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Differential Chaos Shift Keying-Assisted Media-Based Modulation

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ABSTRACT

This study proposes a new energy-efficient and high data-rated communication technique by combining media-based modulation (MBM) and differential chaos shift keying technique (DCSK), called DCSK–MBM. The MBM technique, which forms the infrastructure of this proposed system, is one of the newest members of the index modulation family, while DCSK offers considerable performance improvements for fading channels. Communication comprises two stages in the DCSK system. In the first stage, only the reference symbol is transmitted to the receiver side, whereas in the second stage, information is carried along with the reference symbol. The negative aspect of this method is that it reduces both transmission data rate and spectral efficiency. The MBM technique provides a significant increase in both spectral efficiency and data rate because it performs index modulation with reconfigurable antennas and transmits extra information bits. To minimize the disadvantages of the DCSK technique and create a more energy-efficient and high data-rated technique, the MBM technique is combined with the DCSK technique. Thus, considerable progress is made. All performance analyses are performed over Rayleigh fading channels for M-ary phase shift keying/quadrature amplitude modulation.

Keywords: Differential chaos shift keying, media-based modulation, index modulation, radio frequency mirrors, reconfigurable antennas, bit error rate

Introduction

In today's world, high-speed internet surfing; downloading and uploading high-sized documents, photos, and video files; mobile radio, television, and videoconferencing applications; virtual private networks; online gaming, massively multiplayer online role-playing games, and augmented reality applications; and many other areas that cannot be counted demand very high data-rated internet access. Previously, communication was mostly one way. However, with the development of 5G technology, communication began to evolve into a more flexible and interactive structure. In recent years, humans have been involved in several enhancements such as smart traffic lights, sensor systems of smart cities, smart home systems, smart home appliances, smart industrial automation systems, medical devices, drones, robots, and internet of things devices. In this regard, considering that 75.4 billion devices will be connected to the internet until the end of 2025, it is an indisputable fact that next-generation communication systems must be innovative, high data-rated, high energy and spectral-efficient, and secure [1-5].

Networks that are 5G and beyond require highly flexible radio communication techniques. The basic principle of index modulation (IM) involves the transmission of information through the indices of the main components (transmit antennas, subcarriers, time intervals, modulation types, orthogonal codes, etc.) of the communication system under consideration. Thus, the IM systems offer high energy and spectral efficiency. Unlike traditional modulation techniques based on the amplitude, phase, and frequency of the carrier signal, the information in the IM techniques is embedded in the signal. In this way, additional information is transmitted using much less energy or without using any energy. Therefore, spectral efficiency is increased and additional hardware costs are reduced to minimum levels [6-9].

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The media-based modulation (MBM) technique, one of the newest members of the IM family, has brought a new dimension to the wireless communication system. The MBM technique has advantages such as high data speed, high spectral efficiency, and better system performance compared with conventional communication systems. The MBM system creates different channel states through reconfigurable antennas. The MBM technique uses radio frequency (RF) mirrors in the transmission scheme to carry additional information bits. With this feature, the MBM method provides great advantages over spatial modulation (SM) and space shift keying (SSK) methods that require a large number of transmitting antennas to increase spectral efficiency. The spectral efficiency is limited by the logarithm of the number of antennas on two bases in the SM and SSK methods. However, the spectral efficiency of the systems increases linearly with the number of RF mirrors used in the MBM technique. With these marvelous advantages, MBM has become the focus of attention for several researchers. In the MBM system, the RF mirrors positioned around the transmitting antenna serve as RF signal distributors. Thus, channel gains and spreading environments are altered. RF mirrors contain PIN diodes, and these mirrors are turned on or off according to the information bits to change the radiation pattern. The open/closed status of the mirrors is called the mirror activation pattern (MAP). In the MBM technique, information bits are transmitted using the indices of different MAPs in addition to the transmitted symbol. For example, when m_{rf} mirrors are used in the transmitting antenna, a total of $N = \{1, 2, \ldots 2^{m_{rf}}\}$ MAP states occur, each with a different channel structure. The multilevel quadrature amplitude modulation (M-QAM) symbol selected by the information bitstream in the transmitter is transmitted via the active channel selected from these N different combinations. The spectral efficiency of the MBM technique is $n_{MBM} = m_{rf} + \log_2 M$ (bits/s/Hz). With the addition of each RF mirror, the spectral efficiency increases by 1 bit. Thus, the MBM technique provides high spectral efficiency while providing many independent channels [10-12].

The use of chaotic systems is preferred in the next-generation communication and cryptology systems, where reliability is the basic need, because it gives good results. Moreover, chaotic-based communication systems are good carrier candidates for spread spectrum communication through the use of a broadband nonperiodic chaotic signal. Chaotic signals obtained from chaotic systems have high bandwidth and low power spectrum density. The essential reason for preference for the use of these produced signals is because they are not periodic and they appear as a kind of noise in nature which enabled these systems to be used in reliable communication. The differential chaos shift keying (DCSK) system transmits the reference signal that does not contain information within half the symbol time of the communication but transmits the information bits in the remaining half of the communication. Although the DCSK systems have low spectrum efficiency, these systems have a low receiver complexity structure between chaos shift keying modulation, and their performance is very good for fading channels. The number of chaotic arrays that can be produced with a single formula depending on the initial situation cannot be limited and does not repeat itself due to the branching of the DCSK systems. These features of the DCSK systems provide an increase in system capacity and performance security [13-15]. However, while the aperiodic nature of chaotic signals increases the reliability of the systems, the DCSK systems, which use chaotic signals in transmission, provides low data security with increased reliability. Different solutions such as permutation transformation have been proposed to increase DCSK reliability. In [16], the proposed permutation-based DCSK system requires additional conversion and inverse transformation in the transmitter and receiver, unlike the traditional DCSK structure. In this system, where a simple permutation is made in each signal block, a reverse permutation is made on the receiver side to save the original signal block. Thus, data reliability is increased by eliminating the similarity between the reference and data samples.

A novel high data-rated and high-spectral and energy-efficient communication technique, which is obtained by combining DCSK and MBM techniques, and briefly called the DCSK–MBM, is proposed in this study for the new-generation wireless communication systems. The symbol selected by the information bits is multiplied by the chaotic signal produced in the DCSK system and transmitted through the active antenna pattern determined according to the information bits of the MBM system. The computer simulations in the study show that the DCSK–MBM system is more energy-efficient, has a higher data rate, and has a good error performance compared with the traditional DCSK, MBM, and QAM systems. All performance analyses of the system are performed over Rayleigh fading channels for M-ary phase shift keying (M-ary PSK)/QAM modulation.

DCSK–MBM System Model and maximum likelihood (ML) Detector

The proposed DCSK–MBM system model is shown in Figure 1. Although the proposed system model has only one transmitter and receiver antenna ($N_t = N_r = 1$), m_{rf} mirrors are positioned around the transmit antenna. Considering the transmitter of the DCSK–MBM system, the vector **b** applied to the input is an information bitstream that will be transmitted over a symbol duration and has a dimension of $m_T \times 1$. Here, the information bit sequence $m_T = m_j + m_{rf}$ is divided into two subvectors ($m_j = \log_2 (M)$ and m_{rf}). Here, the m_j bit sequence selects the **j** symbol from the M-QAM/PSK modulation, while the m_{rf} bits select one of the N MAP states by adjusting the different on/off options of the RF mirrors via mirror switch controller (MSC). Consequently, the DCSK signal is transmitted from the mirrors selected by the MBM scheme.

In the transmitter structure shown in Figure 1, the chaos generator (CG), using a quadratic Chebyshev polynomial function, produces a β length chaotic reference sequence [17]

$$x_{j+1} = 1 - 2x_j^2, \quad j = 1, 2 \ldots, \beta. \tag{1}$$

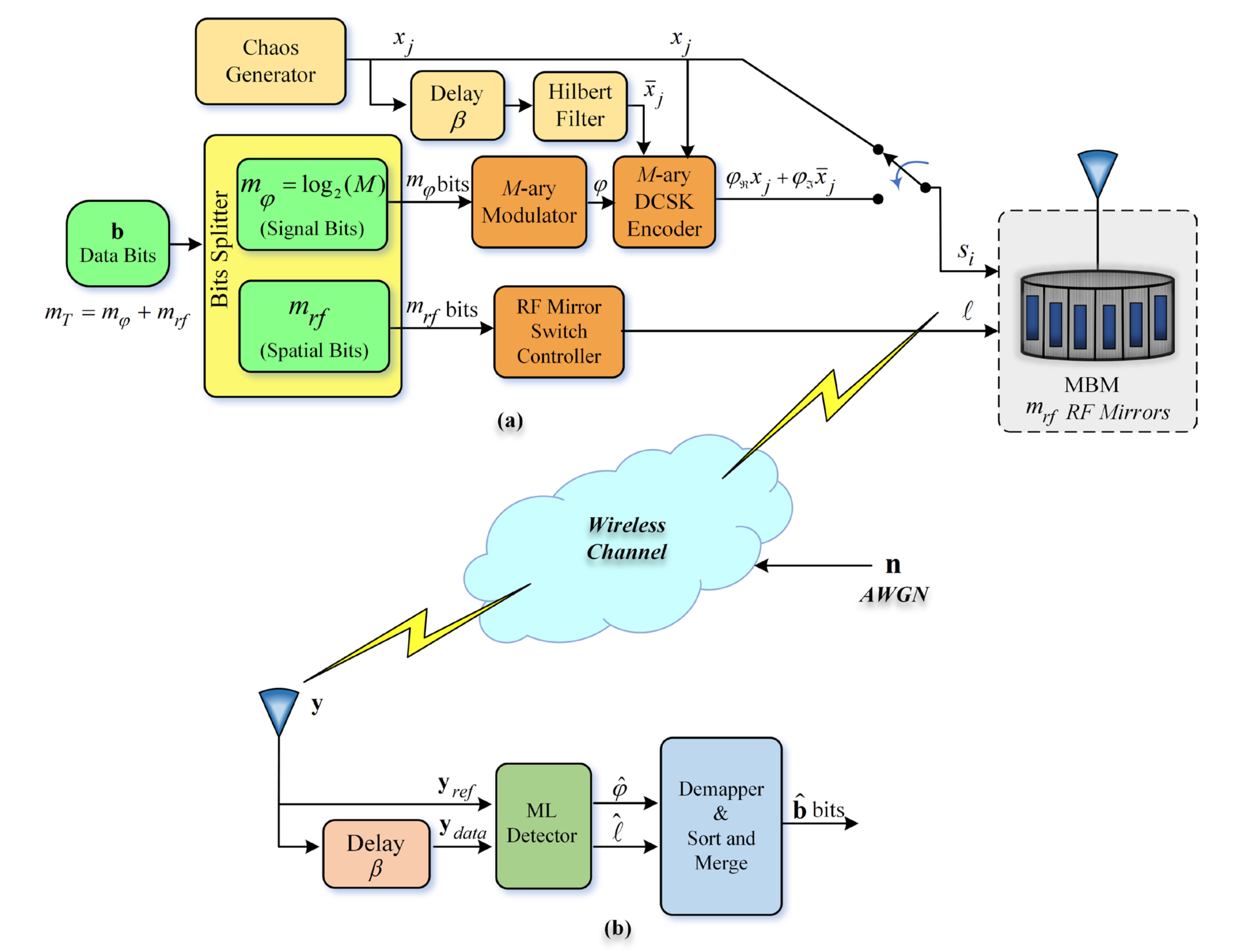

Figure 1. System model of the DCSK-MBM scheme; (a) transmitter, (b) receiver

For the transmission of the M-ary modulated symbol, two independent and orthogonal chaotic reference sequences are required. The $\bar{x}_j$ signal, which is the orthogonal form of the chaotic reference signal x_j, is obtained using the Hilbert transform [18]. Thus, two independent and orthogonal chaotic reference sequences are obtained by using the Hilbert transform for the transmission of the M-ary modulated symbol (Figure 1a).

The DCSK based M-ary s symbol to be transmitted by the MBM can be generated as a linear combination of quadrature signals x_j and $\bar{x}_j$ in the form of $s = \phi_\Re x_j + \phi_\Im \bar{x}_j$, where $\phi_\Re$ and $\phi_\Im$ represent the real and imaginary parts of the M-ary symbol ϕ (Figure 1a). The communication protocol takes place over a symbol period time (T_s) and comprises two stages with each phase consisting of the $T_s/2$ symbol period interval. In the first phase of the communication protocol, the reference sequence x_j produced by CG is transmitted from the mirrors selected by the RF MSC. In the second phase of the communication protocol, the reference sequence delayed by the amount of β and transformed using the Hilbert transform is transmitted from the same MAP by multiplying with the real and imaginary parts of the information symbol $\phi = \phi_\Re + j\phi_\Im$, i.e., $s = \phi_\Re x_j + \phi_\Im \bar{x}_j$. The signal sent in the first and second stages of the communication protocol in this paper are called the reference and the information-bearing signals, respectively [19]. Thus, during the ith symbol duration, the output of the DCSK–MBM transmitter can be expressed as

$$s_{i,j} = \begin{cases} x_j, & 0 < j \leq \beta \\ \varphi_{i,\Re} x_{j-\beta} + \varphi_{i,\Im} \bar{x}_{j-\beta}, & \beta < j \leq 2\beta \end{cases} \quad (2)$$

where, $j = 1,2,\ldots\beta$ and the chaotic sequence x_j refers to the reference signal. In addition, $\phi_{i\Re} x_{j-\beta} + \phi_\Im \bar{x}_{j-\beta}$ is the information-bearing signal constructed from the modulated symbol and the reference signal, which is delayed by the amount of β. Also, where $E_R = \Sigma_{j=1}^{\beta} x_j^2 = \Sigma_{j=1}^{\beta} \bar{x}_j^2$ and E_R is the energy of the reference sequence. In the first transmission phase of the DCSK–MBM system, the x_j reference signal consisting of β-length chaos samples is transmitted. In the second phase, the $\phi_{i\Re} x_{j-\beta} + \phi_\Im \bar{x}_{j-\beta}$ information signal is transmitted, where $\phi_i = \phi_{i\Re} + j\phi_{i,\Im}$

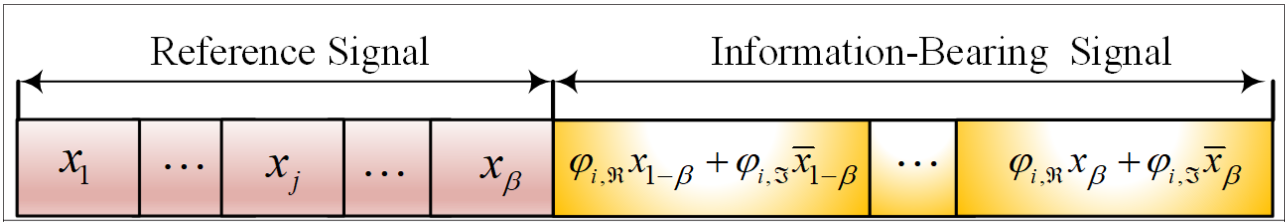

Figure 2. Frame structure of DCSK based symbol

represents the ith symbol of the M-ary modulation, where $i = 1,2,\ldots,M$. The frame structure of the transmitted symbol s_i is shown in Figure 2.

The DCSK symbol is transmitted with one of the $2^{m_{rf}}$ different MAP states with the MBM technique. The vector expression of the noisy signal coming to the receiver after passing through the wireless transmission channel can then be written as

$$y = s_i h_l + n, \tag{3}$$

where, $y = [y_1 y_2 \ldots y_{2\beta}]^T$ with the size of $2\beta\times1$, and hl is the Rayleigh fading channel coefficient with zero mean and $\sigma_h^2 = 1$ variance, i.e., $h \sim CN\ (0,\ \sigma_h^2 = 1)$, where $l \in \{1,2,\ldots,N\}$. The channel state information (CSI), i.e., h_l is assumed to be perfectly known by the receiver. The performance degradation caused by the channel estimation error will be eliminated and will provide a significant performance advantage over the noncoherent system because the receiver knows CSI perfectly. $\mathbf{n} \sim CN\ (0,\ N_o)$ is the additive white Gaussian noise with zero mean and $N_o / 2$ variance per dimension. Also, $\mathbf{s}_i$ is defined as

$$\mathbf{s}_i = \left[\mathbf{x}_{\text{ref}}^T, \left(\varphi_{i,\Re} \mathbf{x}_{\text{ref}} + \varphi_{i,\Im} \overline{\mathbf{x}}_{\text{ref}} \right)^T \right]^T \tag{4}$$

In (4), the vector representation of the reference and the information signals can be expressed respectively as

$$\mathbf{x}_{\text{ref}} = \left[x_1, x_2, \ldots, x_j, \ldots, x_\beta \right]^T, \tag{5}$$

$$\varphi_{i,\Re} \mathbf{x}_{\text{ref}} + \varphi_{i,\Im} \overline{\mathbf{x}}_{\text{ref}} = \\ = \left[\left(\varphi_{i,\Re} x_{\beta+1} + \varphi_{i,\Im} \overline{x}_{\beta+1} \right), \ldots, \left(\varphi_{i,\Re} x_{2\beta} + \varphi_{i,\Im} \overline{x}_{2\beta} \right) \right]^T \tag{6}$$

The received signal in (3) is also expressed in a compact form as

$$\mathbf{y} = \left[\mathbf{y}_{\text{ref}}\ \mathbf{y}_{\text{data}} \right]^T. \tag{7}$$

The subsignals of the received signal $\mathbf{y}$ carrying the reference and information signals are represented in vector form as

$$\mathbf{y} = \Big[\underbrace{y_1\ y_2 \cdots y_\beta}_{\mathbf{y}_{\text{ref}}}\ \underbrace{y_{\beta+1}\ y_{\beta+2} \cdots y_{2\beta}}_{\mathbf{y}_{\text{data}}} \Big]^T. \tag{8}$$

At the receiver, the transmitted symbol and the MAP indices are estimated using the ML detectors as

$$\left(s_{\hat{i}}, \hat{\ell} \right) = \arg \min_{\substack{i \in \{1,2,\ldots,M\} \\ \ell \in \{1,2,\ldots,N\}}} \left\{ \left\| \mathbf{y} - \mathbf{s}_i h_\ell \right\|^2 \right\} \tag{9}$$

Finally, with the bit-back matching technique using the obtained indices $(\hat{i}, \hat{\ell})$, the transmitted bit sequence is reconstructed at the receiver as $\hat{\mathbf{b}}$.

Simulation Results and Discussions

The performance results of the DCSK–MBM system are presented in this section for the number of antenna $N_t = N_r = 1$. Moreover, simulations are performed on Rayleigh fading channels for M-QAM and M-PSK modulations. Besides, the ML technique is used to estimate the transmitted symbols and indices of MAPs at the receiver side. The proposed system has been compared with the traditional DCSK, MBM, and QAM systems in various fair schemes (i.e., with the same number of bits) and its superiority has been clearly demonstrated. The signal-to-noise ratio (SNR) used in the simulations here is defined as $\text{SNR(dB)} = 10\log_{10}(E_s / N_0)$, where E_s is the average energy per symbol.

The performance of the DCSK–MBM system is compared with the traditional DCSK system for the QAM modulation by keeping the number of mirrors constant $m_{rf} = 2$, while modulation degree changes of $M = 4,8,16,32$ and $M = 16,32,64,128$ were obsereved for DCSK–MBM and DCSK, respectively (Figure 3). Here, the DCSK–MBM system for the $m_{rf} = 2$, $M = 4,8,16,32$ and the DCSK scheme for the $M = 16,32,64,128$ transmits $m_T = 4,5,6,$ and 7 bits, respectively. Considering Figure 3, the DCSK–MBM system provides approximately 5.62, 5.88, 6.18, and 6.28 dB gains compared with the related DCSK schemes.

Figure 4 shows the performance comparisons of the DCSK–MBM system with the DCSK scheme for the QAM by keeping the modulation degree constant at $M = 4$ while the number of mirrors changes of $m_{rf} = 2,3,4,5,6$ and $M = 16,32,64,128,256$ were observed for DCSK–MBM and DCSK, respectively. Here, the DCSK-MBM system ($m_{rf} = 2$, $M = 4$) and the DCSK scheme ($M = 16$) transmits $m_T = 4$ bits, the DCSK-MBM system ($m_{rf} = 3$, $M = 4$) and the DCSK scheme ($M = 32$) transmits $m_T = 5$ bits, the DCSK-MBM system ($m_{rf} = 4$, $M = 4$) and the DCSK scheme

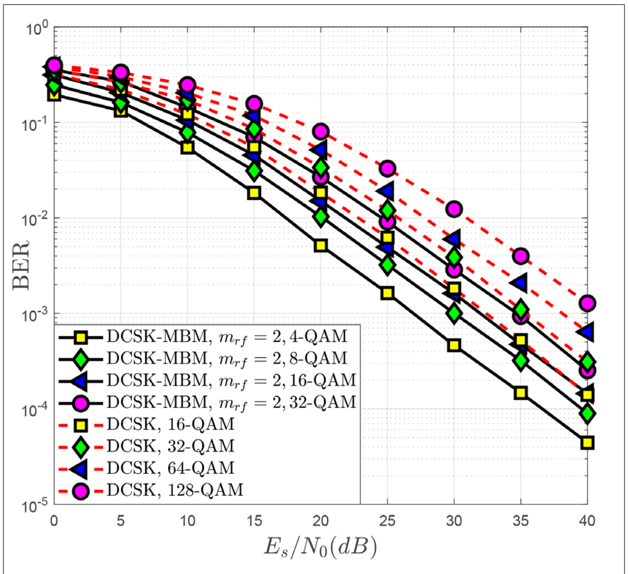

Figure 3. Performance comparisons of DCSK-MBM and traditional DCSK systems for m_T=4,5,6,7 bits and QAM modulation

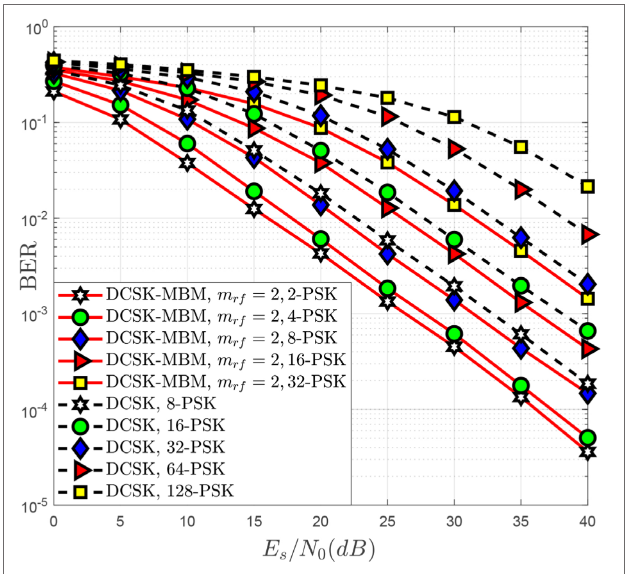

Figure 5. Performance comparisons of DCSK-MBM and traditional DCSK systems for m_T=3,4,5,6,7 bits and PSK modulation

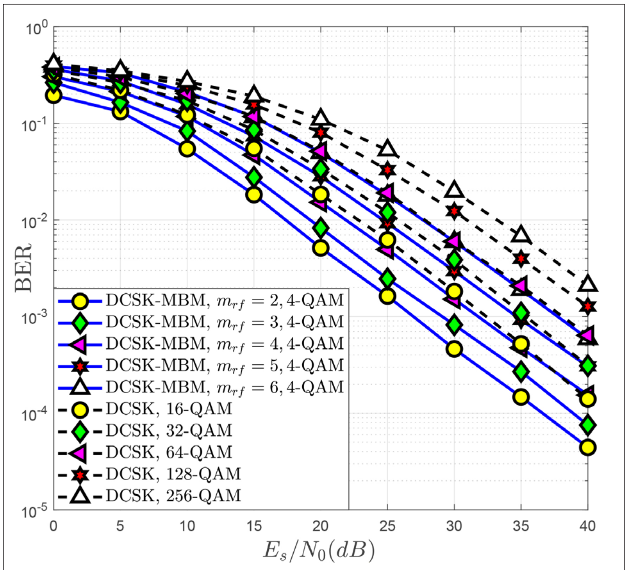

Figure 4. Performance comparisons of DCSK-MBM and traditional DCSK systems for m_T=4,5,6,7,8 bits and QAM modulation

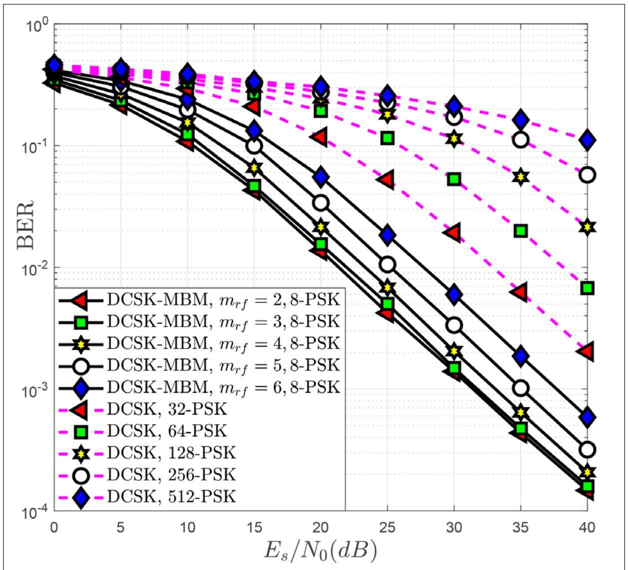

Figure 6. Performance comparisons of DCSK-MBM and traditional DCSK systems for m_T=5,6,7,8,9 bits and PSK modulation

($M = 64$) transmits $m_T = 6$ bits, the MBM-DCSK system ($m_{rf} = 5$, $M = 4$) and the DCSK scheme ($M = 128$) transmits $m_T = 7$ bits, and the DCSK-MBM system ($m_{rf} = 6$, $M = 4$) and the DCSK scheme ($M = 256$) transmits $m_T = 8$ bits. The DCSK–MBM system provides approximately 5, 5.88, 5.89, 6.37, and 5.78 gains compared to the related DCSK schemes as shown in Figure 4.

The performance of the DCSK–MBM scheme is compared with the DCSK system in Figure 5 for the PSK modulation by keeping the number of mirrors constant at $m_{rf} = 2$ while the modulation degree changes of $M = 2,4,8,16,32$ and $M = 8,16,32,64,128$ were observed for DCSK–MBM and DCSK, respectively. In this figure, the MBM-DCSK system for the $m_{rf} = 2$, $M = 2,4,8,16,32$ and the DCSK scheme for the $M = 8,16,32,64,32,64,128$ transmits m_T = 3,4,5,6, and 7 bits, respectively. The DCSK–MBM system provides a very high SNR gain compared to the DCSK schemes as shown in Figure 5.

Figure 6 depicts the performance comparations of the DCSK–MBM with the traditional DCSK system for the PSK modulation by keeping the modulation degree constant at $M = 8$ while the number of mirrors changes of $m_{rf} = 2,3,4,5,6$ and $M = 32,64,128,256,512$ were observed for DCSK–MBM and DCSK, re-

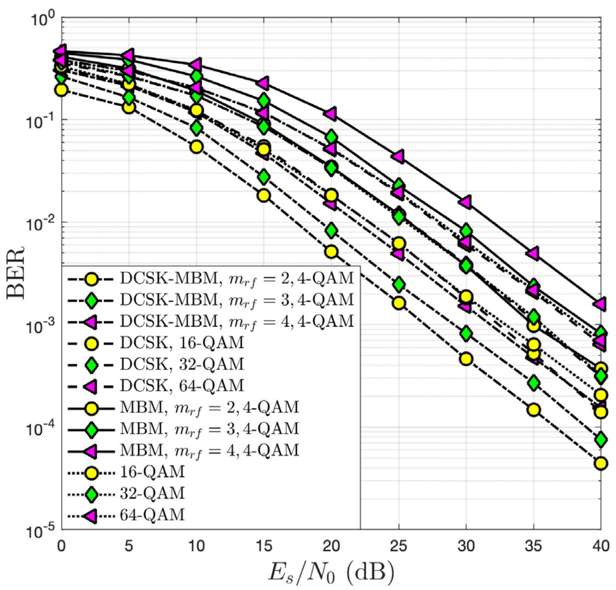

Figure 7. Performance comparisons of DCSK-MBM, traditional DCSK, MBM and QAM systems for m_T=4,5,6 bits

spectively. Moreover, the MBM-DCSK system with m_{rf} = 2,3,4,5,6 M = 8 and the DCSK scheme with M = 32,64,128,256,512 conveys m_T = 5,6,7,8, and 9 bits, respectively. The DCSK–MBM system provides a very high SNR gain compared to the DCSK schemes as shown in Figure 6.

Figure 7 shows the performance comparisons of the DCSK–MBM system with the DCSK, MBM, and QAM schemes by keeping the modulation degree constant at $M = 4$ while the number of mirrors changes of m_{rf} = 2,3,4 for the DCSK–MBM and MBM systems was observed. On the other hand, the number of mirror changes of M = 16,32,64 for the DCSK and QAM schemes was observed. Here, the DCSK-MBM and MBM systems (m_{rf} = 2, $M = 4$) and the DCSK and QAM schemes ($M = 16$) transmits $m_T = 4$ bits, the DCSK-MBM and MBM systems ($m_{rf} = 3$, $M = 4$) and the DCSK and QAM schemes (M = 32) transmits m_T = 5 bits, and the DCSK-MBM and MBM systems ($m_{rf} = 4$, M = 4) and the DCSK and QAM schemes (M = 4) transmits m_T = 6 bits. The DCSK–MBM system provides a very high SNR gain compared to the other systems as shown in Figure 7.

Conclusion

This study proposed a novel high data-rated and high-spectral and energy-efficient communication technique by combining the DCSK and MBM techniques, briefly called DCSK–MBM, for new-generation wireless communication systems. In the DCSK–MBM system, the symbol is multiplied by the chaotic sequence generated in the DCSK system and transmitted through the active antenna pattern determined according to the MBM system. The computer simulations show that the DCSK–MBM system is more energy efficient, has a higher data rate, and has a good error performance compared with the traditional DCSK, MBM, and QAM systems. As a result, the DCSK–MBM system provides a considerable SNR gain compared with the traditional DCSK system, as seen from the bit error rate performance curves.

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References

1. S. Buzzi, I. Chih-Lin, T. E. Klein, H. V. Poor, C. Yang, A. Zappone, "A survey of energy-efficient techniques for 5G networks and challenges ahead", IEEE J. Sel. Areas Commun., vol. 34, no. 4, pp. 697-709, April, 2016. [Crossref]
2. S. K. Sharma, I. Woungang, A. Anpalagan, S. Chatzinotas, "Towards tactile internet in beyond 5G era: Recent advances, current issues and future directions", IEEE Access, pp. 1-1, March, 2020. [Crossref]
3. J. Navarro-Ortiz, P. Romero-Diaz, S. Sendra, P. Ameigeiras, J. J. Ramos-Munoz, J. M. Lopez-Soler, "A survey on 5G usage scenarios and traffic models", IEEE Commun. Surv. Tutorials, pp. 1-1, February, 2020. [Crossref]
4. X. Chen, D. W. K. Ng, W. Yu, E. G. Larsson, N. Al-Dhahir, R. Schober, "Massive access for 5G and beyond", February, 2020. [Crossref]
5. E. Aydin, F. Cogen, E. Basar, "Code-index modulation aided quadrature spatial modulation for high-rate MIMO systems", IEEE Trans. Veh. Technol., vol. 68, no. 10, pp. 10257-10261, 2019. [Crossref]
6. M. Wen, X. Cheng, L. Yang, Index modulation for 5G wireless communications. Cham: Springer International Publishing, 2017. [Crossref]
7. E. Basar, M. Wen, R. Mesleh, M. Di Renzo, Y. Xiao, H. Haas, "Index modulation techniques for next-generation wireless networks", IEEE Access, vol. 5, pp. 16693-16746, August, 2017. [Crossref]
8. F. Cogen, E. Aydin, N. Kabaoğlu, E. Başar, H. Ilhan, "Code index modulation and spatial modulation: A new high rate and energy efficient scheme for MIMO systems", in 2018 41st International Conference on Telecommunications and Signal Processing, TSP 2018, 2018. [Crossref]
9. E. Aydin, F. Cogen, "Two-way code index modulation", in 27th Signal Processing and Communications Applications Conference, SIU 2019, 2019. [Crossref]
10. Y. Naresh, A. Chockalingam, "On media-based modulation using RF mirrors", IEEE Trans. Veh. Technol., vol. 66, no. 6, pp. 4967-4983, June, 2017. [Crossref]
11. Y. Naresh, A. Chockalingam, "Full-duplex media-based modulation", in 2017 IEEE Globecom Workshops (GC Wkshps), vol. 2018-Janua, pp. 1-6, 2017. [Crossref]
12. F. Yarkin, I. Altunbas, E. Basar, "Cooperative space shift keying media-based modulation with hybrid relaying", IEEE Syst. J., vol. 14, no. 1, pp. 500-509, March, 2020. [Crossref]
13. W. Xu, T. Huang, L. Wang, "Code-shifted differential chaos shift keying with code index modulation for high data rate transmission", IEEE Trans. Commun., vol. 65, no. 10, pp. 1-1, October, 2017. [Crossref]
14. M. Türk, H. Oğraş, "Kaos tabanlı sayısal modülasyon tekniklerinin simulink ortamında modellenmesi ve benzetimi", Fırat Üniversitesi Fen Bilim. Derg., vol 30, no. 1, pp. 45-50, 2018.
15. X. Cai, W. Xu, L. Wang, F. Xu, "M-ary code-shifted differential chaos shift keying with in-phase and quadrature code index modulation", IET Commun., vol. 13, no. 19, pp. 3253-3259, December, 2019. [Crossref]

16. F. C. M. Lau, K. Y. Cheong, C. K. Tse, "Permutation-based DCSK and multiple-access DCSK systems", IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications vol. 50, no. 6, pp. 733-742, 2003. [Crossref]
17. G. Kaddoum, F. D. Richardson, F. Gagnon, "Design and analysis of a multi-carrier differential chaos shift keying communication system", IEEE Transactions on Communications, vol. 61, no. 8, pp. 3281-3291, 2013. [Crossref]
18. L. Wang, G. Cai, G. R. Chen, "Design and performance analysis of a new multiresolution M-ary differential chaos shift keying communication system", IEEE Transactions on Wireless Communications, vol. 14, no. 9, pp. 5197-5208, September, 2015. [Crossref]
19. Z. Galias, G. M. Maggio, "Quadrature chaos-shift keying: Theory and performance analysis", IEEE Trans. Circuits Syst. I Fundam. Theory Appl., vol. 48, no. 12, pp. 1510-1519, December, 2001. [Crossref]

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