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Efficient Low-Complexity Spatial Modulation Techniques for MIMO Technology

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A B S T R A C T

In this paper, we study a new low-complexity algorithm to reduce computational complexity in a maximum-likelihood (ML) decoder used in fully generalized spatial modulation (FGSM) and fully quadrature spatial modulation (FQSM). The computational complexity was reduced based on the maximum ratio combining (MRC) algorithm where the detection process has been divided into two stages including active antennas detection and modulated information bits detections. The active antennas detections are processed using MRC while modulated information bits have been detected using the conventional ML scheme. The outperformance of the proposed approaches is validated via simulation in term of computational complexity and energy efficiency compared against their benchmarks which employ the optimal ML detector at the receiving end.

تقنيات التعديل المكاني منخفضة التعقيد والفعالة لتقنية MIMO

عبدالله المصروب و نجية السنوسي

قسم الهندسة الكهربائية والحاسوب، جامعة المرقب، الخمس، ليبيا

الكلمات المفتاحية:
التداخل في القناة
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التعقيد
معدل خطأ البت
نظام متعدد المدخلات والمخرجات
.MIMO

الملخص

في هذه الورقة، ندرس خوارزمية جديدة منخفضة التعقيد لتقليل التعقيد الحسابي في مفكك تشفير الاحتمال الاقصى التقليدي Maximum-Likelihood decoder (ML) المستخدم في مخططات التعديل المكاني التربيعي الكامل FQSM والتعديل المكاني المعمم بالكامل FGSM . تم تقليل التعقيد الحسابي بناء على خوارزمية الجمع بين نسبة الجمع القصوى Maximum Ratio Combining (MRC) حيث تم تقسيم عملية الكشف إلى مرحلتين: أولا اكتشاف الهوائيات النشطة بناء على MRC. ثانيا تنفيذ مفكك تشفير الاحتمال الاقصى ML التقليدي بناء على الهوائيات النشطة المكتشفة في المرحلة الأولى. يتم التحقق من تفوق الاساليب المقترحة من خلال المحاكاة من حيث التعقيد الحسابي وكفاءة الطاقة مقارنةً بمعاييرها التي تستخدم كاشف ML الأمثل في الطرف المستقبل.

1. Introduction

Spatial modulation techniques (SMTs) have recently introduced as an alternative of the conventional Massive multi-input multi-output (MIMO), addressing key challenges such as computational complexity required for the receiver, inter-channel interference (ICI) and power efficiency, which represent the main limits for the practical implementation [1]. The SMTs avoid the simultaneous activation of all available transmit antennas (Tx) to transmit the constellated data symbols by using the index of that active antenna out of the total Tx to transmit additional information bits. On the other hand, Spatial modulation (SM) [2] transmits additional information by selecting the index of active antenna however it doesn't offer any antennas diversity to enhance the performance. Therefore, modulated data and index bits are transmitted in SM by using the modulation order and index active antenna, respectively. As a result, the information bits carried by the index of the Tx are considered as free power consummation. Also, activating few antennas decreases the receiver's computational complexity, and overcome the inter-antenna interference exist in conventional MIMO systems.
SMTs have recently been presented as a candidate solution key for the next generation of wireless networks (5G) since they offer better

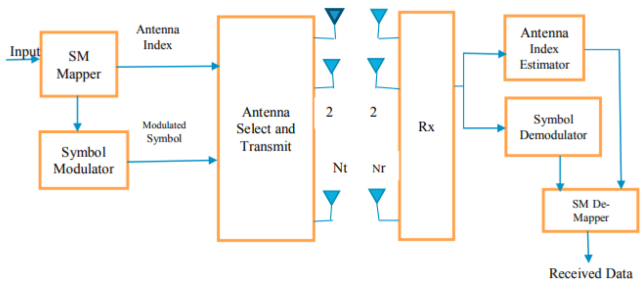

Fig. 1: System Model of Spatial modulation MIMO System

performance in terms of spectrum efficiency (SE), energy efficiency (EE), and reduced system complexity [3]. Additionally, they are considered today as a modern modulation technique that enhance the transmission rates without higher required complexity. Among these modulation techniques is the SM, which is considered pioneer of

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SMTs, where an antenna is selected based on the incoming index bits to carry the modulated data and to provide higher transmission rates than the existed single-input-multiple-output (SIMO), and less ICI and inter-antennas synchronization than the MIMO systems. Following that purpose, researchers tried hard to increase the information bits transmitted based on the antenna index using many methods such as: activating one single transmit antennas during slot time [2], transmitting the constellated symbol through more than one single antennas [4, 5], separating the real and imaginary parts before transmitting each part via one or multiple Tx [3], or enhancing the transmission rate using the index of other dimensions such as another type of signal constellation and/or employing the number of active antennas as an additional dimeson to transmit more indexed bits [6]. The SMTs principle has attracted the attention of many researchers to employ it in several transmission methods. On one hand, in the orthogonal frequency division multiplexing (OFDM) resulting new technique named OFDM indexed modulation (OFDM-IM) [7-9] were the purpose of the transmit antennas index was applied into the OFDM subcarriers in order to improve the performance of bit error rate (BER) or increase the SE of OFDM. On the other hands, it was combined with the spread spectrum (SS) to use the spreading code and overcome the complexity required for the hardware by utilizing single input single output (SISO) system [10, 11] such as generalized spatial modulation (GSM) [12], fully generalized spatial modulation (FGSM), fully quadrature spatial modulation (FQSM) [3, 4] and enhanced fully generalized spatial modulation (EFGSM) [6]. The aforementioned approached were introduced to improve the bandwidth utilization and enhance the power consummation in wireless communication systems. On the other hand, the FGSM and FQSM employ the number of active antennas itself to convey additional index information bits. Particularly, the physical modulated data is carried via one or multiple Tx while and the number of used antennas also carries the index information bits. However, the required computational complexity and power consummation in FGSM and FQSM resulted of using maximum-likelihood decoder or activating many antennas are still representing the main challenges in those two schemes. Therefore, in our works, we investigate new algorithms for decreasing the computational complexity in FGSM and FQSM by avoiding the use of maximum-likelihood decoder.

The rest of our paper is structured as follows: Section II introduces the system model of the SMTs systems. Section III discussed the proposed techniques. Then, sections IV and V, respectively, discuss the performance of the proposed techniques and conclude this paper.

2. System Model

Unlike conventional MIMO systems, the data bits in SM are not conveyed simultaneously by multiple antennas at the transmitting end. In SM, instead of completely modulated and information bits and transmit them physically, only a part of incoming bit sequence are modulated while the other part is mapped to be transmitted via the active antenna indices. As results, the inter-antenna interference, system complexity, and transmit antenna synchronization are significantly reduced when using SM system compared to h MIMO systems. The model corresponds to SM is given in the Figure 1, where it is shown that SM [2] improves the data rate by transmitting constellated habitual data symbols via the active antenna. Particularly, additional modulated data are sent physically through the active antenna resulting a given data rate (R_{SM}) :

$$R_{SM} = log_2(M) + log_2(T_x), \tag{1}$$

where M and T_x indicate the modulation order and the number of available antennas, respectively.

On the other hand, GSM was introduced in [12] to improve the spectral efficiency (SE) of SM by activating multiple antennas instead of one signal antenna at the expense of computational complexity on the receiving side. The data rage of GSM (R_{GSM}) complexity computation on the receiver side:

$$R_{GSM} = log_2(M) + \left\lfloor log_2 \binom{T_x}{T_u} \right\rfloor, \tag{2}$$

where $\lfloor\cdot\rfloor$, $\binom{\cdot}{\cdot}$ and T_u represent the floor operator, the binomial coefficient, and the number of transmitting active antennas, respectively.

FGSM was proposed in [4] by combining SM and GSM to increase the achievable data rate where the variable number of transmit antennas are activated during time instant. In FGSM, either one or more transmit antennas are activated to transmit the physical modulated information bits. That variation of number of active antennas is employed for carrying additional indexed information bits. Therefore, the data rate of FGSM (R_{FGSM}) becomes linear with the number of transmit antennas. The achievable R_{FGSM} is expressed as [4]:

$$R_{FGSM} = log_2(M) + \left\lfloor log_2 \sum_{T_u=1}^{T_x} \binom{T_x}{T_u} \right\rfloor$$
$$= log_2(M) + T_x - 1. \tag{3}$$

Table 1: FGSM mapping system example

Transmitted bits		*Antenna combination*
Data bits	*Antennas bits*	
b_1b_2	*000*	T_{x1}
b_1b_2	*001*	T_{x2}
b_1b_2	*010*	T_{x3}
b_1b_2	*011*	T_{x4}
b_1b_2	*100*	$T_{x1}T_{x2}$
b_1b_2	*101*	$T_{x1}T_{x3}$
b_1b_2	*110*	$T_{x1}T_{x4}$
b_1b_2	*111*	$T_{x2}T_{x4}$

Table 2: FQSM mapping system example

Transmitted bits			*Antenna combination*	
Data bits	*Antennas bits*		*Antennas index*	
	real	*Imaginary*	*Real*	*imaginary*
b_1b_2	*000*	*000*	T_{x1}	T_{x1}
b_1b_2	*001*	*001*	T_{x2}	T_{x2}
b_1b_2	*010*	*010*	T_{x3}	T_{x3}
b_1b_2	*011*	*011*	T_{x4}	T_{x4}
b_1b_2	*100*	*100*	$T_{x1}T_{x2}$	$T_{x1}T_{x2}$
b_1b_2	*101*	*101*	$T_{x1}T_{x3}$	$T_{x1}T_{x3}$
b_1b_2	*110*	*110*	$T_{x1}T_{x4}$	$T_{x1}T_{x4}$
b_1b_2	*111*	*111*	$T_{x2}T_{x4}$	$T_{x2}T_{x4}$

Another SMTs technology called FQSM has been proposed in [3] to further enhance the achieved SE of FGSM. In FQSM, the real and imaginary parts of the modulated data are first separated, and each part is mapped to one of more active antenna to carry additional indexed bits. As a results, the total transmitted indexed bits are duplicated. That combination increases the number of indexed information bits significantly. Therefore, the data rate of FQSM (R_{FQSM}) is expressed as [3]:

$$R_{FGSM} = log_2(M) + 2\left\lfloor log_2 \sum_{T_u=1}^{T_x} \binom{T_x}{T_u} \right\rfloor$$
$$= log_2(M) + 2(T_x - 1). \tag{4}$$

Despite the data rate significant improvement of FGSM and FQSM, the higher computational complexity at the receiving end is considered as one of the main issue. That complexity is resulted of the use of ML detector to detect higher number of combinations. In this paper, we enable the MRC detectors for FGSM and FQSM to decrease the computational complexity at the receiving end. It's worth mentioning that MRC is straightforward implemented for SM and GSM in literature, but the use of varied number of active antennas in FGSM and FQSM raise an issue of straightforwardly implementing the MRC technique detect the active antennas and hence reduce the required computational complexity.

3. Proposed System

FGSM and FQSM approaches, respectively, map the constellated and indexed bits following the example shown in Table (1) and Table (2). In Table (1) and Table (2), the two bits (b_1b_2) represent the modulated data carried by such QAM or QPSK modulation while the other bits

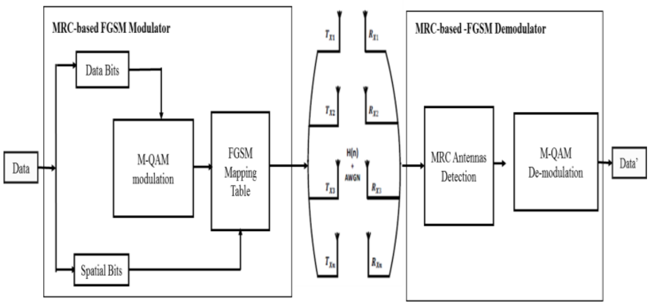

Fig. 2: MRC-based FGSM scheme

in the second column represent the indexed bits carried by the indices of activated antennas; as shown in both tables the number of active antennas can be either one of two. Without the loss of generality, we will explain here the proposed algorithm for FGSM while the same process can be implemented for FQSM straightforward. For illustration, let the information bits to be transmitted to be [10 101]. The first two bits 10 represent the modulated data bits carried by the used constellation, i.e., QAM modulation while the three following bits 101 will be transmitted using the index of transmit antennas which is corresponding in that case to first and third antennas $T_{x1}T_{x3}$. Thus, a vector of NT_{x1} FGSM transmitted vector is $\boldsymbol{x} = [s\ 0\ s\ 0]$, where the constellated symbol is represented by s. The vector $\boldsymbol{x}$ is then transmitted through $T_r \times T_x$ uncorrelated channel $\boldsymbol{H}$, and corrupted by additive white Gaussian noise (AWGN) where T_r represents the number of receive. Hence, the receiver vector signal y can be explained as:

$$y = h_l x + v; \quad h_l = \sum_{i=1}^{T_u} h_{li}\boldsymbol{x}; \; T_u = 1,2, \ldots\ldots, \left\lfloor \frac{T_x}{2} \right\rfloor. \quad (5)$$

Therefore, as explained earlier, the FGSM and FQSM approaches employ one or more antennas for transmitting the modulated data and then utilize the index of the activated antennas index to transmit more data bits. Although the spectral efficiency increases, the complexity is also increased with number of antennas and modulation order exponentially [13, 14]. To that aim, we enable the MRC to be used with those schemes to reduce the receiver's computational complexity. As it's shown in Table (1) and Table (2), the main difference between FGSM and FQSM is that FQSM separates the real part and imaginary part before transmitting them via one or more active antennas while FGSM doesn't separate them. Furthermore, the number of active antennas is varied in both FGSM and FQSM making the use of conventional iteration MRC (i-MRC) not possible. The process of i-MRC is illustrated in Figure 2. It's worth mentioning that figure illustrates the process of FGSM while FQSM can be easily implied using the same steps. So, our algorithm to separately detect the index of active antennas and the modulated information bits can be summarized as follows:

i - The estimated transmit antenna index can be defined based on the i-MRC algorithm by applying it to the vector of the received data y as follows:

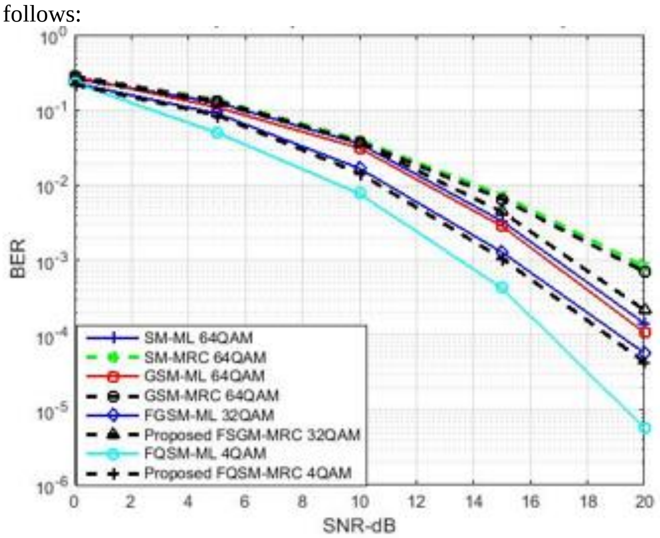

Fig. 3: BER comparison performance with rate 8 bpcu

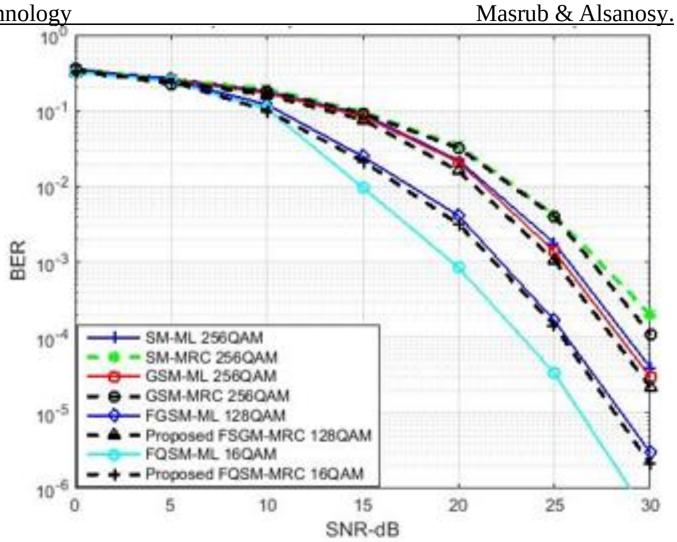

Fig. 4: BER comparison performance with rate 10 bpcu

$$k_l = \frac{h_l^{\mathcal{H}} y}{\|h_l\|_F}, \qquad \text{for } l \in \left[1 : 2^{(T_x - 1)}\right], \quad (6)$$

Where h_l , $\|h_l\|_F$, and $(.)^{\mathcal{H}}$ represent the channel of each antennas represented by every column of that matrix **H**, Frobenius norm and conjugate-transpose, respectively. The index of activated antennas is represented following table 1 and Eq. (5), where if more than one antennas are activated, the parameters l will be considered to be the sum of two columns of **H** representing the two active antennas.

ii – The transmitted active antennas $\hat{l}$ are estimated based on Eq. (6) as below:

$$\hat{l} = \arg\max_{l} \; (k_l). \quad (7)$$

iii – Finally, the transmitted bits in the modulated symbol $\tilde{s}$ is estimated by ML decoder based on the estimated parameters $\hat{l}$,

$$\hat{s} = \arg\min_{s} \|y - h_{\hat{l}} x\|^2. \quad (8)$$

By this way, the ML decoder will only perform the search complexity of $\tilde{s} \in [1\!:\!M]$ and that decreases the complexity of the detection method, where M denotes the modulation order utilized in the transmitter.

4. Simulation Results and Discussion

A. Bit Error Rate performance analysis

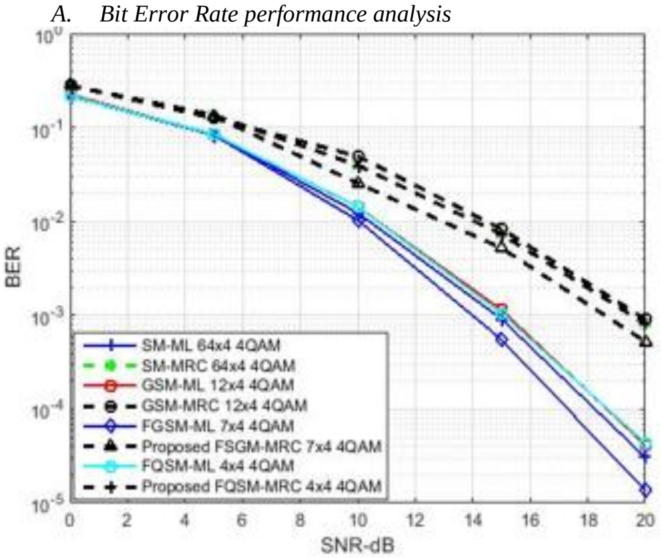

Fig. 5: BER comparison performance using fixed modulation order with rate 8 bpcu

We, in this section, evaluate the performance of the proposed approached by simulation using a Rayleigh channel over 10^6 transmitted symbols. The Bit Error Rate (BER) has been first analyzed by comparing it against the benchmarks such as SM, GSM, QSM and FGSM-ML under the same achieved spectral efficiency. Two scenarios have been considered to analyze the performance. The first scenario is the we same the same number of antennas at the transmitting/receiving ends for all scheme while varying the modulation order to achieve same spectral efficiency. On the other hand, the second scenario is by fixing the modulation order and increasing the number of antennas to achieve higher data rate.

Figure 3 shows BER performance comparison when all schemes achieve 8 bits per channel use (8bpcu). The configuration of number of antennas is set to be fixed for all schemes while the modulated order has been changed to achieve the required data rate. As shown in figure 3, the two proposed FGSM-MRC and FQSM-MRC achieved the best performance compared against the conventional schemes. FGSM-MRC and FQSM provide up to 2dB and 3dB improvement compared to the conventional GSM-ML, respectively. Furthermore, the performance is slightly deteriorated compared with the optimal ML detector, but ML requires exhaustive computational complexity as we will show later. Similarly, Figure 4 shows the BER performance comparison when using similar number of transmit/receive antennas and different modulation order to achieve equal achieved data rate in all schemes. The proposed FQSM-MRC offers up to 3 dB performance compared into the conventional FGSM-ML scheme. On the other hand, Figure 5 and Figure 6 shows the performance of the second scenario which is using different number of transmit/receive antennas and fixed modulation order. For example, without the loss of generality, 4QAM is used in Figure 5 to achieve 8 bpcu in all schemes. So, 64 transmit antennas is required for the conventional SM scheme to achieve the required data rate while the proposed FGSM-MRC and

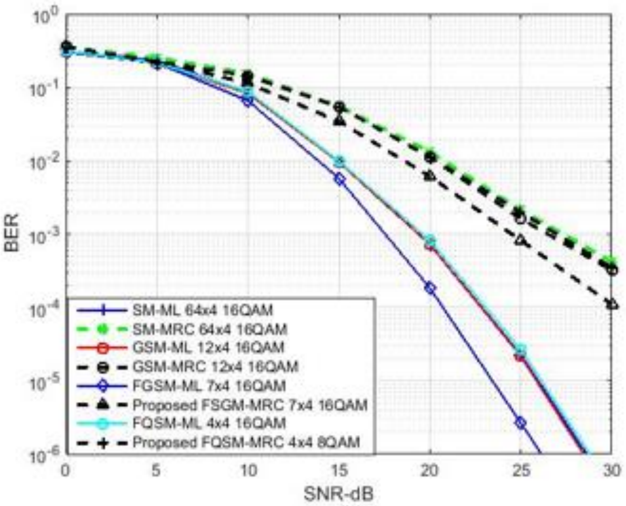

Fig. 6: BER comparison performance using fixed modulation order with rate 10 bpcu

FQSM-MRC required 7 transmit antennas and 4 transmit antennas, respectively. It's important to mention that increasing the number of transmit antennas doesn't only increase the effect of inter-antennas interference, but also the hardware must be larger to design the system. Figure 6 illustrate the proposed FGSM-MRC and FQSM still slightly outperformance the conventional SM-MRC and GSM-MRC systems despite the less required number of antennas at the transmitting end.

B. Bit Error Rate performance analysis

In order to compute and compared the required computational complexity, we considered herein the required floating-point number (flops) required to perform the detection process using the ML decoder, where TNCO is the total number of flops. It's straightforward to notice the current ML detector at SMTs schemes require searching of $(2)^R$ combinations, where R indicates the number of transmitted information bits. In addition, in each time, $\sum_{i=1}^{T_r}\|y_i - h_{li}x\|^2$ is required to be considered such as a combined multiplication that includes i.e., four actual multiplications to compute $h_{li}x$ and four real multiplications are also needed for the square norm. consequently, the ML decoder for the conventional SM schemes utilizes this method to compute the TNCO; and its decoder computational complexity is given by [3]:

$$\mathrm{TNCO}_{SM} = 8N_r(2)^{R_{SM}}\,. \tag{9}$$

Using the same method to calculate the required total TNCO required for the GSM considering that multiple transmit antennas are activated. The ML-based decoder of GSM requires a TNCO given by [3]:

$$\mathrm{TNCO}_{GSM} = 8N_r\big(2(N_u-1)\big)(2)^{R_{GSM}}. \tag{10}$$

In FGSM, the ML-based decoder at the receiving end used different method to calculate the required TNCO, where FGSM ML maximum summation is $\frac{T_x}{2}-1$ for all $T_x \geq 3$. Therefore, the total required computational complexity is given as in [3]:

$$\mathrm{TNCO}_{FGSM} = 8N_r\left(2\left\lceil\frac{N_t}{2}-1\right\rceil\right)(2)^{R_{QSM}}. \tag{11}$$

Table 3: Computational Complexity Comparison

Scheme	SM ML	GSM ML	FGSM ML	FGSM MRC	FQSM MRC
Tx × Tr	4 ×4	4 ×4	4 ×4	4 ×4	4 ×4
Modulation Order QAM	256	256	128	128	16
TNCO	32768	65536	65535	4184	1216

Different from the previous explained scheme, the complexity contribution in the proposed schemes is the computed for every part including antennas detection and ML decoder. Then, they are summed to find the total receiver's complexity. Therefore, antenna detection in (6) for FGSM-MRC requires T_r and $T_r - 1$ complex multiplications and complex additions, respectively, while the Frobenius norm can be found by multiplying a vector of length T_r with its complex conjugate and taking its square root resulting T_r complex multiplication. That process is evaluated over $l \in [1:(2)^{T_x-1}]$ resulting a total computation for antennas detection of $2T_r(2)^{T_x-1} + (2)^{T_x-1}(T_r - 1)$. Regarding the ML decoder used to detect the physical modulated information bits, it requires computational complexity of $8T_r(2)^{log_M}$ calculated following same way of (11). Also, the needed TNCO of the proposed FQSM-MRC is $2T_r(2)^{2(T_x-1)} + (2)^{2(T_x-1)}(T_r-1)$ to detect the index of the active antennas, and $8T_r(2)^{log_M}$ for the ML decoder. Thus, that can be expressed as follows:

$$\mathrm{TNCO}_{FGSM-MRC} = 2T_r(2)^{T_x-1} + (2)^{T_x-1}(T_r-1) + 8T_r(2)^{log_M}\,. \tag{12}$$

$$\mathrm{TNCO}_{FGSM-MRC} = 2T_r(2)^{2(T_x-1)} + (2)^{2(T_x-1)}(T_r-1) + 8T_r(2)^{log_M}\,. \tag{13}$$

Table (3) illustrates the complexity comparison over the conventional schemes when achieving the same data rate (e.g., 10bpcu) following the above analysis. It's clear the receiver's computational complexity has been significantly reduced validating the outperformance of the proposed approaches.

5. Conclusion

In this paper, FGSM-MRC and FQSM-MRC schemes are presented, to decrease the high required complexity of the decoders of the conventional approaches FGSM-ML and FQSM-ML, respectively. In the proposed approaches, the MRC-based algorithm has been employed for separately detecting the active antennas and modulated information bits. Based on the simulation results provided throughout the paper, the required computational complexity at receiver side has been meaningfully decreased at the expense of slight deterioration compared over the optimal ML decoder. In future work, new low-complexity schemes with higher spectral efficiency will be proposed.

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