A Half-Full Transmit-Diversity Spatial Modulation Scheme

Sakher AbuTayeh[1], Mohammad Alsalahat[1], Ibrahim Kaddumi[1],
Yahya Alqannas[1], Saud Althunibat[1](✉), and Raed Mesleh[2]

[1] Department of Communications Engineering, Al-Hussein Bin Talal University,
Maan, Jordan
`Saud.althunibat@ahu.edu.jo`
[2] School of Electrical Engineering and Information Technology, German Jordanian
University, Amman, Jordan
`raed.mesleh@gju.edu.jo`

Abstract. One of the main limitations in Spatial Modulation (SM) systems is the lack of transmit diversity, which directly impacts its error rate performance. The lack of the transmit diversity refers to activating only a single transmit antenna in SM systems. In this paper, we propose a novel scheme that aims at improving the performance of SM systems by achieving half-full transmit diversity. The proposed scheme, called *Half-Full Transmit-Diversity SM (HFTD-SM)*, divides the transmit antennas into two-antenna groups. From each group, only a single antenna is activated, and all active transmit antennas emits one modulated symbol. The proposed HFTD-SM scheme is shown to outperform the conventional SM performance in terms of spectral efficiency, error rate, and design flexibility, while maintaining the main property of SM representing by the need of only a single RF chain. Simulation results corroborate the superior performance of the proposed scheme as compared to other SM variants in the literature.

Keywords: MIMO · Space modulation · Spatial modulation
Transmit diversity

1 Introduction

Space modulation systems have been widely investigated in the literature due to their promising features as compared to traditional multi-antenna systems [1,2]. In space modulation, the transmitted bits are not only conveyed by the conventional signal modulation, but also the index of the transmit antenna is exploited to convey additional bits. The earlier version of space modulation is called Spatial Modulation (SM) [3]. SM implies activating only a single transmit antenna to carry a modulated symbol, while other transmit antennas are left silent. As such, SM overcomes a main problem in Multi-Input Multi-Output (MIMO) systems represented by the inter-channel interference. This is attained by avoiding

V. Sucasas et al. (Eds.): BROADNETS 2018, LNICST 263, pp. 257–266, 2019.
https://doi.org/10.1007/978-3-030-05195-2_25

parallel transmissions from different antennas in typical MIMO systems. Moreover, SM is shown to require a single RF chain, which reduces installation and running costs [4].

SM has been extended to the Generalized SM (GSM) [5], where a combination of transmit antennas can be simultaneously used to transmit identical data symbol aiming at improving the spectral efficiency. Another promising advanced SM scheme has been proposed in [6], referred to Quadrature SM (QSM), where the in-phase and the quadrature components of the modulated symbol are emitted over two different transmit antennas. QSM has also been widely investigated in the literature [7–11].

It has been reported that SM encounters several problems and constraints that limit its performance. A first problem is that SM can exploit only a number of transmit antennas that is a power-of-two. Therefore, extra transmit antennas may left unused in the conventional SM scheme. Although GSM scheme releases this constraint by using combinations of transmit antennas, the constraint has been actually moved to the number of antennas' combinations [12]. Other solutions have also been proposed in [13–15]. Another problem is the bit-to-symbol mapping in SM, where it becomes difficult to satisfy the Gray mapping principles in SM due to the dependency on the random channel characteristics [16], and thus, error performance is degraded. In [17,18], efficient bit-to-symbol mapping schemes are proposed aiming at minimizing the hamming distance between adjacent symbols, which consequently, improves the attainable bit error rate. Many other studies investigate SM and QSM from different aspects, including performance under fading channels [19,20], hardware implementation [21], cooperative networks [22–24], spectrum sharing and cognitive radio networks [25,26], wireless sensor networks [27,28], and non-coherent variants [29,30].

Transmit diversity is one of the main features in MIMO systems, which is considered a source of enhanced performance. However, conventional SM does not achieve any transmit diversity due to activating only a single transmit antenna at each transmission time. Improving the transmit diversity should definitely improve the error performance at the receiver. Several works in the literature have attempted to improve the transmit diversity in SM. In [31], the spatial constellation and the diagonal space time block code are combined to improve the transmit diversity. However, it is limited to low modulation orders. Phase alignment is used at the transmitter to improve the diversity of SM schemes in [32]. The impact of several parameters, such as shaping filters and signal constellations, on the transmit diversity has been investigated in [33]. The transmit diversity of QSM is enhanced by using two sets of dispersion matrices in [34]. Recently, the transmit diversity of SM is improved by interleaving the quadrature components of two successive symbols in [35].

In this paper, aiming at improving the transmit diversity in SM, a new SM scheme is proposed. The proposed scheme is referred to Half-Full Transmit-Diversity SM (HFTD-SM) scheme. The proposed HFTD-SM scheme implies dividing the transmit antennas into groups, where each group includes only two transmit antennas. From each group, only a single antenna is activated at each transmit time. All activated antennas at a time instance will emit the same modulated symbol. As such, the proposed scheme still maintains the most important property of SM, which is represented by the need of a single RF chain. On the other hand, the proposed scheme can provide transmit diversity that is equal to the half of the full transmit diversity. Moreover, for the same number of transmit antennas, the proposed HFTD-SM can achieve higher spectral efficiency than the conventional SM. Also, the proposed HFTD-SM scheme does not require a power-of-two number of transmit antennas, whereas an even number of transmit antennas can be fully exploited. Simulation and analytical results demonstrate the high performance of the proposed scheme in terms of the spectral efficiency and the bit error rate as compared to other schemes in the literature.

The rest of the paper is organized as follows. Section 2 presents the system model with a description of the conventional SM scheme. The proposed HFTD-SM is presented and discussed in Sect. 3. The performance of the proposed HFTD-SM scheme in terms of the spectral efficiency and the error rate is analyzed in Sect. 4. Simulation results are presented and discussed in Sect. 5, and conclusions are drawn in Sect. 6.

2 System Model

A MIMO system that includes N_t transmit antennas and N_r receive antennas is considered in this paper. The channel distribution between the i^{th} transmit antenna and the j^{th} receive antenna, denoted by h_{ij}, is modeled as a Rayleigh fading channel with zero mean and unity variance. No correlation is assumed among transmit nor receive antennas.

The transmitted vector is denoted by $\mathbf{x} = [x_1, x_2, \cdots, x_{N_t}]^T$, where x_i represents the transmitted signal from the i^{th} transmit antenna and ^{T} denotes the transpose operator. Accordingly, the received signal vector $\mathbf{y}$ is expressed as

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

where $\mathbf{H}$ is the $N_r \times N_t$ channel matrix, and $\mathbf{w}$ is the additive white Gaussian noise vector at the receive antennas. The entries of $\mathbf{w}$ are modeled as complex Gaussian random variables with zero mean and σ_w^2 variance.

At the receiver end, Maximum Likelihood (ML) detection is applied to retrieve the transmitted vector as

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

where $\hat{\mathbf{x}}$ is the detected vector, $\mathcal{X}$ is a set containing all possible transmission vectors, and $\| \cdot \|_F^2$ is the squared Froeinius norm.

In the conventional SM scheme, only a single antenna is activated which is selected based on $\log_2 N_t$ transmitted bits. Other $\log_2 M$ bits (M is the modulation order) are modulated, and the modulated symbol is sent via the selected transmit antenna. As such, a block of $\log_2 N_t M$ bits is transmitted at each transmission time in the conventional SM. Notice that, as only a single transmit antenna is activated, the transmission vector $\mathbf{x}$ includes only a single nonzero element, which limits the transmit diversity in SM systems. Also, it is clear that N_t should be a power-of-two in order to have an integer number of transmitted bits.

3 Half-Full Transmit Diversity SM (HFTD-SM)

Motivated by the limited transmit diversity in SM systems and the constraint on the number of transmit antennas, a new SM scheme is proposed in this section, aiming to overcome the mentioned limitations. The proposed HFTD-SM scheme is able to achieve to the half of the full transmit diversity, which consequently improves its performance in terms of the error rate at the receiver end.

The proposed HFTD-SM scheme implies that transmit antennas are divided into $\frac{N_t}{2}$ groups, where each group includes only two transmit antennas. A single antenna from each group is activated based on a single transmitted bit. As such, $\frac{N_t}{2}$ bits are used to select the active antennas in all groups. Other $\log_2 M$ bits are modulated and emitted from the selected transmit antennas. As such, the transmitted block includes $\frac{N_t}{2} + \log_2 M$ bits.

It is worth mentioning that the proposed scheme still requires a single RF chain as in the conventional SM, although multiple transmit antennas are simultaneously activated. This is due to the fact that all active antennas will transmit the same modulated symbol at each transmission time, and hence, all active antennas can use the same RF chain. Also, a power-of-two number of the transmit antennas is not anymore a requirement in the proposed HFTD-SM scheme, where an even number of the transmit antennas can be utilized.

3.1 Example

Consider a system with $N_t = 8$ and $M = 4$. Let us denote the transmit antennas by $a_1, a_2, ..., a_8$. HFTD-SM will divide the transmit antennas into 4 groups as follows (a_1, a_2), (a_3, a_4), (a_5, a_6) and (a_7, a_8). Assume the first antenna in each group is labeled by 0, while the second antenna in each group is labeled by 1. The transmitted bit block should include $\frac{N_t}{2} + \log_2 M = 6$ bits. Assume the transmitted block at a specific time is 110101. The first 4 bits are used to determine the active antennas in the four groups, respectively. Therefore, based on the bits and the antennas' labels, the transmit antennas a_2, a_4, a_5 and a_8 will be selected to transmit the modulated symbol. The modulated symbol is generated by modulating the last two bits 01. Using 4-QAM constellation, the modulated symbol is $-1 + j$. Hence, the transmission vector $\mathbf{x}$ is formulated by substituting the value of the modulated symbol in the corresponding elements of the active antennas as follows $\mathbf{x} = [0, -1 + j, 0, -1 + j, -1 + j, 0, 0, -1 + j]$. Notice that to normalize the transmit power to unity, the vector $\mathbf{x}$ is multiplied by $\sqrt{\frac{2}{N_t}}$.

4 Performance Analysis

An analytical discussion on the performance of the proposed HFTD-SM scheme in terms of the spectral efficiency and the average BER is discussed in this section.

4.1 Spectral Efficiency

The spectral efficiency of the proposed HFTD-SM scheme (η_{HF}) is expressed as

$$\eta_{HF} = \frac{N_t}{2} + \log_2 M \tag{3}$$

while the conventional SM can achieve a spectral efficiency given as

$$\eta_{SM} = \log_2 N_t + \log_2 M \tag{4}$$

Clearly, the proposed HFTD-SM can achieve higher spectral efficiency for high values of N_t (i.e., $N_t > 4$). The spectral efficiency difference between the two schemes (Δ) can be expressed as

$$\Delta = \frac{N_t}{2} - \log_2 N_t, \tag{5}$$

which is equal to zero for $N_t = 2$ and 4, while it starts increasing as N_t increases. For example, at $N_t = 16$, the spectral efficiency difference is 4 bps/Hz, which represents a great enhancement in the spectral efficiency as compared to the conventional SM scheme.

4.2 Bit Error Rate

The average BER for the proposed HFTD-SM scheme can be upper-bounded using the well-known union-bound technique [36] given by

$$\zeta = \frac{1}{m2^m} \sum_{k=1}^{m} \sum_{\hat{k}=1}^{m} e_{k\hat{k}} \mathrm{PEP}_{k\hat{k}}, \tag{6}$$

where m is the block length ($m = \frac{N_t}{2} + \log_2 M$), $\mathrm{PEP}_{k\hat{k}}$ is the average pair-wise error probability defined as the probability that $\mathbf{x}_{\hat{k}}$ is detected given that $\mathbf{x}_k$ is actually transmitted, and $e_{k\hat{k}}$ is the hamming distance between the corresponding bit blocks of $\mathbf{x}_{\hat{k}}$ and $\mathbf{x}_k$.

The pair-wise error probability for a given $\mathbf{H}$ can be computed and written with the aid of the Q-function [37] as [20]

$$\mathrm{PEP}_{k\hat{k}/\mathbf{H}} = Q(\mu), \tag{7}$$

where μ is given by

$$\mu = \frac{1}{2\sigma_n^2} \|\mathbf{H}(\mathbf{x} - \hat{\mathbf{x}})\|_F^2 \tag{8}$$

The unconditional pair-wise error probability can be computed by averaging (7) over the pdf of the channel, where it is usually expressed as

$$\mathrm{PEP}_{k\hat{k}} = \frac{2^{N_r-1}\Gamma(N_r+0.5)}{\sqrt{\pi}(N_r)!}\left(\frac{1}{\overline{\mu}}\right)^{N_r}, \tag{9}$$

where $\overline{\mu}$ is the average value of μ, and $\Gamma(\cdot)$ is the Gamma function [37].

5 Simulation Results

This section provides simulation results of the performance of the proposed HFTD-SM scheme in terms of the spectral efficiency and the average BER. The proposed scheme is compared to two other schemes, namely SM and QSM. The average SNR is defined as the symbol energy per noise power. As the symbol energy is set to unity, the SNR is equal to $\frac{1}{\sigma_n^2}$.

Figure 1 shows the attainable spectral efficiency, η, versus the number of transmit antennas N_t for SM, QSM and HFTD-SM schemes. The modulation order is set to $M = 4$. In both SM and QSM, when N_t is not a power-of-two, the spectral efficiency is equal to the one achieved by the nearest power-of-two lower than N_t. For example, at $N_t = 6$, the spectral efficiency for SM and QSM is 4 and 6 bps/Hz, respectively, which are equal to the spectral efficiency achieved at $N_t = 4$. On the other hand, the proposed HFTD-SM does not require that N_t to be a power-of-two, where it can achieve higher spectral efficiency once N_t becomes an even number. Also, it can be seen that the proposed scheme can achieve higher spectral efficiency than SM for $N_t > 4$, and higher than QSM for $N_t > 8$.

The average BER versus the average SNR for the proposed HFTD-SM and SM schemes is shown in Fig. 2 at a spectral efficiency of 8 bps/Hz. The considered configuration of SM to achieve the desired spectral efficiency is $N_t = 8$ and $M = 32$-PSK, while $N_t = 8$ and $M = 16$-PSK are the considered parameters for the proposed HFTD-SM scheme. The number of receive antennas is set to $N_r = 2$. A clear SNR gain is achieved by the proposed HFTD-SM as compared to the conventional SM scheme, especially at high SNR values. For instance, at a BER of 10^{-4}, the SNR gain is about 4 dB.

Figure 3 confirms the high performance of the proposed HFTD-SM scheme indicated in Fig. 2. The spectral efficiency is set at 10 bps/Hz, which is achieved by $N_t = 8$, $M = 128$-PSK for the SM scheme, and by $N_t = 8$ and $M = 64$-PSK for the proposed HFTD-SM scheme. At a BER of 10^{-4}, the SNR gain is about 6 dB due to the improved transmit diversity provided by the proposed HFTD-SM scheme.

The last result is shown in Fig. 4, where the average BER versus the SNR is plotted for the QSM and the HFTD-SM schemes at a spectral efficiency of 17 bps/Hz. For QSM, $N_t = 32$ and $M = 128$-PSK, while for HFTD-SM, $N_t = 32$ and $M = 2$ (BPSK). In both schemes, $N_r = 2$. At 10^{-4} BER, the proposed scheme can outperform the QSM scheme by about 3 dB SNR gain.

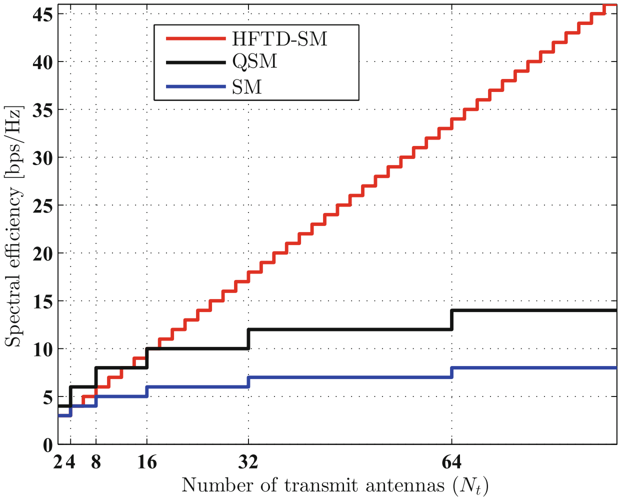

Fig. 1. The spectral efficiency versus the number of transmit antennas for the proposed HFTD-SM, QSM and the conventional SM schemes at a modulation order of 4.

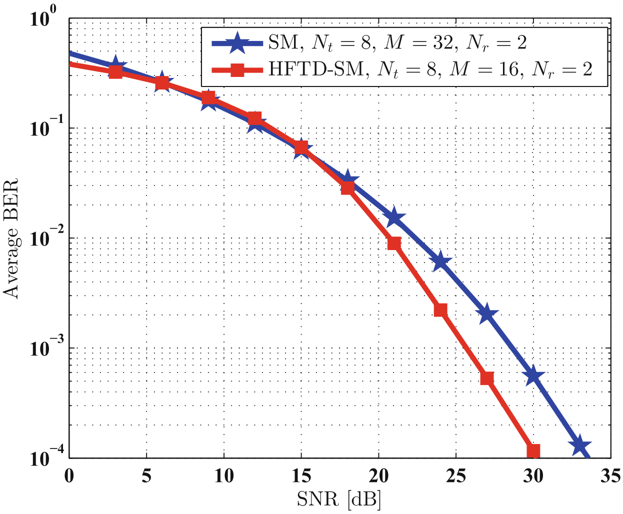

Fig. 2. The average BER versus the SNR for the proposed HFTD-SM and the conventional SM schemes at spectral efficiency of 8 bps/Hz.

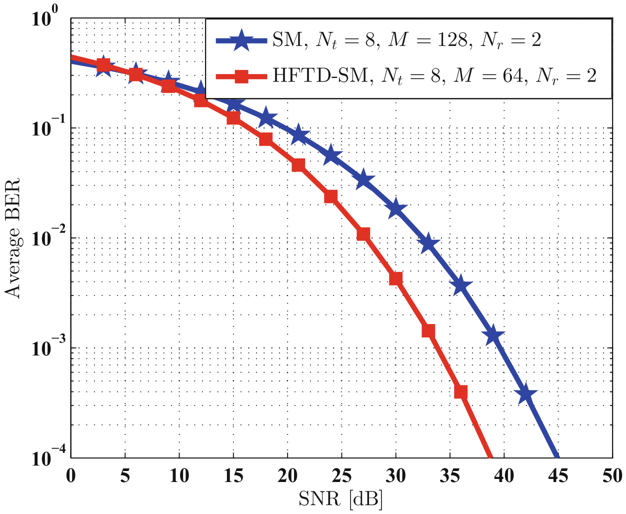

Fig. 3. The average BER versus the SNR for the proposed HFTD-SM and the conventional SM schemes at spectral efficiency of 10 bps/Hz.

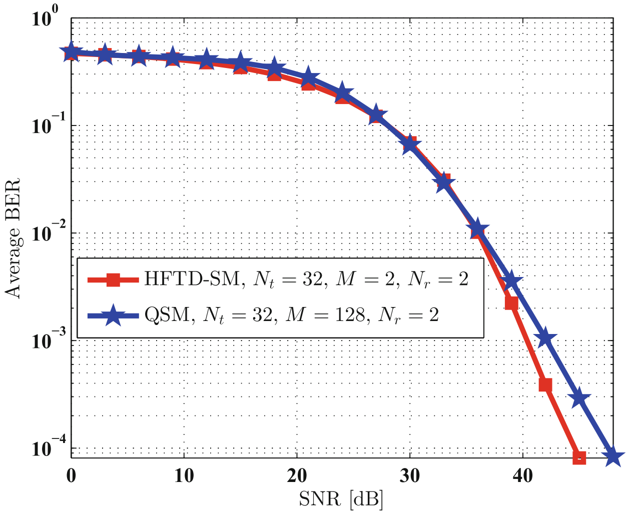

Fig. 4. The average BER versus the SNR for the proposed HFTD-SM and the QSM schemes at spectral efficiency of 17 bps/Hz.

6 Conclusions

A new spatial modulation scheme that is able to achieve half of the full transmit diversity is proposed in this paper. The proposed scheme implies dividing the transmit antennas into two-antenna groups. For each group, a single antenna is activated, and all active antennas will transmit the same modulated symbol. Analytical and simulation results prove the high performance of the proposed scheme in terms of the spectral efficiency and the bit error rate.

References

1. Ishikawa, N., et al.: 50 years of permutation, spatial and index modulation: from classic RF to visible light communications and data storage. IEEE Commun. Surv. Tuts. **20**, 1905–1938 (2018)
2. Basar, E., et al.: Index modulation techniques for next-generation wireless networks. IEEE Access **5**(1), 16693–16746 (2017)
3. Mesleh, R.Y., et al.: Spatial modulation. IEEE Trans. Veh. Technol. **57**(4), 2228–2241 (2008)
4. Yang, P., et al.: Design guidelines for spatial modulation. IEEE Commun. Surv. Tuts. **17**(1), 6–26 (2015)
5. Younis, A., et al.: Generalised spatial modulation. Asilomar Pacific Grove, CA, pp. 1498–1502 (2010)
6. Mesleh, R., et al.: Quadrature spatial modulation. IEEE Trans. Veh. Technol. **64**(6), 2738–2742 (2015)
7. Althunibat, S., Mesleh, R.: Cooperative decode-and-forward quadrature spatial modulation over correlated and imperfect $\eta - \mu$ fading channels. Wireless Networks (2017). https://doi.org/10.1007/s1127
8. Younis, A., et al.: Quadrature spatial modulation performance over nakagami- m fading channels. IEEE Trans. Veh. Technol. **65**(12), 10227–10231 (2016)
9. Afana, A., et al.: Performance of quadrature spatial modulation in amplify-and-forward cooperative relaying. IEEE Commun. Lett. **20**(2), 240–243 (2016)
10. Badarneh, O.S., Mesleh, R.: A comprehensive framework for quadrature spatial modulation in generalized fading scenarios. IEEE Trans. Commun. **64**(7), 2961–2970 (2016)
11. Xiao, L., et al.: Low-complexity signal detection for large-scale quadrature spatial modulation systems. IEEE Commun. Lett. **20**(11), 2173–2176 (2016)
12. Mesleh, R., et al.: Generalized space modulation techniques: Hardware design and considerations. Phys. Commun. **26**, 87–95 (2018)
13. Althunibat, S.: A mapping technique for Space Shift Keying with arbitrary number of transmit antennas. IEEE CAMAD, Lund (2017)
14. Serafimovski, N., et al.: Fractional bit encoded spatial modulation (FBE-SM). IEEE Commun. Lett. **14**(5), 429–431 (2010)
15. Yang, Y., Aissa, S.: Information guided channel hopping with an arbitrary number of transmit antennas. IEEE Commun. Lett. **16**(10), 1552–1555 (2012)
16. Al Sukkar, G., Althunibat, S.: Gray codes for Spatial Modulation systems: an open research issue. IEEE CAMAD, Lund, pp. 1–6 (2017)
17. Yang, P., et al.: Hybrid bit-to-symbol mapping for spatial modulation. IEEE Trans. Veh. Technol. **65**, 5804–5810 (2015)

18. Althunibat, S., Mesleh, R.: A bit-to-symbol mapping scheme for spatial modulation with partial channel state information. IEEE Commun. Lett. **21**(5), 995–998 (2017)
19. Mesleh, R., et al.: Performance analysis of spatial modulation and space-shift keying with imperfect channel estimation over generalized $eta-mu$ fading channels. IEEE Trans. Veh. Technol. **64**(1), 88–96 (2015)
20. Jeganathan, J., et al.: Spatial modulation: optimal detection and performance analysis. IEEE Commun. Lett. **12**(8), 545–547 (2008)
21. Mesleh, R., et al.: Transmitter design and hardware considerations for different space modulation techniques. IEEE Trans. Wirel. Commun. **16**(11), 7512–7522 (2017)
22. Afana, A., et al.: Quadrature Spatial Modulation for Cooperative MIMO 5G Wireless Networks, pp. 1–5. IEEE Globecom Workshops, Washington, DC (2016)
23. Althunibat, S., Mesleh, R.: Performance analysis of quadrature spatial modulation in two-way relaying cooperative networks. IET Commun. **12**(4), 466–472 (2018)
24. Yu, X., et al.: Power allocation and performance analysis of cooperative spatial modulation in wireless relay networks. IEEE Access **6**, 12145–12155 (2018)
25. Ustunbas, S., et al.: Performance analysis of cooperative spectrum sharing for cognitive radio networks using spatial modulation at secondary users. IEEE VTC Spring, Nanjing, pp. 1–5 (2016)
26. Bouida, Z., et al.: Adaptive spatial modulation for spectrum sharing systems with limited feedback. IEEE Trans. Commun. **63**(6), 2001–2014 (2015)
27. Althunibat, S., et al.: On the performance of wireless sensor networks with QSSK modulation in the presence of co-channel interference. Telecommun. Syst. **68**(1), 105–113 (2018)
28. Althunibat, S., Mesleh, R.: Index modulation for cluster-based wireless sensor networks. IEEE Trans. Veh. Technol. **PP**(99), 1. https://doi.org/10.1109/TVT.2018.2820602
29. Bian, Y., et al.: Differential spatial modulation. IEEE Trans. Veh. Technol. **64**(7), 3262–3268 (2015)
30. Mesleh, R., et al.: Differential quadrature spatial modulation. IEEE Trans. Commun. **65**(9), 3810–3817 (2017)
31. Nguyen, T.D., et al.: A spatial modulation scheme with full diversity for four transmit antennas. In: ATC Conference, Ho Chi Minh City, pp. 16–19 (2015)
32. Masouros, C.: Improving the diversity of spatial modulation in MISO channels by phase alignment. IEEE Commun. Lett. **18**(5), 729–732 (2014)
33. Renzo, M.D., Haas, H.: On transmit diversity for spatial modulation MIMO: impact of spatial constellation diagram and shaping filters at the transmitter. IEEE Trans. Veh. Technol. **62**(6), 2507–2531 (2013)
34. Wang, L., et al.: Diversity-achieving quadrature spatial modulation. IEEE Trans. Veh. Technol. **66**(12), 10764–10775 (2017)
35. Althunibat, S., Mesleh, R.: Enhancing spatial modulation system performance through signal space diversity. IEEE Commun. Lett. **22**(6), 1136–1139 (2018). https://doi.org/10.1109/LCOMM.2018.2817621
36. Simon, M.K., et al.: Digital Communication Techniques: Signal Design and Detection. Prentice Hall PTR, Englewood Cliffs (1995)
37. Abramnowitz, M., Stegun, I.A.: Handbook of Mathematical Functions. US Dept. of Commerce, National Bureau of Standards, Washington, DC (1972)