A PARALLEL DETECTION AND DECODING TECHNIQUE FOR MIMO COMMUNICATION SYSTEMS

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Abstract - Two of important requirements of fifth generation new radio (5G- NR) access networks are very high capacity and ultra-reliability. In this paper, we proposed a V-BLAST $N_t \times N_r$ MIMO system that is analyzed and improved, and expected to achieve both very high throughput and ultra-high reliability simultaneously. A new detection technique called parallel detection and decoding algorithm is developed and compared with existing linear detection algorithms. It was seen that the proposed technique increases the speed of signal transmission, provides high throughput and prevents error propagation, which may be present in serial decoding techniques. The new algorithm reduces the bit error probability and increases the capacity simultaneously without using STC. However, it was seen that the BER of MIMO systems using the proposed algorithm is higher than a similar systems using standard STC technique, and it is lower than system using MGSTCs technique. Simulation results show the advantages of the proposed technique.

Index terms - Index Terms_ MIMO, Parallel Detection and Decoding, V-BLAST.

I. INTRODUCTION

The major challenge of for 4G- LTE and 5G New Radio (NR) is to maximize both the reliability and data rate of Multiple Input Multiple Output (MIMO) techniques simultaneously [19] [21]. The goal of the MIMO is to combat or exploit the multipath propagations between multiple transmit and receive antennas through two separate techniques, which are called spatial diversity and spatial multiplexing [4]. Spatial diversity is a technique that improves the reliability of the transmission through transmitting multiple replicas of the same signal by using space time coding (STC) method [3]. This implies that spatial diversity combats fading in the multipath channel.

There are two common metrics that characterize the amount of spatial diversity, which are diversity order and diversity gain [4]. Diversity order represents the number of independent replicas of the same transmitted signal that are available at the receiver. In an$N_t \times N_r$ MIMO system, there are N_tN_r propagation paths between the N_t transmit antennas and the N_r receive antennas. The general property of the MIMO communication system that holds for many modulation types in Rayleigh fading channel is that the diversity order (N_d) equals to the diversity gain (G_d), and this system achieves full diversity if the $N_d = G_d = N_tN_r$.
However; spatial multiplexing technique exploits multipath propagation to transmit the information at a rate up to channel capacity (channel capacity improvements) without increasing the required bandwidth by using the spatial de-multiplexing method.

In this paper, we propose a novel detection and decoding algorithm for MIMO communication systems. Our algorithm improves the reliability of transmission without employing STC, and it prevents any possible error propagation that may be presented in the other methods using serial detection and decoding algorithms. The performance of the proposed method compared with current methods, which include STC and SM techniques.

The performance of MIMO communication systems in Rayleigh fading environment is improved by the proposed decoding technique. This technique exploits the multipath propagation to detect and decode N_t received symbols simultaneously and independently. The rest of this paper is organized as follows. Section II provides the transmitter model and its related expressions. Section III explains the proposed detection algorithm. Simulation results are provided and discussed in section IV. Finally, we conclude in section V.

II. TRANSMITTER MODEL

This section focuses on the transmitter. The data stream after channel encoder [6] splits into N_t data streams, each of which modulated separately and transmitted by its respective antenna as shown in Figure.1 [4].

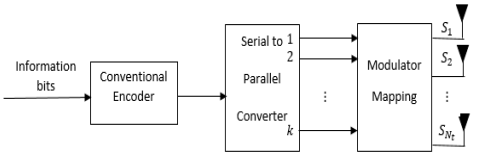


Figure 1: MIMO Communication Transmitter Model Using V-BLAST.

This transmitter is implemented using V-BLAST architecture and transmits N_t modulated symbols over one symbol period. Therefore, the transmitted signal matrix Sis expressed as follows.

$$S = \begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_{N_t} \end{bmatrix} (1)$$

It is assumed the channel is Rayleigh fading and channel state information is known at the receiver. Therefore the channel matrix is

$$H = \begin{bmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,N_t} \\ h_{2,1} & h_{2,2} & \dots & h_{2,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \dots & h_{N_r,N_t} \end{bmatrix} \quad (2)$$

The received signal matrix in the Rayleigh fading environments is [2], [3] and [4].

$$R = \sqrt{\rho}\begin{bmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,N_t} \\ h_{2,1} & h_{2,2} & \dots & h_{2,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \dots & h_{N_r,N_t} \end{bmatrix}\begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_{N_t} \end{bmatrix} + \begin{bmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_{N_r} \end{bmatrix} (3)$$

Where Z_i is the noise term that is received with the $i-th$ receive antenna.

III. PARALLEL DETECTION AND DECODING TECHNIQUE [16]

Using parallel detection and decoding technique shown in [16-17] and [23], all received symbols will be detected and decoded independently and simultaneously. In addition, with the new model, $N_r$replicas for each transmitted symbol are extracted as the following procedure shows. We decompose the channel matrix $H(N_r \times N_t)$as follows [4].

$$H = [H_1 \quad H_2 \quad \dots \quad H_{N_t}] (4)$$

Where H_1 $(N_r \times 1)$ refers to the channel component vector that is associated with the transmitted symbolS_1. Thus, the received interference that is associated with the transmitted symbol $S_1$is cancelled through truncating the resulting channel matrix

$H_{h-1}(N_r \times (N_t - 1))$, where

$$H_{h-1} = [H_2 \quad \dots \quad H_{N_t}] \quad (5)$$

$$\text{where } H_j = \begin{bmatrix} h_{1,j} \\ h_{2,j} \\ \vdots \\ h_{N_r j} \end{bmatrix} \quad (6)$$

Figure.2 shows the receiver model that uses the proposed parallel detection and decoding algorithm.

From Figure.2, the received signal components are

$$\begin{aligned} r_1 &= \sqrt{\rho}\left(h_{1,1}S_1 + h_{1,2}S_2 + \dots + h_{1,N_t}S_{N_t}\right) + Z_1, \\ r_2 &= \sqrt{\rho}\left(h_{2,1}S_1 + h_{2,2}S_2 + \dots + h_{2,N_t}S_{N_t}\right) + Z_2, \quad (7) \\ r_{N_r} &= \sqrt{\rho}\left(h_{N_r,1}S_1 + h_{N_r,2}S_2 + \dots + h_{N_r,N_t}S_{N_t}\right) + Z_{N_r} \end{aligned}$$

The output of the Front End Receiver block provides the received signal in matrix form, R, as it is shown in

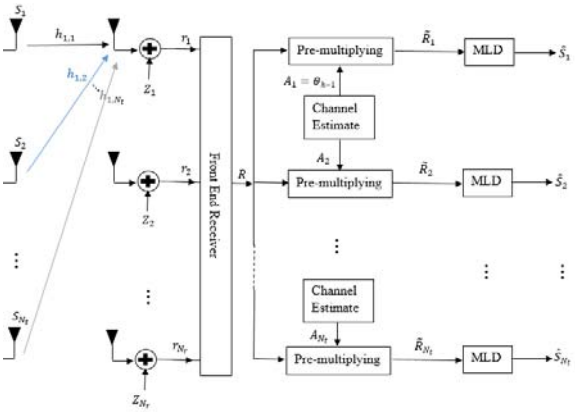


Figure 2: Proposed Detection and Decoding Model for MIMO Communication Systems.

(3).To decode the symbol (S_1) that is transmitted over the first transmitting antenna and to suppress all the remaining signals which constitute interference that are associated with H_{h-1}, it is necessary that the number of receiving antennas satisfies $N_r \geq N_t$. This suppression can be achieved through pre-multiplying the received signal matrix R by the matrix Θ_{h-1} as shown in the following equation.

$$\tilde{R}_1 \triangleq \Theta_{h-1}R (8)$$

Where $\tilde{R}_1$is the estimate of the received signal after interference suppression, and Θ_{h-1} is the set of null space vectors of H_{h-1} $(N_r \times (N_t - 1))$, which implies the following equation.

$$\Theta_{h-1}H_{h-1} = 0_{[(N_r - N_t + 1)\times(N_t - 1)]} (9)$$

Under the assumption of Rayleigh distribution, the received signal matrix is$R = \sqrt{\rho}HS + Z$[2], [8]. Using the previous equations, it is easy to verify that $\tilde{R}_1$can be express as:

$$\tilde{R}_1 = \sqrt{\rho}H_1^{(eff)}S_1 + \bar{Z}_1 \quad (10)$$

Where $H_1^{(eff)}$ refers to the effective channel matrix that is associated with decoding S_1 and it represents the following.

$$H_1^{(eff)} = \Theta_{h-1}H_1 (11)$$

The noise term is$\bar{Z}_1 = \Theta_{h-1}Z$. It is interesting to note expression (10) indicates that the energy of $\tilde{R}_1$ is only from the S_1 symbol. This demonstrates that the interferences from all remaining transmitted symbols are nullified. In addition, N_r replicas of S_1 symbol are available at the receiver. This showsthat the proposed model achieves spatial diversity without using STC technique. We can decode symbol S_1 by applying maximum likelihood decoding algorithm to (10). Let $\hat{S}_1$represents the estimate of S_1, which is computed using MLD as shown below.

$$\hat{S}_1 = \arg\min_{\{S_1\}}\left\{\left\|\tilde{R}_1 - \sqrt{\rho}H_1^{(eff)}S_1\right\|_F^2\right\} \quad (12)$$

Simultaneously, during the detection of the first symbol, the receiver can detect and decode all the other received symbols through the following proposed detection method. Decoding of the second symbol S_2 can be achieved by suppressing the interference that is associated with all the remaining

transmitted symbols. This suppression is obtained by pre-multiplying the received signal matrix by matrix A_2.

$\widetilde{R}_2 \triangleq A_2 R (13)$

Where $\widetilde{R}_2$refers to the estimate of the received signal matrix after the interference suppression, and A_2 is to the overall per-multiplying matrix, which can be expressed as follows.

$A_{2_{[(N_r - N_t+1)\times(N_r)]}} = N[\Theta_1 H_{h-1,2}]\Theta_1 (14)$

Where Θ_1 refers to the null space of $[H_1]$, and $N[\Theta_1 H_{h-1,2}]$ represents the null space of $[\Theta_1 H_{h-1,2}]$.

Under Rayleigh distribution assumption the received signal matrix is$R = \sqrt{\rho}HS + Z$ and the resulting $\widetilde{R}_2$ matrix from equation (13) can be expressed as follows.

$\widetilde{R}_2 = \sqrt{\rho} H_2^{(eff)} S_2 + \bar{Z}_2 \quad (15)$

Where $H_2^{(eff)}$ refers to the effective channel matrix that is associated with decoding of S_2,which is defined by the following

$H_2^{(eff)} = A_2 H_2 (16)$

The associated noise term expression is $\bar{Z}_2 = A_2 Z$.

Thus, the received symbol estimate, $\hat{S}_2$, can be obtained by applying maximum likelihood decoding algorithm to (15) as shown in the following equation.

$$\hat{S}_2 = \arg\min_{\{S_2\}} \left\{ \left\| \widetilde{R}_2 - \sqrt{\rho} H_2^{(eff)} S_2 \right\|_F^2 \right\} \quad (17)$$

The detection and decoding of the remaining symbols $S_3 \ldots . S_{N_t}$are similar to the previous processing steps.

In summary, the transmitter sends N_t modulated symbols over one symbol period using spatial multiplexing technique, and the receiver detects and decodes all these symbols simultaneously and independently by using the new detection and decoding algorithm as outlined above. This implies that the speed of signal processing at the receiver and the throughput will be increased. In addition, at any given symbol period, this algorithm enables the receiver to have access to several replicas of each transmitted symbol. This implies that the reliability of the system will be improved also. Thus, it is important to note that the proposed system achieves both spatial diversity and spatial multiplexing simultaneously without employing STC. However; Multi-Group Space Time Codes (MGSTCs) method also achieves both spatial diversity and spatial multiplexing simultaneously [17], but there are three major differences between two methods which are as follows:

1. The MGSTCs method requires that number of transmit antenna to satisfy $N_t \geq 4$, while the new algorithm requires that $N_t \geq 2$. For example, using $N_t = 4$ for MGSTCs and $N_t = 2$ for the proposed parallel decoding technique, we have the same throughput for both systems but better bit error probability for our model.
2. The speed of signal processing at the receiver is increased by the new model. In standard MGSTCs method, the decoding of the component codes is performed iteratively and in a serial way. While, using the new algorithm, the decoding of component codes are performed simultaneously and in a parallel way.
3. The proposed parallel processing technique prevents possible error propagation. In standard MGSTCs method, the decoding of current component code symbol depends on the values of all previously decoded component codes. This implies that if an error occurs in decoding of a component code symbol, such error will propagate to all remaining component code symbols. This problem is vanished in the proposed decoding algorithm since the receiver decodes the symbols independently and simultaneously.

In general, the diversity order depends mostly on the difference between the numbers of receive and transmit antennas. This difference also increases the gain of the replicas of each symbol. Thus, the diversity order depends on the number of the rows of the pre-multiplying matrix, which is $(N_r - N_t + 1)$. The diversity order (N_d) of a MIMO communications system using the proposed parallel decoding technique is [24]

$$N_d = 2 * (N_r - N_t + 1) \quad (18)$$

Also, the channel capacity of this type MIMO communications system is shown in (19), where the rank of channel matrix is $r = \min(N_t, N_r)$ [2], [3] and [4].

$$C_{(N_t \times N_r)MIMO} = \sum_{i=1}^{r} \log_2 \left(1 + \frac{\rho}{2}\lambda_i\right) (19)$$

Where λ_i is the i^{th}eigenvalue of the channel matrix.

IV. SIMULATION RESULTS [20]

In this section, first, we assume that $N_t = 2$ and $N_r = 2,3,$ and 4 respectively, and that the transmitter employs a spatial multiplexing technique. The receiver can extract two transmitted symbols independently and simultaneously by using the new decoding algorithm. The bit error probability expression of a parallel decoding system is

$$P_{b(N_t \times N_r)MIMO-Paralleldecoding} = \left[\frac{1}{2}(1-\mu)\right]^L \sum_{k=0}^{L-1} \binom{L-1+k}{k} \left[\frac{1}{2}(1+\mu)\right]^k (20)$$

Where $L = 2(N_r - N_t + 1)$and$\mu = \sqrt{\frac{\bar{\rho}}{1+\bar{\rho}}}$.

Where $\bar{\rho}$ refers to the time averaged signal to noise ratio.

Figure.3 show the performance results of the proposed decoding method for $(2 \times N_r)$ MIMO communication systems which were compared with two similar systems in [24]. One system used Alamouti code that can achieve only spatial diversity, and another employed spatial multiplexing that uses serial decoding and it can achieve only spatial multiplexing. In figure 3, the bit error probability is

plotted versus E_b/N_0in dB in Rayleigh fading channel and using BPSK modulation for different systems.

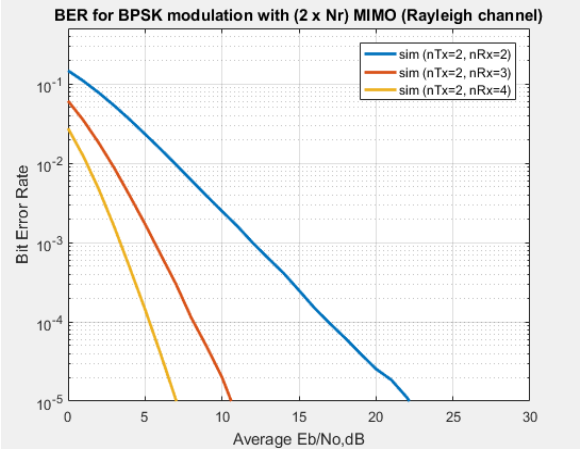


Figure.3: Bit error probability of $2 \times N_r$ MIMO communication systems.

It is interesting to note that BER of proposed parallel technique gets more closer to the BER of systems using Alamouti code by increasing the difference between number of receive and transmit antennas [24]. It is known that the diversity order of a MIMO system represents the slop of the bit error probability curve. The diversity order of proposed parallel decoding technique in the above figure approaches to $N_d = 2, N_d = 4, \text{and } N_d = 6$, respectively. Therefore; the diversity order increases with increasing the difference between the number of receiver and the transmitter as shown in (18). On the other hand, these three different MIMO communication systems have almost the same channel capacity as shown in Figure.4.

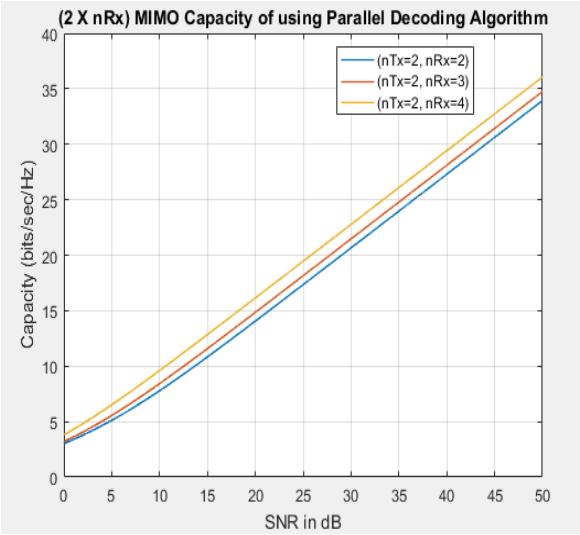


Figure.4: MIMO channel capacity comparison.

This implies the diversity order and BER of $N \times N$ MIMO communications systems is the same as shown in Figure.5.

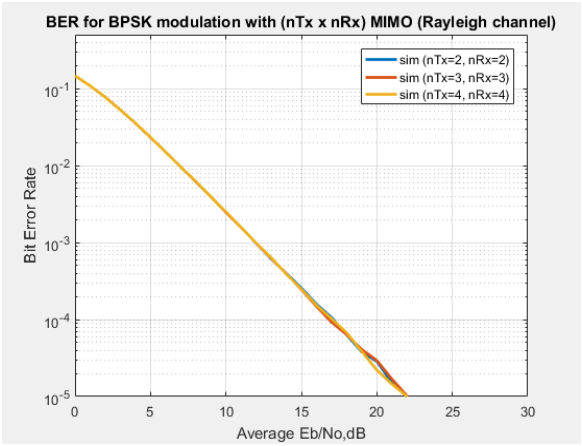


Figure.5: Bit error probability of $N \times N$ MIMO communication systems.

However; the channel capacity of these three different $N \times N$MIMO communication systems increases with increasing the number N of transmit and receive antennas as shown in Figure.6. Table 1 summarizes the advantages of the proposed parallel detection and decoding technique for $N \times N$ MIMO communication systems.

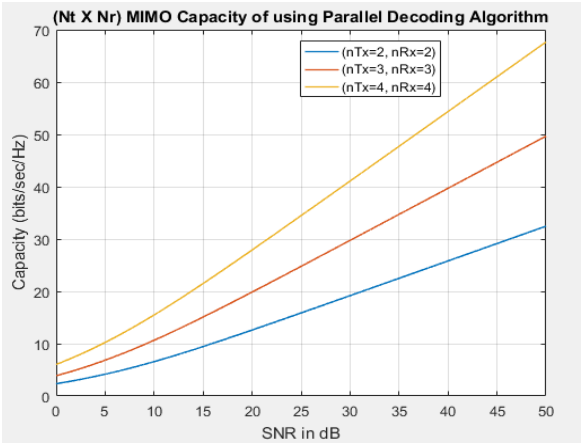


Figure.6: MIMO channel capacity comparison.

Table 3: $N \times N$ MIMO Communications comparison

	2×2 MIMO	3×3 MIMO	4×4 MIMO	
Channel capacity	$C_{(2\times2)MIMO} = 2 * C_{SISO}$	$C_{(3\times3)MIMO} = 3 * C_{SISO}$	$C_{(4\times4)MIMO} = 4 * C_{SISO}$ $= 2 * C_{(2\times2)MIMO}$	4×4 MIMO capacity is twice 2×2 MIMO capacity
Diversity order	$N_d = 2$	$N_d = 2$	$N_d = 2$	All of them have the same diversity order

The proposed system is also compared with MGSTCs system. To make the comparison simple, we use (2×4) MIMO with the proposed model and (4×4) MIMO with MGSTCs system [17]. These two systems have the same channel capacity. They both transmit two different modulated symbols over a single symbol period. The bit error probability for each of these systems versus E_b/N_0 in Rayleigh fading channel and using BPSK modulation is shown in Figure.7.

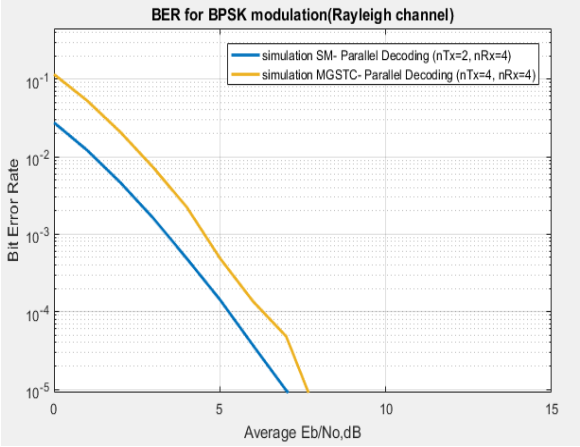


Figure.7:BER of different types of MIMO systems.

The above result shows that proposed parallel detection technique performs better in in terms of BER. Also, the proposed model provides more other enhancements such as prevents error propagation, increases speed of signal processing at the receiver, lowers the cost and simplifies the transmitter design due to not employing STCs.

The above analysis shows the system that employs a spatial multiplexing technique at the transmitter and applies the parallel detection and decoding algorithm at the receiver improves both throughput and transmission reliability simultaneously, which cannot be achieved by other serial detection algorithms having similar dimensions.

Future research may investigate the performance of the proposed receiver model when the decoding is performed on symbols in parallel manner by applying a variety of MIMO decoding technique, Sphere Decoding (SD), Set Partitioning and others.

CONCLUSION

The 5G- NR access networks are expected to provide very high capacity and ultra-reliability. To achieve these requirements, we focused on the study and investigation of MIMO communication techniques that use large number of antenna elements at both end of communication systems and developed novels ways to enhance the overall performance of $(N_t \times N_r)$ MIMO systems. A new detection and decoding technique called parallel decoding algorithm was developed and applied to V-BLAST $N_t \times N_r$ MIMO communications systems. The performance results show that the proposed parallel detection method improves both throughput and transmission reliability simultaneously, provided that spatial multiplexing technique is used at the transmitter. It was shown that the new technique increases the rate of decoded symbols when compared with similar systems that use linear serial detection and decoding method. In addition, it was observed that the proposed method prevents error propagation by extracting all received symbols independently and simultaneously. Also, it was shown that parallel decoding technique reduces the bit error probability and increases the speed of signal transmission without using a standard STC technique. However, it was seen that the BER of the proposed algorithm is higher than a similar system using STC technique such as Alamouti code. Also, it was seen that the BER of the proposed algorithm is significantly less than of a similar system using MGSTCs technique.

Finally, it was seen that with new decoding method the bit error probability, BER, decreases dramatically with increasing the difference between the number of receiving and transmitting antennas.

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