00055)	4QAM (0)	8PSK (0)
15	4QAM (0.00021)	4QAM (0)	8PSK (0)	32QAM (0)
20	4QAM (0.00003)	4QAM (0)	32QAM (0)	64QAM (0)
25	4QAM (0)	32QAM (0)	64QAM (0)	64QAM (0)
30	16PSK/16QAM (0)	32QAM (0)	64QAM (0)	64QAM (0)

Figure 4.6: Best performing modulation scheme per MIMO configuration

As mentioned before, a given spectral efficiency can be achieved by many combinations of antenna configurations and modulation schemes. So, useful observations can be made when we compare them in terms of errors and throughput, given the provided spectral efficiency. In this regard, our simulations showed a clear advantage of BPSK modulation in every MIMO setup (2x2, 4x4, 8x8, and 16x16) until reaching its limit, an efficiency of 5 bit/s/Hz. An increase in the efficiency, above 5 bit/s/Hz, can be obtained by using a 16x16 setup and gradually increasing the modulation scheme. All the tested combinations are listed in figure 4.7 below.



Spectral Efficiency	Modulation	MIMO setup
2	BPSK	2x2
3	BPSK	4x4
4	BPSK	8x8
5	BPSK	16x16
6	4QAM	16x16
7	8PSK	16x16
8	16PSK	16x16
9	32QAM	16x16
10	64QAM	16x16

Figure 4.7: Best performing combination per spectral efficiency

As for the performance of SM compared to other transmission techniques, the results of [10], [13], [14] shown SM outperforming most of the comparing techniques under the same conditions. More specifically, Jeganathan et al. in [10] used SM with an optimal ML detector in a 4x4 antenna configuration with BPSK modulation, a simple APM transmitted symbol with one transmitting antenna and 8QAM modulation and a Vertical-Bell Laboratories Layered Space-Time (V-BLAST) with Minimum Mean Square Error (MMSE), Ordered Successive Interference Cancellation (OSIC) detector, using three transmitting antennas and BPSK modulation. All of the above targeted at a performance of 3 bit/s/Hz. They found SM to achieve results better by 3dB over the APM and by 1dB over the V-BLAST technique.

Similar results found Mingxi et al. [13] when tested the performance of SM on 6 and 8 bit/s/Hz. They evaluated SM and V-BLAST techniques, various SM detectors such as Normalized Maximum Ratio Combination (NMRC), Zero Forcing (ZF), ML, AI-List, and several antenna-modulation combinations. They concluded that the best performing combination at 6 bit/s/Hz was SM with an ML detector with close second again the SM with the AI-List algorithm. At 8 bit/s/Hz results were a little different as V-BLAST with ZF was superior for SNR values lower than 18dB and SM taking over for greater values of dB. One thing was conclusive in all tests, the SM-NMRC combination was outperformed by every other combination.

Wen et al. [14] with their testing at 8 bit/s/Hz found that SM with ML performs better than V-BLAST under the same number of receiving antennas, except very low dB of SNR. They also tested SM with ML against a Signal Vector-Based List (SVBL) detector and found that SVBL with $L = 1$ performs worse than ML but if $1 < L < N_t$ then SVBL achieves very close performance to SM-ML.

CHAPTER 5

CONCLUSION

In this paper, we have presented a promising MIMO technique called Spatial Modulation. A transmission technique, part of the Index Modulation family. It stands out from its competing techniques because it uses the transmitting antenna's position as an additional way to implicitly transmit information through the channel. Because of the use of one antenna at each transmission, we need one RF chain and thus ending up with a lower complexity transmitter. This results at a reduced cost for the transmitter and opens the possibility of constructing a larger antenna array with lower total complexity compared to competing systems. As a result of the one transmitting antenna principle, we avoid ICI at the receiver and the need for IAS. Eliminating much of the MIMO drawbacks and simultaneously achieving comparable results is what draw our attention to examine SM. Our results confirmed those claims and revealed a highly competitive performance in most of the cases compared to popular architectures. Much work has already been done by the scientific community on Index modulation techniques as a whole and will continue to. We think, apart from performance improvements, that there is also room for advancing this technique in terms of security. A field of much importance if this technique is going to be implemented in future telecommunication standards.

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ACRONYMS AND ABBREVIATIONS

4G Fourth Generation
5G Fifth Generation
AI-List Antenna Index-List
APM Amplitude Phase Modulation
AWGN Additive White Gaussian Noise
BER Bit Error Ratio
CDS Channel-Dependent Scheduling
CSI Channel State Information
DCA Dynamic Channel Allocation
IAS Inter-Antenna Synchronization
ICI Inter-Channel Interference
IM Index Modulation
IM-OFDM Index Modulation-Aided Orthogonal Frequency Division Multiplexing
MBM Media-Based Modulation
MIMO Multiple-Input and Multiple-Output
ML Maximum Likelihood
MMSE Minimum Mean Square Error
MRC Maximal-Ratio Combining
NMRC Normalized Maximum Ratio Combination
OFDMA Orthogonal Frequency-Division Multiple Access
OSIC Ordered Successive Interference Cancellation
PSK Phase Shift Keying
QAM Quadrature Amplitude Modulation
QPSK Quadrature Phase Shift Keying
SM Spatial Modulation
SNR Signal to Noise Ratio

SVBL Signal Vector-Based List

TD-IM Time Domain-Index Modulation

V-BLAST Vertical-Bell Laboratories Layered Space-Time

ZF Zero Forcing