Fully-Quadrature Spatial Modulation over Rician Fading Channels

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Abstract—**Space modulation techniques (SMTs) are promising multiple-input multiple-output (MIMO) schemes that draw an intriguing attention lately due to their superior performance enhancement in terms of energy efficiency, spectral efficiency and unpretentious receiver's complexity. In the SMTs, the indices of the building blocks of the communication system are harnessed in an innovative way to embed an additional information. More specifically, the SMTs use the transmit antenna indices to fulfill higher transmission efficiency than the other MIMO opponents. Although of their appealing advantages, the SMTs suffer from a main disadvantage which is represented in the logarithmic proportion between their achievable data rates and the number of the transmit antennas. Therefore, the authors proposed the fully-quadrature spatial modulation (F-QSM) in order to vanquish the main disadvantage of the SMTs. In the F-QSM, the transmit antenna indices are varied in an innovative way to achieve a linear proportion between the achievable data rate and the number of the transmit antennas. In this paper, the performance of the F-QSM over Rician fading channel is considered. The average bit error rate performance (ABER) of the F-QSM is assessed and weighted against the ABER of the conventional SMTs under different values of Rician factor. Furthermore, the computational complexity of the F-QSM is obtained as well and weighted against the computational complexity of the conventional SMTs. The conducted Monte-Carlo simulations substantiate the outweighing of the proposed scheme in terms of achievable data rate and ABER performance but with a slight increase in the computational complexity compared to the conventional SMTs.**

Keywords—Space modulation techniques (SMTs); F-QSM; Energy efficency; Spectral efficency; Computational complexity.

I. INTRODUCTION

In the last few decades, the multiple-input multiple-output (MIMO) systems have witnessed unprecedented development in both academic and industrial levels. The MIMO systems harness multipath signal propagation to fulfill a multiplexing or/and a spatial diversity gain. Hence, integrating the MIMO systems with the prevailing wireless networks promises a linear increase in the system capacity along with a quality-of-service (QoS) (e.g. better bit error rate performance, high bandwidth efficiency,…etc.) [1]. As such, the MIMO systems have been protruded as one of the main components of the modern communication standards such as IEEE 802.11n, IEEE 802.16, and the fourth-generation long term evolution (4G-LTE) [2].

Space modulation techniques (SMTs) have recently been emerged as one of the spatial multiplexing MIMO technologies that enhance the spectral efficiency of the conventional MIMO by embedding additional information via the entities of the building blocks of the communication system [3]. In particular, the SMTs alter the on/off status of the transmit antennas in the transmit antenna array for the sake of conveying an additional information. Therefore, a single or multiple transmit antennas is/are activated to transmit the data constellation symbols and the index/indices of this/these active antennas is/are considered another source of information. Altering the on/off status of the transmit antennas in the transmit antenna array, enables the use of limited number of radio frequency (RF) chains at the transmitter (TX) side, relaxes the sought-after inter-antenna synchronization (IAS) and permits the use of low complexity decoding algorithms at the receiver (RX) side [4].

In the last few years, more research efforts have been relentlessly poured into advancing the field of the SMTs. At the forefront of these advances, the spatial modulation (SM) [5] has been protruded. In the SM, a single RF chain is utilized at the TX side to generate the habitual data constellation symbols and the information is embedded by both the data constellation symbol and the index of the transmit antenna. As such, an achievable rate of $log_2(M) + log_2(N_t)$ bits can be fulfilled in the SM [5] with N_t denotes the number of the transmit antennas and M stands-for the modulation order or the constellation size.

Inspired by the goal of reducing the number of transmit antennas used in the SM, the generalised spatial modulation (GSM) was introduced [6]. In the GSM, a constant arbitrary number of active antennas are used to transmit the same data constellation symbol. Hence, the information is embedded by the indices of the active antennas as well as the transmitted data symbol. As such, an achievable rate of $log_2(M) + \left\lfloor log_2 \binom{N_t}{N_u} \right\rfloor$ bits can be fulfilled in the GSM [6] with N_u denotes the number of active of antennas and $\binom{\cdot}{\cdot}$ denotes the binomial coefficient.

However, in the quadrature spatial modulation (QSM) [7], a single RF chain with in-phase (I) and quadrature-phase (Q) paths is utilized at the TX side to generate the real and the imaginary parts of the data constellation symbol respectively. The real part is then transmitted using one antenna and the imaginary part is transmitted by another antenna. As such, an achievable rate of $log_2(M) + 2log_2(N_t)$ can be fulfilled [7].
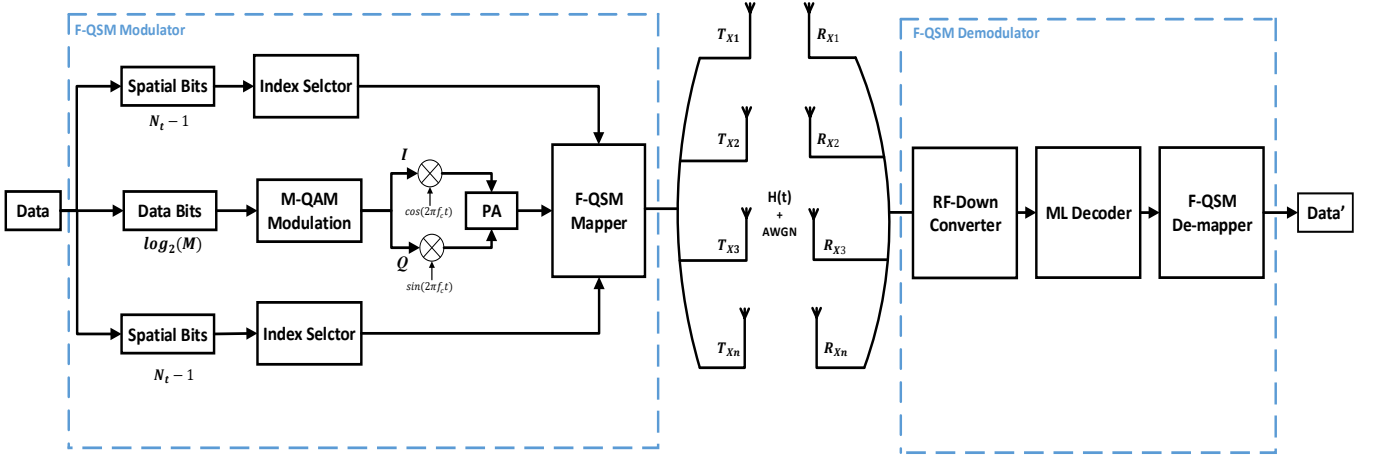
Fig. 1. The fully-quadrature spatial modulation system model.

With reference to the existing literature, the achievable data rates of most of SMTs are logarithmically increased with the number of the transmit antennas. This logarithmic proportion, impedes the SMTs to achieve the linear increase in the system capacity as the conventional MIMO systems [1]. Therefore, the authors proposed the fully-generalised spatial modulation (F-GSM) [8] and the fully-quadrature spatial modulation (F-QSM) [9] for the sake of acquiring a linear proportion between the achievable data rate and the number of the transmit antennas. The F-GSM and the F-QSM, alter the on/off status of a variable number of transmit antennas to embed more information than the conventional SMTs. In particular, in the F-GSM and the F-QSM, the transmit antennas used for the data transmission are varied from the state where only one transmit antenna is activated to the state where multiple/all transmit antennas are activated. Hence, a linear proportion between the achievable data rate and the number of transmit antennas can be acquired.

In this paper, the performance of the F-QSM over Rician fading channel is considered. Hence, the ABER performance of the F-QSM is evaluated and weighted against the ABER of the conventional SMTs [10] at different values of Rician factor. Furthermore, the receiver's computational complexity of the F-QSM is evaluated and weighted against the computational complexity of the conventional SMTs.

The rest of the paper is structured as follows. Section II introduces the F-QSM system model. In Section III, the receiver's computational complexity of the F-QSM is analyzed. The simulation results are introduced in Section IV. Finally, the paper is concluded in Section V.

II. The Fully-Quadrature Spatial Modulation

A general $N_t \times N_r$ system model of the F-QSM is shown in Fig. 1 with N_t and N_r denote the number transmit and receive antennas respectively. As shown in Fig. 1, the upcoming block of bits to be emitted at any instant of time is parted into three distinct groups. The first group of bits embeds $log_2(M)$ data bits which are used to modulate a signal constellation symbol S from an arbitrary M-ary quadrature amplitude modulation (M-QAM) or from any other signal constellation diagram. The data symbol S is then partitioned into its real ($S_\Re$) and imaginary ($S_\Im$) parts respectively to be emitted using a single/multiple

transmit antenna/s depending on the subsequent group of bits. The second group of bits embeds (N_t-1) spatial bits. This group of bits is responsible to choose the antenna subset required to emit the real part of the data symbol $S_\Re$. Likewise, the third group of bits embeds (N_t-1) spatial bits that are responsible to choose the antenna subset required to emit the imaginary part of data symbol $S_\Im$. Hence, the achievable rate of the F-QSM can be expressed as follows:

$$R_{F-QSM} = log_2(M) + 2\left\lfloor log_2\left(\sum_{k=1}^{Nt}\binom{N_t}{k}\right)\right\rfloor$$

$$= log_2(M) + 2\lfloor log_2(2^{N_t} - 1)\rfloor$$

$$= \underbrace{log_2(M)}_{Data\ Bits} + \underbrace{2(N_t - 1)}_{Spatial\ Bits} \qquad (1)$$

Example: For better explanation of the transmission procedure of the F-QSM, an example (for certain block of bits) is given in Table I. Herein, the F-QSM uses 4 transmit antennas and 4-QAM modulation to fulfill a spectral efficiency of 8 bits per channel use (8 bpcu). However, the SM and QSM use 64 and 8 antennas respectively to fulfill the same spectral efficiency. Thus, if the upcoming block of bits to be emitted at any time instant is [$\underbrace{11}_{Data}$ $\underbrace{111110}_{Spatial}$]. The first group of bits [1 1], embeds the data bits which modulate the data symbol S. The second group of bits [1 1 1], represents the spatial bits that are responsible to map $S_\Re$ to the transmit antennas T_{x2} and T_{x3} respectively. Likewise, the third group of bits [1 1 0], are responsible to map the $S_\Im$ to the transmit antennas T_{x1} and T_{x4} respectively. Therefore, the resultant transmission vector of the F-QSM $x \in \mathbb{C}^{N_t \times 1}$ can be written as $x = [jS_\Im \quad S_\Re \quad S_\Re \quad jS_\Im]^T$.

In this paper, the resultant transmission vector of the F-QSM undergoes uncorrelated Rician fading channel $H \in \mathbb{C}^{N_r \times N_t}$ which can be expressed as follows:

$$H = \left(\sqrt{\frac{K}{K + 1}}\right) + \left(\sqrt{\frac{1}{K + 1}}\right)H' \qquad (2)$$

TABLE I.
EXAMPLE OF THE F-QSM FOR 8BPCU TRANSMISSION WITH $M = 4$, $N_t = 4$.

Block of Bits		Transmitted Data			
Data Bits	Spatial Bits	T_{x1}	T_{x2}	T_{x3}	T_{x4}
$b_1 b_2$	000000	S	-	-	-
$b_1 b_2$	000001	$S_\Re$	$S_\Im$	-	-
$b_1 b_2$	000010	$S_\Re$	-	$S_\Im$	-
$b_1 b_2$	000011	$S_\Re$	-	-	$S_\Im$
$b_1 b_2$	111100	$S_\Im$	S	$S_\Re$	-
$b_1 b_2$	111101	$S_\Im$	$S_\Re$	S	-
$b_1 b_2$	111110	$S_\Im$	$S_\Re$	$S_\Re$	$S_\Im$
$b_1 b_2$	111111	-	S	S	-

where K denotes the Rician factor, $\left(\frac{K}{K+1}\right)$ indicates the average power of the line-of-sight (LOS) component, $\left(\frac{1}{K+1}\right)$ is the average power of the non-LoS (i.e. scattered) component and $H' \in \mathbb{C}^{N_r \times N_t}$ is random matrix whose elements are assumed to be i.i.d. complex Gaussian random variables (RVs) with zero mean and unity variance. Moreover, the resultant transmission vector of the F-QSM experiences an additive white Gaussian noise (AWGN) $\boldsymbol{v} \in \mathbb{C}^{N_r \times 1}$ whose real and imaginary parts are independent Gaussian distributed RVs and is distributed as $\boldsymbol{v} \sim \mathcal{CN}(0, \sigma_n^2)$. Therefore, the received vector $\boldsymbol{y} \in \mathbb{C}^{N_r \times 1}$ at the RX side of the F-QSM can be expressed as follows:

$$\boldsymbol{y} = \boldsymbol{h}_{\ell_\Re} S_\Re + j\boldsymbol{h}_{\ell_\Im} S_\Im + \boldsymbol{v} \tag{3}$$

where

$$\boldsymbol{h}_{\ell_\Re} = \sum_{i=1}^{N_{\ell_\Re}} \boldsymbol{h}_{li} \quad , \quad \boldsymbol{h}_{\ell_\Im} = \sum_{k=1}^{N_{\ell_\Im}} \boldsymbol{h}_{lk} \tag{4}$$

with $\boldsymbol{h}_{\ell_\Re}$ and $\boldsymbol{h}_{\ell_\Im}$ denote the summation of the active antennas channel columns required to emit $S_\Re$ and $S_\Im$ respectively and $N_{\ell_\Re}, N_{\ell_\Im} = 1, 2, \dots \left\lceil \frac{N_t}{2} \right\rceil$, with $\lceil . \rceil$ denotes the ceiling operator.

At the RX side, a full knowledge of the channel state information (CSI) is assumed as in [6, 7] and a maximum likelihood (ML) decoder is utilized to detect the antenna indices $\tilde{\ell}_\Re$ and $\tilde{\ell}_\Im$ along with the real and the imaginary parts of the data symbol $\tilde{S}_\Re$ and $\tilde{S}_\Im$ as follows:

$$\left[\tilde{\boldsymbol{h}}_{\tilde{\ell}_\Re}, \tilde{\boldsymbol{h}}_{\tilde{\ell}_\Im}, \tilde{S}_\Re, \tilde{S}_\Im\right] = \arg \min_{\ell_\Re, \ell_\Im, S_\Re, S_\Im} \left\| \boldsymbol{y} - \boldsymbol{h}_{\ell_\Re} S_\Re - j\boldsymbol{h}_{\ell_\Im} S_\Im \right\|^2 \tag{5}$$

III. COMPUTIOTIONAL COMPLEXITY ANALYSIS

The RX's computational complexity of the conventional SM is given by evaluating the total number of real operations (TNRO) required at the ML decoding process as follows [5]:

$$TNRO_{SM} = 8N_r (2)^{R_{SM}} \tag{6}$$

where, $R_{SM} = log_2(M) + log_2(N_t)$ is the SM data rate.

Furthermore, the computational complexity of the QSM is given in [7] as follows:

$$TNRO_{QSM} = 8N_r (2)^{R_{QSM}} \tag{7}$$

where, $R_{QSM} = log_2(M) + 2log_2(N_t)$ is the QSM data rate.

However, the main difference between the computational complexity of the F-QSM and the computational complexity of the SMTs lies primarily in the way of calculating $\boldsymbol{h}_{\ell_\Re}$ or $\boldsymbol{h}_{\ell_\Im}$. In the F-QSM, $\boldsymbol{h}_{\ell_\Re}$ or $\boldsymbol{h}_{\ell_\Im}$ costs at maximum $\left(\left\lceil \frac{N_t}{2} - 1 \right\rceil\right)$ complex summation for $N_t \geq 3$. Hence, $\left(2\left\lceil \frac{N_t}{2} - 1 \right\rceil\right)$ real summations are required. Thus, the TNRO of the F-QSM is given as follows:

$$TNRO_{F-QSM} = 8N_r \left(2\left\lceil \frac{N_t}{2} - 1 \right\rceil\right) (2)^{R_{F-QSM}} \tag{8}$$

where R_{F-QSM} is the data rate of the F-QSM provided by (1).

IV. SIMUALTION RESULTS

In this section, the performance of the F-QSM is assessed using variety of system metrics. Firstly, the ABER performance of the F-QSM is evaluated and weighted against the ABER performance of the conventional SMTs under different values of Rician factor [10]. Secondly, the computational complexity of the F-QSM is evaluated and tested against the computational complexity of the conventional SMTs [6, 7].

Herein, the ABER comparison is conducted by using comprehensive Monte Carlo simulations where each BER value is evaluated by averaging at least 10^6 symbol transmissions over uncorrelated Rician channel. To compare meaningfully, all the considered schemes are tested under the assumption of fulfilling the same spectral efficiency.

Fig. 2 depicts the ABER performance of the F-QSM weighted against the ABER performance of the SM and QSM [10] for Rician factor $K = 2$. Herein, all the considered schemes are assumed to employ 4×4 transmit and receive antenna configurations. Hence, to achieve a spectral efficiency of 8 bpcu, the F-QSM employ 4-QAM modulation while, 64-QAM and 16-QAM are used in the SM and QSM respectively.

As depicted in Fig. 2, the simulation results manifest that the proposed F-QSM exhibits significantly better BER performance compared to the conventional SMTs. More specifically, the proposed F-QSM provides about 4 dB improvement over the conventional SM and about 2 dB over the conventional QSM.
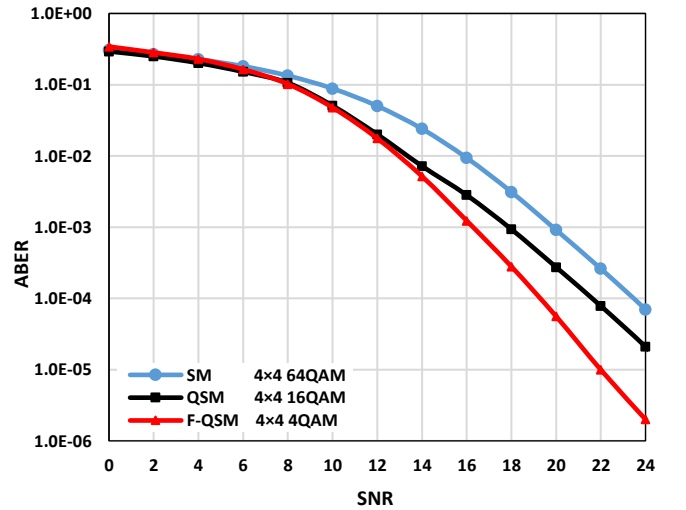

Fig. 2. The ABER performmnce of the F-QSM wighted against the ABER performance of the conventional SM and QSM [10] for $K=2$.
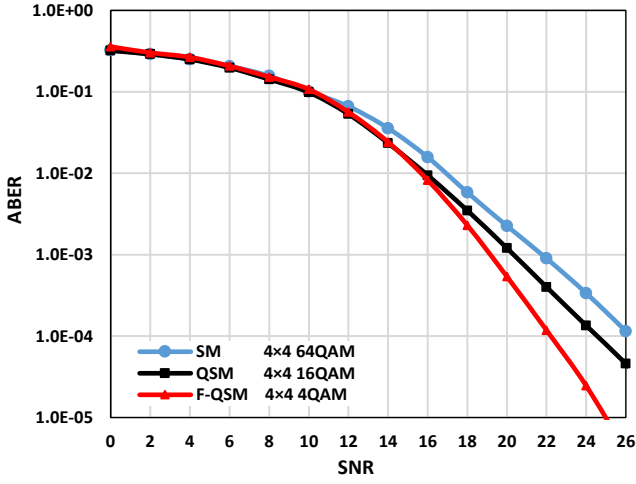
Fig. 3. The ABER performnce of the F-QSM wighted against the ABER performance of the conventional SM and QSM [10] for *K=5*.
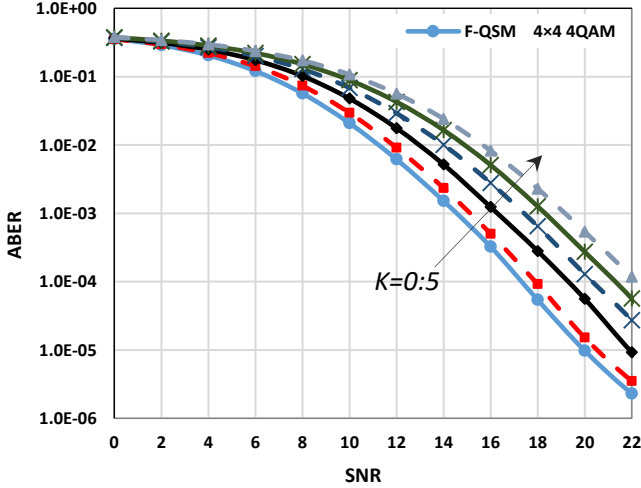

Fig. 4. The ABER performnce of the F-QSM for *K=0:5*.

Likewise, Fig. 3 depicts the ABER comparison for a Rician factor $K = 5$. Again, the ABER performance of the F-QSM outweighs the performance of the conventional SMTs. As, it provides about 3 dB over the SM and about 1.6 dB over the QSM. It should be noted here that, the better error performance of the F-QSM comes with a superior enhancement in the achievable data rate. Since, for example, for $N_t = 16$ and $M = 4$, the F-QSM fulfills 32 bpcu spectral efficiency while, 6 bpcu and 10 bpcu are fulfilled in the SM and QSM respectively [9].

In Fig. 4, the effect of varying the Rician factor on the performance of the F-QSM is investigated. Herein, values of *K=0:5* are considered. As depicted in Fig. 4, the ABER of the F-QSM degrades by increasing the *K* factor. This backs to the effect of the LOS component which complicates the process of differentiating between the variant paths of the channel and therefore, results in a degradation in the BER performance [10].

Fig. 5, depicts the computational complexity of the F-QSM (8) compared to that of the SM and QSM provided by (6) and (7) respectively. Herein, 8 bpcu spectral efficiency is assumed in all schemes. As depicted in Fig. 5, the F-QSM exhibits a higher computational complexity than SM and QSM due to the high number of real operations required to calculate $\boldsymbol{h}_{\ell_\Re}$ or $\boldsymbol{h}_{\ell_\Im}$.
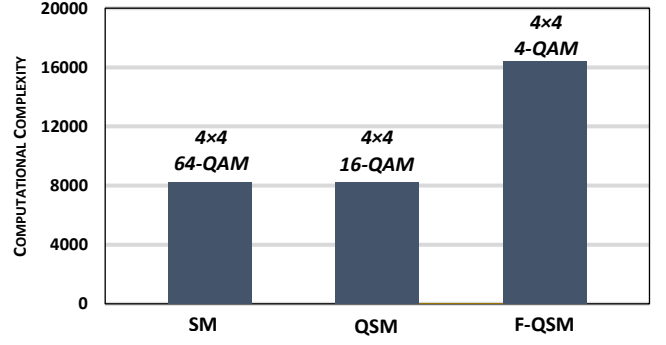

Fig. 5. The computational complexity of the F-QSM wighted against the computational complexity of SM [5] and QSM [7] for 8 bpcu transmission.

V. CONCLUSION

The F-QSM is a class of SMTs that is dedicatedly proposed to vanquish the main drawback of the SMTs which constrains the data rate enhancement to be logarithmically increased with the number of transmit antennas. In this paper, the performance of the F-QSM over Rician fading channel is considered. The ABER performance of the F-QSM is assessed using Monte Carlo simulations and weighted against the ABER of the variant SMTs at different values of Rician factor. Furthermore, the computational complexity of the F-QSM is evaluated as well and compared with the computational complexity of the conventional SMTs. The simulation results substantiate the outweighing of the F-QSM in terms of achievable rates and ABER performance but at the expense of a slight increase in the computational complexity compared to the conventional SMTs.

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