Hardware Implementation of Generalized Space Modulation Techniques Using Simulink RF Blockset

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Abstract. Generalized space modulation techniques (GSMTs) are attractive multiple-input multiple-output (MIMO) technologies that promise significant advantages for future wireless systems. Most existing studies of GSMTs in literature tackle several theoretical issues analytically or through Monte Carlo simulations. However, practical implementation and hardware limitations are yet to be studied. In this paper, GSMTs implementations using RF hardware components within the Simulink RF blockset library is considered. The implementation targets minimum hardware components and proposes fundamental baseband models for different GSMTs. The developed models facilitate the investigation of the impact of different parameters on the overall system performance. The accuracy of these models is corroborated through calculating the average BER and compare it to existing curves in literature. In addition, the required hardware components for GSMTs in passband implementation are discussed.

Keywords: MIMO · Space modulation techniques
Simulink–RF blockset

1 Introduction

The number of connected devices to the Internet witnessed tremendous growth in the past few years and the trend is unlikely to cease in the near future. The need for advanced wireless communication systems in terms of spectral and energy efficiencies as well as hardware simplicity are the key elements that drive research in the future 5G standard and beyond. Future systems require devices with marginal cost and energy consumption while achieving fast connectivity, low complexity and very low end-to-end latency [1].

Space modulation techniques (SMTs) [2–4,6] are one of the promising technologies for next generation wireless systems as they promise several advantages in terms of performance, spectral efficiency, hardware complexity and implementation simplicity and cost. In SMTs, multiple transmit antennas exist but

V. Sucasas et al. (Eds.): BROADNETS 2018, LNICST 263, pp. 247–256, 2019.
https://doi.org/10.1007/978-3-030-05195-2_24

only certain number of them is active at each time instant. It has been revealed in [6] that these techniques can be implemented with a maximum of a single RF-chain while achieving superior performance as compared to other state-of-the-art MIMO technologies. Yet, in SMTs, the number of transmit antennas must be a power of two integer and the use of arbitrary number of antennas is not feasible. Therefore, a generalization of SMTs is proposed in literature to relax these constraints and allow the use of an arbitrary number of transmit antennas. Such generalization is referred to as generalized space modulation techniques (GSMTs) and include generalized space shift keying (GSSK), generalized quadrature space shift keying (GQSSK), generalized spatial modulation (GSM), and generalized quadrature spatial modulation (GQSM) [5].

In this study, we consider the hardware implementation of different GSMTs using Simulink RF blockset and study the impact of RF-switch insertion loss (IL) on the average bit error probability (BER) of these systems. IL has been shown recently to significantly degrade the BER of different SMTs in [7]. Similar behavior is also noticed here for different GSMTs.

The rest of the paper is organized as follows, Sect. 2 describes GSMTs system and channel models. Section 3 presents the implementation of different GSMTs using Simulink RF blockset. Section 4 discusses the obtained results and elaborates on some of the properties of the proposed models. Finally, the paper is concluded in Sect. 5.

2 System and Channel Models

A MIMO system with N_t transmit and N_r receive antennas is considered in this study. At each time instant, η bits are to be transmitted using one of the existing GSMTs. In all GSMTs, a group of transmit antennas, $1 < N_u < N_t$, is activated at each time instant to transmit an identical symbol. The received signal at the receiver input can be written as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{1}$$

where $\mathbf{H}$ denotes an $N_r \times N_t$ MIMO channel matrix with complex Gaussian i.i.d entries as $h_{ij} \sim \mathcal{CN}\left(0,1\right),\ i \in \{1:N_r\},\ j \in \{1:N_t\}$, $\mathbf{x}$ is the transmitted vector of modulated or un-modulated symbols with normalized energy, i.e., $\mathrm{E}\left[\mathrm{xx}^{\mathrm{H}}\right] = 1$ and $\mathbf{n}$ denotes a vector with additive white Gaussian noise entries each with a zero mean and σ_n^2 variance, $n_i \sim \mathcal{CN}\left(0, \sigma_n^2\right)$. As such, the average signal to noise ratio at each receive antenna is $\bar{\gamma} = \frac{1}{\sigma_n^2}$. The received signals are then processed and a maximum likelihood detector is used to retrieve transmitted information bits as

$$\hat{\mathbf{x}} = \arg \min_{\mathbf{x}_i \in \mathcal{X}} \|\mathbf{y} - \mathbf{H}\mathbf{x}_i\|_F^2 \tag{2}$$

where $\hat{\mathbf{x}}$ denotes the estimated symbol vector indicating modulated symbol and/or active antennas, $\mathcal{X}$ being a set containing all possible transmitted vectors and $\|.\|_F$ being the Frobenius norm. Finally, the average BER is taken by comparing the transmitted word with the received word using an Error Rate calculation block.

The transmitted vector $\mathbf{x}$ is generated based on the considered GSMTs as discussed hereinafter.

2.1 Generalized Space Shift Keying (GSSK)

In a GSSK system [8], $\eta_{\text{GSSK}} = \left\lfloor \log_2 \binom{N_t}{N_u} \right\rfloor$ bits are transmitted at each time instant with $\lfloor \cdot \rfloor$ denoting the floor operation. In GSSK, the transmitted bits are incorporated in the location of the activated antennas and the transmitted symbol is un-modulated and only indicating which antennas are active at this time [5].

2.2 Generalized Spatial Modulation (GSM)

GSM is an addition to the GSSK system by transmitting modulated symbols [9]. Hence, the spectral efficiency of a GSM system is $\eta_{\text{GSSK}} = \left\lfloor \log_2 \binom{N_t}{N_u} \right\rfloor + \log_2(M)$. The transmitted symbols can be drawn from arbitrary signal constellations such as quadrature amplitude modulation (QAM) or phase shift keying (PSK).

2.3 Generalized Quadrature Space Shift Keying (GQSSK)

GQSSK is similar to GSSK, where the transmitted symbols are un-modulated and data bits only modulate spatial symbols. However, two groups of antennas are activated in GQSSK, N_u^I and N_u^Q [5]. The first group, N_u^I, transmits the in-phase part of the carrier signal whereas the second group, N_u^Q, transmits the quadrature component of the RF carrier signal as discussed in details in [5]. Hence, the spectral efficiency of GQSSK is $\eta_{\text{GQSSK}} = \left\lfloor 2 * \log_2 \binom{N_t}{N_u} \right\rfloor$.

2.4 Generalized Quadrature Spatial Modulation (GQSM)

Modulating the RF carriers in GQSSK results in a GQSM system [5], which achieves spectral efficiency of $\eta_{\text{GQSM}} = \left\lfloor 2 * \log_2 \binom{N_t}{N_u} \right\rfloor + \log_2(M)$.

3 Simulink RF Blockset System Models

In this work, Simulink baseband implementations of GSMTs using the RF Blockset library are introduced. The BER performance of these systems is studied while considering hardware imperfections, namely RF switch IL. The implemented system models for GSSK, GQSSK, GSM and GQSM are respectively shown in Figs. 1, 2, 3, and 4. Each illustrated model consists mainly of four main stages/blocks: The transmitter, the channel, the receiver, and the BER calculation. The depicted models also consider a MIMO setup with arbitrary number of transmit and receive antennas.

It is important to note that practical hardware components suffer from several imperfections other than only IL. Some imperfections include: Frequency offset, weak isolation, return loss, and VSWR. While out of the scope of this work, all of these imperfections need to be studied and their impact on the overall system performance should be analyzed before any practical hardware implementation. However, it would be beneficial to study the imperfections in isolation to better understand the effect on system performance as a whole. Since the RF switch is newly introduced as an active component for the implementation of SMTs in particular, and MIMO in general, it was elected to focus on the switch imperfections first.

In the transmitter blocks, the main function is to handle the input word from the random binary source. The input word, is divided into two parts, the first with $\log_2(M)$ bits (if GSM/GQSK based model) that are routed to a modulator block. The second, are the remainder of the bits that control the RF-switch select lines. Contrary to non-generalized implementations $\log_2(N_t)$ bits cannot be routed directly to the switches since there are different sets of combinations that activate multiple switches. Therefore, a decoder block is utilized to provide a mapping between the received bits and the select line states. In the transmitter blocks, the input signal power is also split through power dividers to the different RF-switch inputs. The number of power dividers needed depends on how many RF-switches are used; two being the minimum.

In the remainder of the model, a channel block exists to generate the $\mathbf{H}$ matrix, modeling Rayleigh fading, and applying AWGN. The resulting $\mathbf{y}$ vector and $\mathbf{H}$ are passed on to the receiver block. Finally, the receiver block applies the maximum likelihood (ML) decoder algorithm where demodulation is applied and the transmitted bits are recovered.

4 Results

The BER of the different GSMTs presented in the previous section is evaluated through Monte Carlo simulations while considering the effect of RF-switch IL. In the results, three different values of IL are considered. Namely, 0 dB IL, which represents the ideal case of no IL, 1.5 dB, and 3 dB IL. The SNR is varied from 0 dB to 30 dB and the average BER is computed for at least 10^6 bits for each depicted SNR value. For fair comparison among different GSMTs, a spectral efficiency of 6 bps/Hz is assumed for all systems while considering $N_r = 4$ receive antennas and varying the number of transmit antennas and/or modulation order. The considered system parameters for different GSMTs to achieve the target spectral efficiency are tabulated in Table 1 (Figs. 5 and 6).

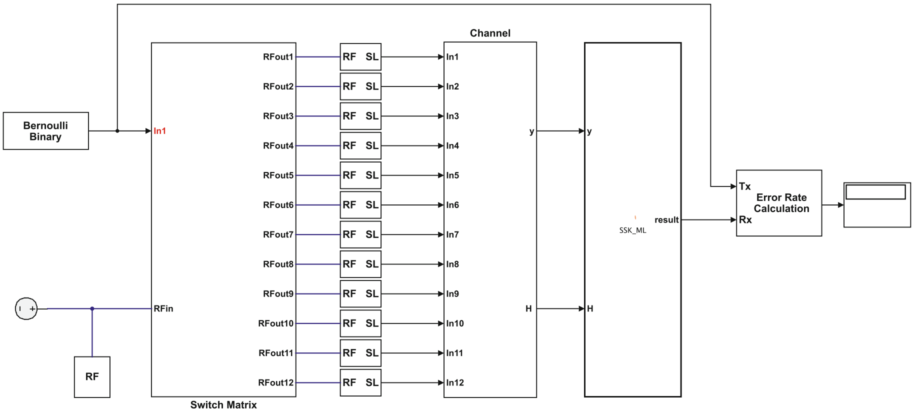

Fig. 1. Simulink model of GSSK with $N_t = 12$, $N_r = 4$, and $N_u = 2$ antennas

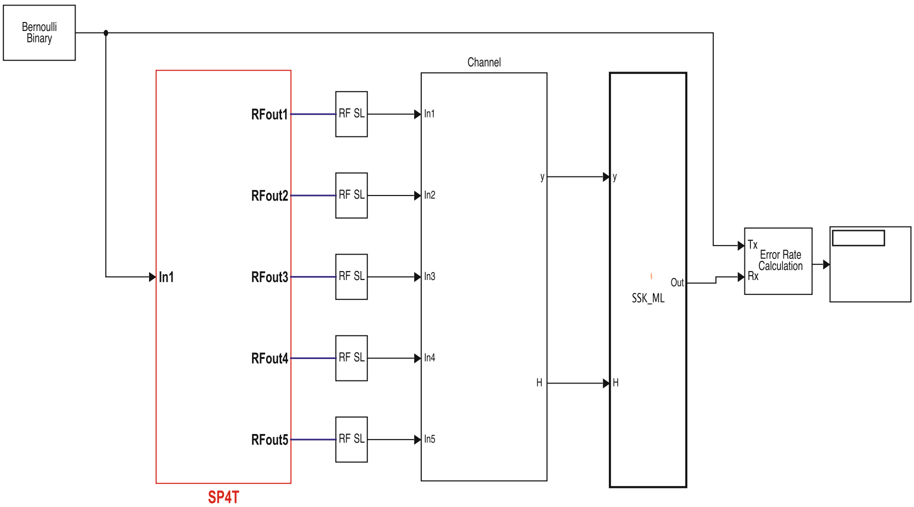

Fig. 2. Simulink model of GQSSK with $N_t = 5$, $N_r = 4$, $N_u = 2$ antennas

Table 1. Simulink GSMTs parameters to achieve a spectral efficiency of $\eta = 6$ bps/Hz.

Model	η (bps/Hz)	$N_t \times N_r$	M	N_u
GSSK	6	12×4	N/A	2
GQSSK	6	5×4	N/A	2
GSM	6	5×4	8	2
GQSM	6	4×4	4	2

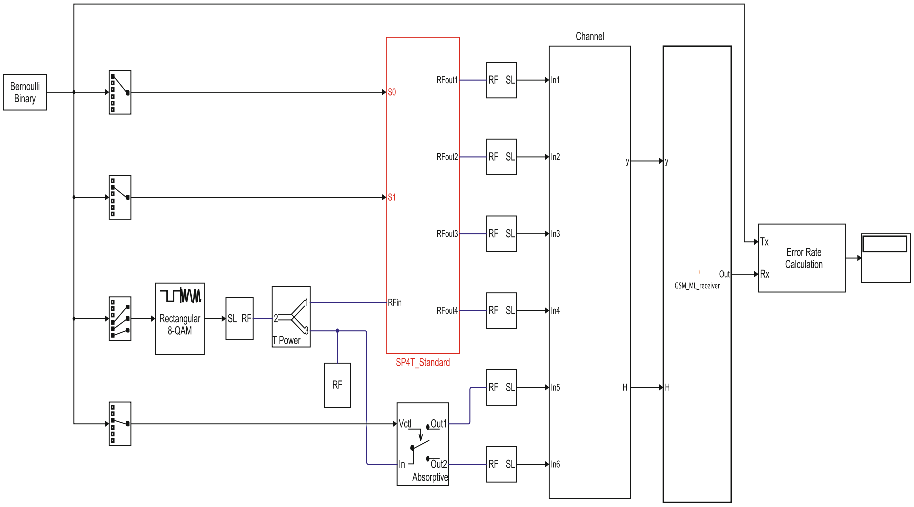

Fig. 3. Simulink model of GSM with $N_t = 5$, $N_r = 4$, $N_u = 2$ antennas

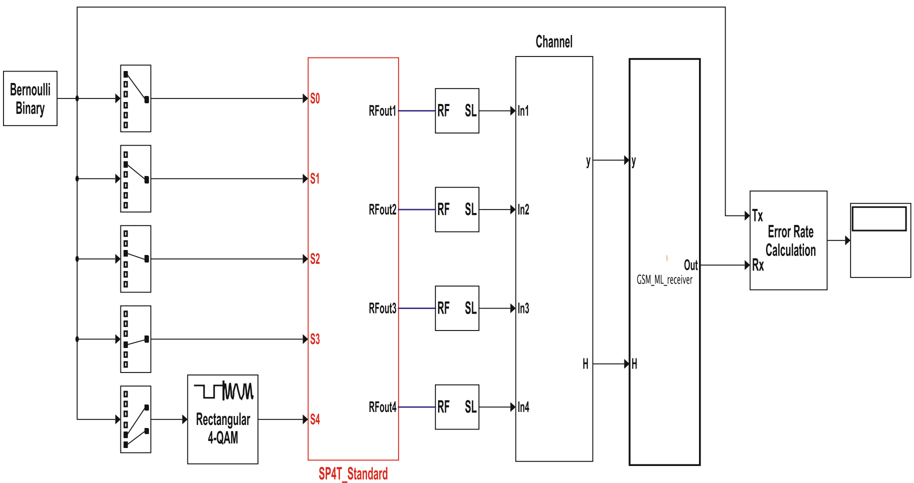

Fig. 4. Simulink model of GQSM with $N_t = 4$, $N_r = 4$, $N_u = 2$ antennas

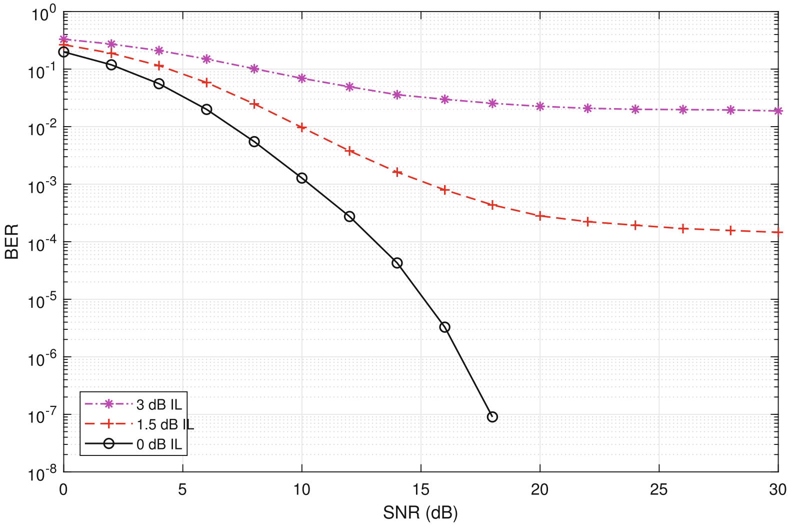

Fig. 5. BER performance of GSSK for different values of IL and with $N_t = 12$, $N_r = 4$, and $N_u = 2$.

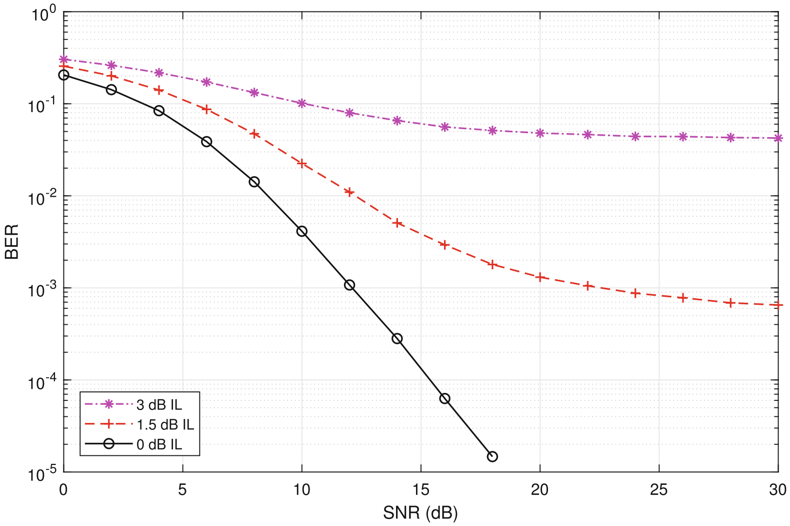

Fig. 6. BER performance of GQSSK for different values of IL and with $N_t = 5$, $N_r = 4$, and $N_u = 2$.

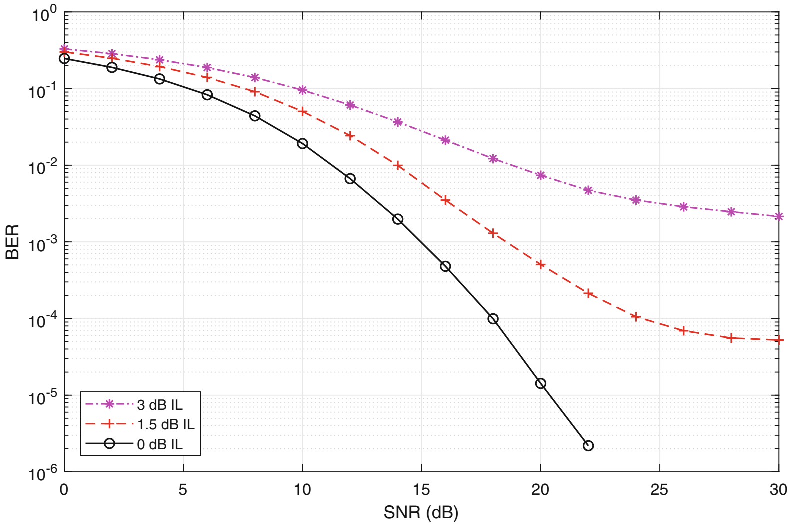

Fig. 7. BER performance of GSM for different values of IL and with $N_t = 5$, $N_r = 4$, $N_u = 2$, and $M = 8$-QAM.

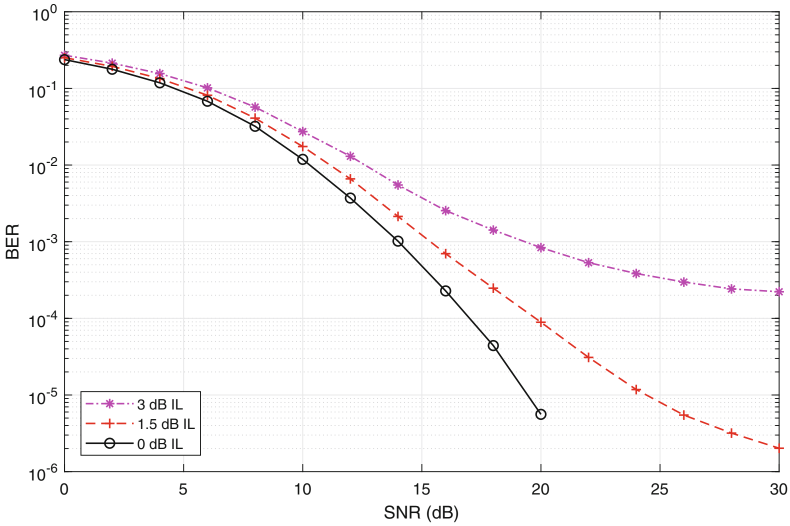

Fig. 8. BER performance of GQSM for different values of IL and with $N_t = 4$, $N_r = 4$, $N_u = 2$, and $M = 4$-QAM.

Depicted results for all systems reveal the negative impact of IL on the average BER performance of all GSMTs. Increasing the IL from 0 dB to 3 dB is shown to significantly deteriorate the system performance and an error floor is noticed for all GSMTs. Comparing the results of the different systems show that GSSK and GQSSK outperform GSM and GQSM in the ideal case of 0 dB IL. However, for large values of IL, GSM and GQSM are shown to be superior over GSSK and GQSSK. This is because IL significantly deteriorates the detection of spatial symbols and increases the BER values of GSSK and GQSSK tremendously (Figs. 7 and 8).

The reported Simulink models in this paper for variant GSMTs can also be used to study the performance of these systems in real time implementations. They are the first step towards practical deployment of these techniques and they can be used to optimize performance and design specific hardware components tailored to the special nature of these techniques.

5 Conclusions

This paper proposes the use of Simulink RF blockset baseband models to implement the different GSMTs and study their performance under practical hardware assumptions and scenarios. To illustrate the effectiveness of the proposed models, the impact of RF switch IL on the overall BER performance of these systems is studied and discussed. Future hardware implementations of GSMTs can be simplified and optimized using the reported models. Future works will address the investigation of different hardware impairments and optimize the design of GSMTs for better and enhanced performance.

Acknowledgments. The authors acknowledge the financial support of the Deanship of Scientific Research at the German Jordanian University under research grant number SIC 41/2016.

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