Turkish Journal of Electromechanics and Energy
ISSN: 2547-975X
Vol:8, No:2, Page 77-84 (2023)
https://www.scienceliterature.com

Turkish Journal of Electromechanics & Energy
an international open access journal

Comparative analysis of dual carrier modulations with channel coding and space-time coding

Y. Karan[1,*], S. Kahveci

[1]*Department of Electrical and Electronics Engineering, Recep Tayyip Erdoğan University, Rize, Türkiye*

[2]*Department of Electrical and Electronics Engineering, Karadeniz Technical University, Trabzon, Türkiye*

ARTICLE INFO

Article Type:
Research Paper

Article History:
Received: 11 August 2023
Revised: 12 September 2023
Accepted: 6 October 2023
Published: 15 October 2023

Editor of the Article:
M. E. Şahin

Keywords:
Convolution coding, Dual carrier modulation, Space-time coding, Wireless body area networks

ABSTRACT

Dual carrier modulation (DCM) is a type of modulation proposed for use at high data rates. DCM was created to make successful communication by making transmitter diversity. In this modulation, the same information is modulated with two different constellation diagrams, forming a kind of 1/2 code rate versus raw modulation. In space-time coding, performance improvement is made by utilizing multiple antenna diversity. This paper presents a comprehensive comparative analysis of DCM with channel coding and space-time coding techniques in the context of wireless body area networks (WBANs). The performance of DCM is evaluated against 1/2 convolution channel coding, 16 quadrature amplitude modulation (16QAM), quadrature phase shift keying (QPSK), and binary phase shift keying (BPSK) modulations. Additionally, the single input single output (SISO) adaptation of Alamouti space-time block coding (STBC) is considered for comparison with DCM. Extensive simulations are conducted on various channel models, including the additive white Gaussian noise (AWGN), Proakis A, B, C, and WBAN channel model 4 (CM4) channels. The results demonstrate that DCM outperforms convolution channel coding and STBC, particularly at high modulation.

Cite this article: Y. Karan, S. Kahveci, "Comparative analysis of dual carrier modulations with channel coding and space-time coding," *Turkish Journal of Electromechanics & Energy*, 8(2), pp.77-84, 2023

1. INTRODUCTION

Development studies in different areas of communication systems continue today. Research continues on many subjects such as error correction, channel structure estimation and equalization, and cooperative communication to increase data rate and reliability in wireless channels. In addition, the hardware and programmatic complexity required for the realization of these operations is a factor in the selection of different methods according to the different communication systems. Alamouti has facilitated the equalization process in single-tap channels with two transmitters by presenting the Alamouti space-time block coding (STBC) to the literature [1].

In the dual carrier modulation technique defined in the literature, 16-quadrature amplitude modulation (16QAM) modulation is used together with orthogonal frequency-division multiplexing (OFDM) to make subcarrier and modulation diversity [2, 3]. The same data arrays are passed through two different modulation constellation schemes and transmitted on two different subcarriers. While it is more resistant to errors by going through two distinct constellations, it also increases its resistance to error explosion with data interleaving. This modulation is recommended in the European Computer Manufacturers Association (ECMA) standard for high data rate transmission. In addition, increasing the modulation level will increase the data rate, while decreasing the modulation level provides transmission reliability.

Performance studies have generally been performed on DCM before. From these studies, the performances of DCM and quadrature phase-shift keying (QPSK) in the additive white Gaussian noise (AWGN) channel were found to be the same in the AWGN channel. However, the performance of DCM in the multipath channel was seen as higher than the AWGN channel [4]. In another study, DCM was examined in an IEEE 802.11ad channel with a two-channel aggregation and achieved a 1.5 dB gain compared to non-DCM ones [5]. For multiband OFDM, outage probability and bit error rate (BER) analysis in DCM's Nakagami- m channel are extracted [6, 7]. Among the high data rate wireless communication studies, dual carrier modulation was used in the communication system, which reaches a data rate of 20.8 Gbps in the 220 GHz band in THz communication [8].

Another study examined the DCM system with space diversity. In previous DCM studies, it was stated that BER performance analyses were performed on systems with a single transmitter and single receiver antenna, and in that study, the error performance of DCM in maximum ratio combining and maximum likelihood techniques in ultra-wideband (UWB) systems with multiple inputs and outputs were extracted. In the study in which the Rayleigh fading channel was used,

*Corresponding author's e-mail: yasinkaran@gmail.com

Science Literature ™ © All rights reserved.

an improvement in receiver sensitivity is presented with spatial diversity. As a result of the examinations made according to the different receiver and transmitter antenna numbers, it is seen that DCM performs better than QPSK. Especially at high signal-to-noise ratio (SNR) values and low receiver antenna numbers, the performance difference is higher. In comparisons of the modulations within themselves, the performance increases with the increase in the number of receiving antennas, while it decreases with the increase in the number of transmit antennas [9].

For high mobility scenarios, a high-rate and diverse communication system is proposed, spatial modulation (SM) space-time block code (STBC) aided orthogonal time frequency space modulation (OTFS). Information bits are grouped based on subcarriers and time slots, modulated by SM. OTFS modulation is applied to SM-STBC symbols with various transmission cycles. A block message passing (BMP) detector is designed for SM-STBC-OTFS in multiple input - multiple output (MIMO) configurations, showing significant BER performance gain over OTFS and MIMO-OTFS systems in simulations [10].

Another study compares the BER performance of SISO, Multiple Input Single Output (MISO), and MIMO systems with orthogonal space-time block coding (OSTBC) and extended orthogonal space-time block coding (EO-STBC) techniques over a flat fading channel [11]. The MIMO systems in LTE and WiMAX support up to four antennas at the transmitter, receiver, or both. The study shows that fully orthogonal signals (OSTBC) achieve full spatial diversity order and the best BER performance. However, when signals are not fully orthogonal (open loop EO-STBC), the spatial diversity order decreases, leading to worse BER performance. To achieve full spatial diversity, closed-loop techniques are utilized [11].

An alternative study contrasts the modulation strategies introduced in the IEEE 802.15.6 ultra-broadband physical layer against the dual carrier modulation techniques founded on OFDM in the context of WBAN channels [12]. The dual carrier modulation employs 16-quadrature amplitude modulation constellation charts and delivers robust communication capabilities even when operating at lower modulation levels such as quadrature amplitude modulation and binary phase shift keying. The simulation outcomes, illustrated through graphs depicting bit error rate relative to signal-to-noise ratio, illustrate that when dealing with lower data rates, both protocol-based modulations and dual carrier modulations perform commendably, albeit the latter surpasses the former. Nevertheless, in scenarios involving higher data rates, the performance of both techniques experiences degradation owing to the substantial dispersion observed within WBAN channels shown in Figure 1 [12, 14].

DCM has notably garnered endorsement within standards and systems characterized by high data rates. However, in certain contexts like body area networks, the emphasis pivots towards transmission reliability over sheer data rate. For instance, the IEEE 802.15.6 standard stipulates an unencoded data rate ceiling of 15.6 Mb/s [13]. Consequently, this study deliberates upon the adoption of QPSK and BPSK as alternatives to 16QAM within the DCM framework. This shift is driven by the pursuit of a reduced data rate while simultaneously achieving a diminished error rate during transmission. Transitioning from 16QAM to QPSK or BPSK inherently entails a widened spacing between symbols, all within the confines of a constant average energy level [12, 14].

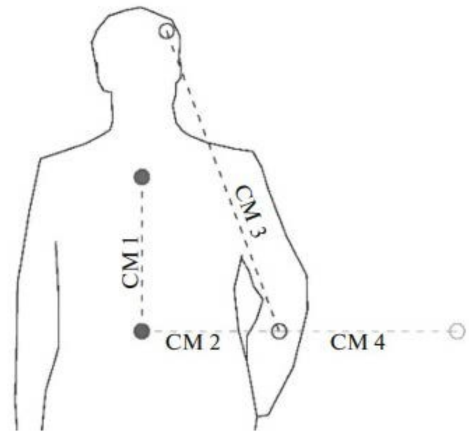


Fig. 1. WBAN channel models [14].

In this study, Alamouti coding is compared with DCM. Since DCM is applicable in SISO systems, Alamouti has been adapted to SISO and compared with this system. In addition, since DCM has a code rate of 1/2, it is compared with convolution coding, one of the channel coding methods at the same rate. Comparisons were made on a single-tap Rayleigh channel and in a multi-tap wireless body area network (WBAN) channel.

2. METHOD

This section discusses key techniques in wireless communication. In this section DCM, convolution coding, space-time coding techniques and their derivatives are explained. DCM segments data into clusters and employs 16QAM modulation. The study explores DCM with BPSK and QPSK for improved reliability in body area networks. DCM-QPSK and DCM-BPSK are derived from DCM. The section also touches on convolution coding, correcting data errors from channel noise, and space-time coding, with a focus on Alamouti space-time block coding.

2.1. Dual Carrier Modulation and Types

DCM has been introduced as a solution to achieve higher data rates according to the ECMA-368 standard [3]. Within this standard, DCM is applied in conjunction with 16QAM modulation. Following the initial implementation of DCM, a further enhancement known as 32QAM DCM has been suggested, aiming to elevate the data rate to 600 Mbps [15].

Within the context of body area networks, prioritizing transmission reliability over sheer data rate becomes paramount. With this perspective in mind, the current investigation contemplates the utilization of DCM paired with BPSK and QPSK, as opposed to 16QAM, leading to a trade-off where the data rate is reduced in favour of a diminished error rate during transmission. Substituting QPSK or BPSK for 16QAM inherently results in an augmented symbol spacing under the constraint of the same average energy level [14].

DCM involves the organization of data into specific clusters, subsequently aligned onto a pair of distinct 16QAM constellation diagrams shown in Figure 2. The data stream undergoes an initial segmentation into 200-bit groups, followed by interleaving. This 200-bit data array is further partitioned into 4-bit segments to construct the 16QAM symbols. Through this approach, the 200-bit data series is subjected to modulation, yielding two separate sets of 50 16QAM symbols each, ultimately resulting in a cumulative count of 100 16QAM symbols [3, 12, 14].

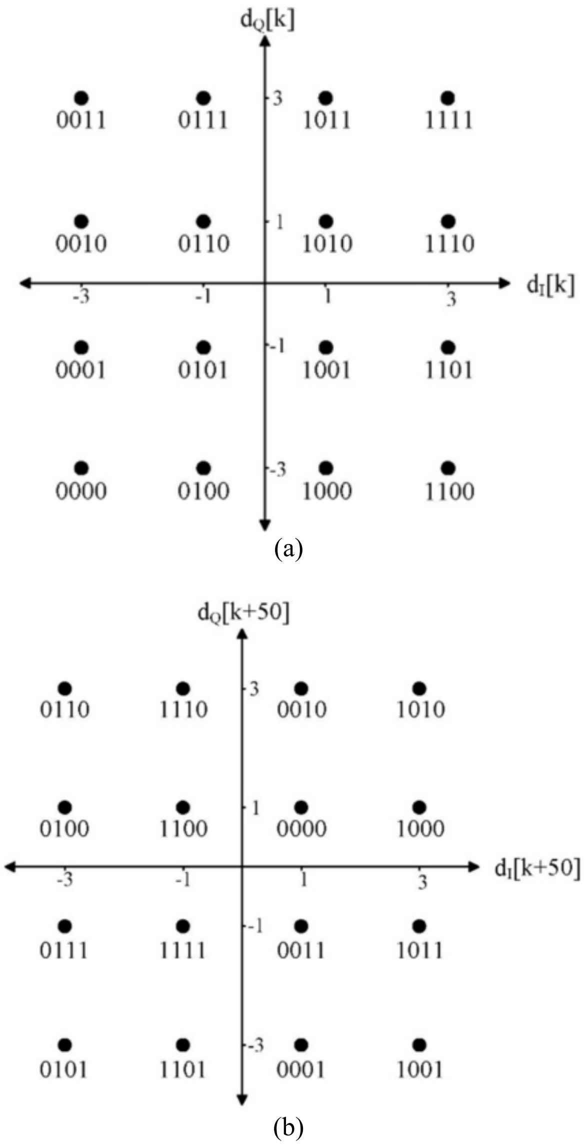
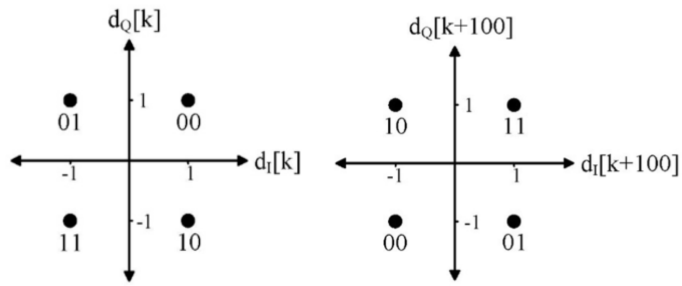


Fig. 2. DCM constellation diagrams; (a) First, (b) Second constellation diagram.

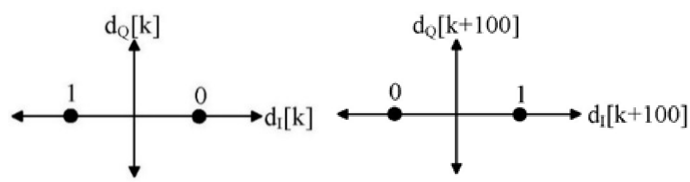
DCM-QPSK and DCM-BPSK are derived from DCM. In the case of DCM-QPSK, data is methodically reorganized into designated clusters, subsequently aligned across a pair of diverse QPSK constellation diagrams. The data flow undergoes an initial partitioning into 200-bit groupings, subsequently subjected to interleaving. Further refinement follows, with the 200-bit data array being meticulously segmented into 2-bit segments, thus forging the building blocks of QPSK symbols. This orchestrated progression leads the 200-bit data sequence through modulation, yielding two discrete sets, each comprising 100 QPSK symbols. Consequently, the amalgamated outcome culminates in a cumulative tally of 200 QPSK symbols, congruent with references [3, 12, 14]. Figure 3 shows the constellation diagrams used in the DCM-QPSK.



(a) (b)

Fig. 3. Constellation diagrams used in DCM-QPSK, (a) First, (b) Second constellation diagram.

Analogously, comparable processes are executed within the realm of DCM-BPSK, as expounded upon in [12]. Constellation diagrams used in DCM-BPSK are given in Figure 4.



(a) (b)

Fig. 4. Constellation diagrams used in DCM-BPSK, (a) First, (b) Second constellation diagram.

2.2. Convolution Coding

In communication systems, noise and interference occur in the channel between the receiver and the transmitter. This situation causes erroneous data reception at the receiver. Channel coding is one of the methods used to correct data corrupted by noise in communication channels. It is also defined as error-correcting coding. With the use of channel encodings, the parity data rate increases, in this case, the energy consumed per information data bit, E_b, increases. On the other hand, error rate performances are expected to increase as well. The first extracted channel coding is in the class of block codes. In the use of block code, the frames must be received synchronously, and the frames must be received completely before decoding.

As an alternative to block codes, convolution codes that can be used in continuous data bit flow have been presented in the literature [16]. Its hardware complexity is simpler. Convolution codes are represented as (n, k, l) with n codeword size, k data size, and l constraint register size. Viterbi algorithm is widely used in convolution decoding [17]. The code rate is found with k/n. Convolution coding generates an output, a code word, from the input data according to the generator polynomial selected.

2.3. Space-Time Coding

One of the methods developed to ensure reliability in fading channels in data transmission is space diversity. Using multiple antennas in the transmitter and receiver; MIMO, the use of antenna arrays from different angles is included in space diversity. However, since the use of multiple transmitter and receiver antennas increases the number of communication channels, the computational complexity also increases.

Alamouti compared the maximum ratio receiver combination (MRRC) method between a transmit antenna and an *M*-receiving antenna with a system he proposed in his article. In the proposed system, there are two antennas transmitting and M antennas at the receiver. If the two antennas in the transmitter send the symbols s_0 and s_1 at the time of $t=0$ and send the symbols $-s_1^*$ and s_0^* respectively in the next step, the symbols sent are determined according to the maximum likelihood method by multiplying the signals coming to the receiving antennas with the conjugates of the predicted channel and adding them. This method is known in the literature as Alamouti STBC.

In the Alamouti method, if the power output from the transmitter antennas is taken in equivalence, it gives the same BER performance as MRRC. In other words, the Alamouti system with two transmit antennas and *M* number of receiving antennas shows the same performance as the MRRC with a transmitting and *2M* receiving antenna. The computational complexity of the Alamouti system is also similar to that of the MRRC [1]. In another study, Alamout STBC was studied on time-varying channels. In that study, Alamouti STBC was compared with the non-transmitter diversity and it was revealed that Alamouti STBC gave better performance [18].

3. COMPARISONS AND DISCUSSIONS

In this section, a series of comparisons and discussions are presented. First, the performance of dual carrier modulation (DCM) models is compared with a 1/2 rate convolution channel coding technique. The simulations include various modulations and channel conditions. In AWGN channels, DCM performs well, particularly with 16QAM, while convolution coding offers similar results at low modulation levels. Proakis and WBAN CM4 channels show varying performance, with DCM outperforming in some scenarios. Notably, when energy spreads into the channel, dual carrier modulations shine.

The section then compares DCM models with both channel coding and space-time coding, focusing on Alamouti space-time block coding. Alamouti STBC is used with both two antennas in the transmitter and a symbol and its complex conjugate. The simulations consider different modulations and channel conditions. In summary, DCM excels in high-level modulation, while SISO-adapted Alamouti performs well at the expense of data rate reduction. In a single-tap channel, ½ convolution coding slightly outperforms Alamouti SISO and DCM, but its reception complexity is higher. In the same data rate, Alamouti STBC shows better performance than others. However, the suitability of using multiple antennas, as in Alamouti, depends on the application's constraints, such as size in body area networks.

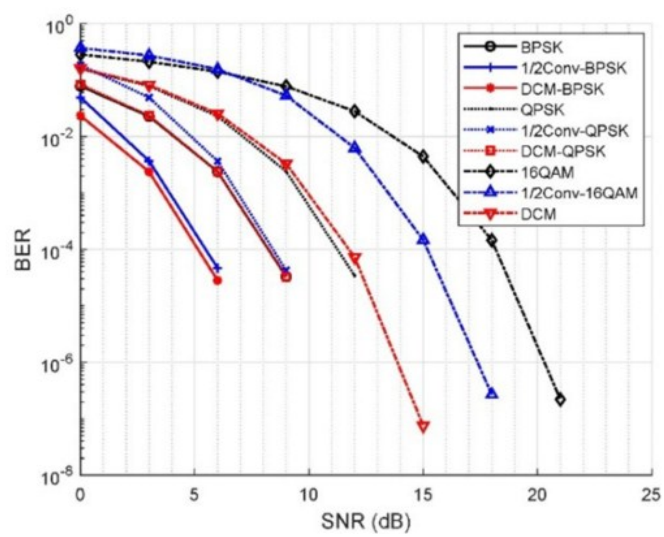
3.1. Comparison of DCM Models with Channel Coding Technique

A code rate of 1/2 rate occurs in dual carrier modulation. To compare the performance of dual-carrier modulation, it is contemplated to use a 1/2 channel coding technique. Convolution coding is a commonly used coding type that can be adjusted to any code rate. Therefore, 1/2 rate convolution channel coding was chosen to compare dual carrier modulation. Convolution coding (2,1,3) was created using the generator polynomials $g_1 = (1, 1, 1)$ and $g_2 = (1, 1, 0)$. The channel coding technique outputs generated according to these generator polynomials are given in Equation (1). The hard decision Viterbi algorithm is used while decoding the channel [19].

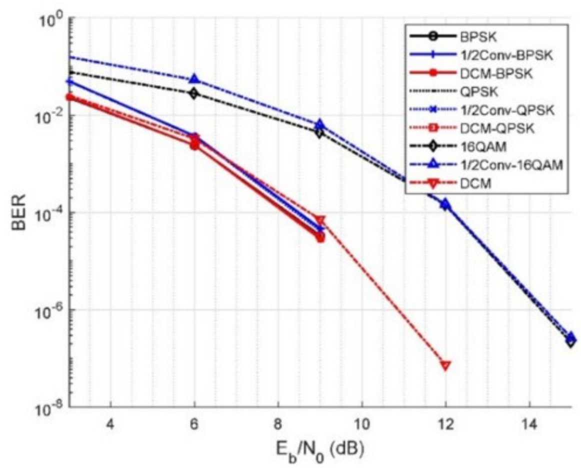
$$\begin{aligned} y_1[n] &= x[n]+x[n-1]+x[n-2] \quad (mod\ 2) \\ y_2[n] &= x[n]+x[n-1] \quad (mod\ 2) \end{aligned} \tag{1}$$

Simulations are performed to compare DCM, DCM-QPSK, DCM-BPSK and 1/2 convolution coding. 16QAM, QPSK and BPSK simulations are also added to these comparisons. Simulations were performed on AWGN, Proakis A, B, C and a randomly generated 1000 WBAN CM4 channel [20]. In the simulations, *1e5* packets were used, with each pack consisting of 1024 symbols. The results are shown in the BER – SNR graphs.

Figures 5(a) and 5(b) show the performance values in the AWGN channel in SNR and E_b/N_0 bases, respectively. At low modulation levels on the SNR base, dual carrier modulations and convolution coding gave similar performance results, while DCM gave better results than the others at 16QAM. At low modulation levels on the E_b/N_0 base, the performances were close to each other.



(a)

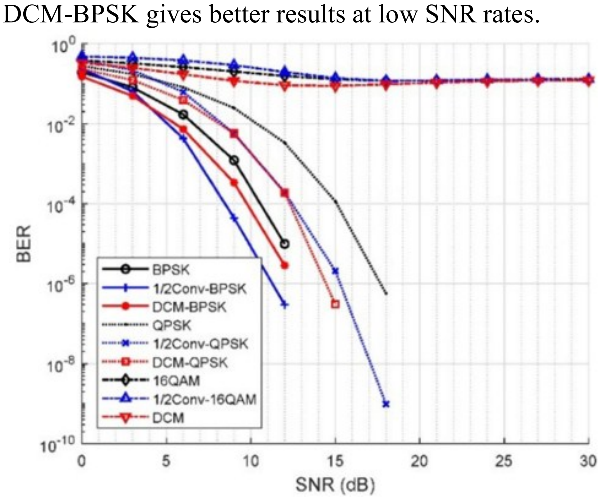


(b)

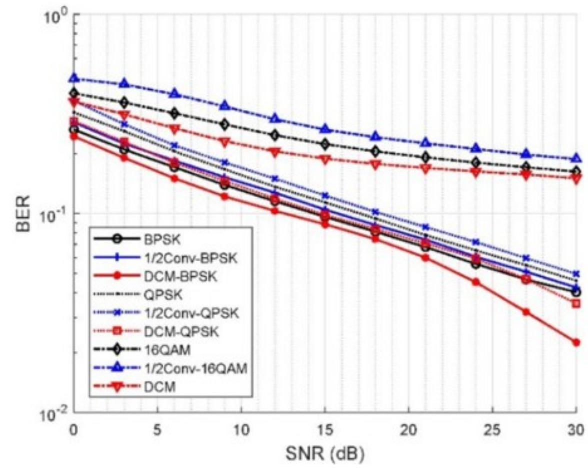
Fig. 5. DCM and channel coding techniques in AWGN channel error rates in (a) SNR, and (b) E_b/N_0 base.

In the simulations made on Proakis and WBAN CM4 channels, the channel estimation was made on the first sent orthogonal frequency-division multiplexing (OFDM) symbol and it was assumed that the channel did not change. The equalization process is realized in the frequency domain. Figure 6(a) shows the performance values in the Proakis *A* channel. In this channel, interference was more effective in modulations with 16QAM. In BPSK and QPSK, the results of dual carrier modulation and channel coding simulations were close to each other.

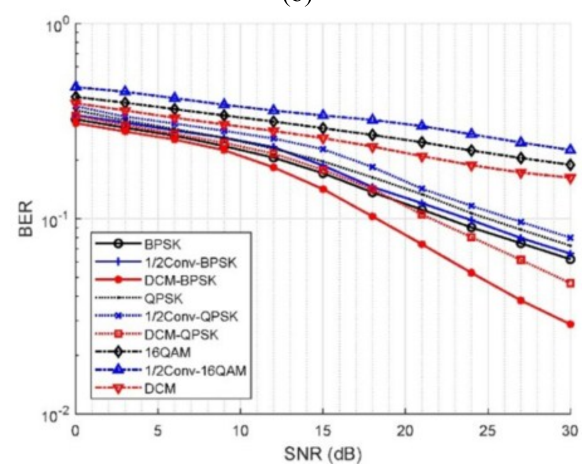
Figures 6(b) and 6(c) show the performances in the Proakis *B* and *C* channels, respectively. It is seen that dual carrier modulations give better performance than channel-coded simulations at all modulation levels in these channels. While the performances in the Proakis A channel are exponential, it is seen that the performances in the Proakis B and C channels are linear. The similarities between Proakis B and C channels can also be seen from the performance results. Figure 6(d) shows the performance results for 1000 WBAN CM4 channels. In the average of these channels, it is seen that channel-coded BPSK modulation gives better performance at high SNR rates. It is seen that DCM-BPSK gives better results at low SNR rates.



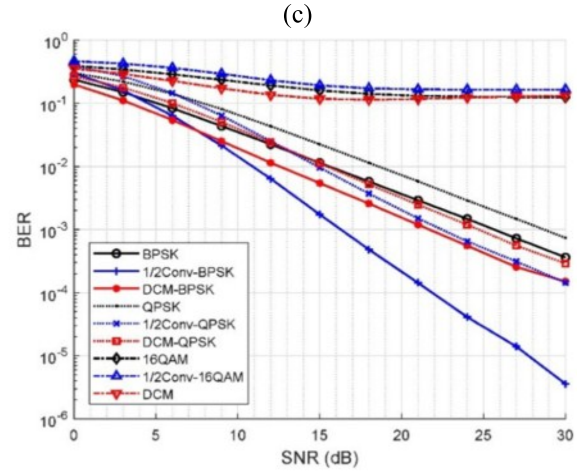
(a)



(b)



(c)



(d)

Fig. 6. Comparison of DCM and convolution coding in (a) Proakis A, (b) Proakis B, (c) Proakis C, (d) WBAN CM4 channel.

When WBAN CM4 channels are examined, it is seen that the energy is not spread even though they have high delay spread [20]. In Proakis B and C channels, the energy spreads to the channel. Dual carrier modulations give a better performance when the energy is spread into the channel.

3.2. Comparison of DCM Models with Channel Coding Technique and Space-Time Coding

As a result of sending the same symbol on two carriers in the DCM structure, diversity gain is achieved. Both spatial and temporal diversity are used in Alamouti Space-Time Block Coding. In Alamouti STBC, there are two antennas in the transmitter and a symbol and a complex conjugate of these symbols are sent from these antennas at consecutive times [1]. In studies on Alamouti STBC, the error performance in the Rayleigh channel has been obtained [21] and compared with the MIMO-OFDM system. It has been observed that using Alamouti STBC in the MIMO system with the maximum ratio combining method gives better results [22, 23]. In a different study, an experimental study was conducted with software-defined radio (SDRs) and a 2 dB diversity gain was found in the line of sight environment at a bit error rate of *5e-4* [24].

To compare Alamouti STBC with DCM, the SISO version is likewise; It can be done by sending a symbol at consecutive times followed by the complex conjugate of that symbol. In this case, the system will have the same data rate as DCM at the same bandwidth. The Alamouti SISO implementation scheme is shown in Figure 7. When sending two consecutive symbols, as shown in Equation (2), it is accepted that the channel does not change.

$$h_0(t) = h_0(t+T) = h_0 = a_0 e^{j\emptyset_0} \tag{2}$$

If the sent signal is s0, the received signal at the receiver will be as in Equation (3).

$$\begin{aligned} r_0 &= r_0(t) = h_0 s_0 + n_0 \\ r_1 &= r_1(t) = h_0 s_0^* + n_1 \end{aligned} \tag{3}$$

In this case, the symbol obtained by combining two consecutive symbols is found as in Equation (4).

$$\begin{aligned} \widehat{s_0} &= h_0^* r_0 + h_0 r_1^* = h_0^*(h_0 s_0 + n_0) + h_0(h_0^* s_0 + n_1^*) \\ &= 2a_0^2 s_0 + h_0^* n_0 + h_0 n_1^* \end{aligned} \tag{4}$$

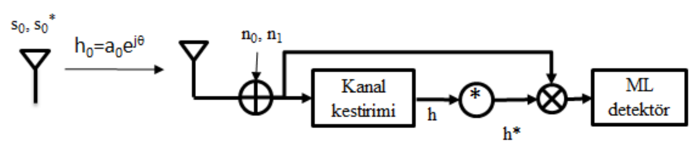


Fig. 7. SISO adaptation of Alamouti STBC encoding.

In the simulations created to examine the error performances of Alamouti (2x1) STBC, the adaptation of this coding to SISO, dual carrier modulations and ½ convolution coding, the number of iterations was kept as 100 and the total number of symbols as *1e6*. Transmitter output powers are set the same. In other words, since there will be simultaneous output from both antennas in MISO (2x1), the powers here are halved for the two antenna outputs. In addition, interleaving in DCMs is not used here to create the same conditions, only the different constellation diagram feature is used in DCMs. Simulations were made on BPSK, QPSK and 16QAM modulations. A single-tap Rayleigh fading channel is used as the wireless channel. Channel state information (CSI) is assumed to be known at the receiver.

Figures 8 and 9 show the simulation results for BPSK and QPSK modulations, respectively. It is seen that the performance of Convolution coding in BPSK modulation and 2x1 Alamouti STBC in QPSK modulation, especially at high SNR ratios, gives better performance. When comparing DCM and Alamouti SISO implementation, DCM stands out.

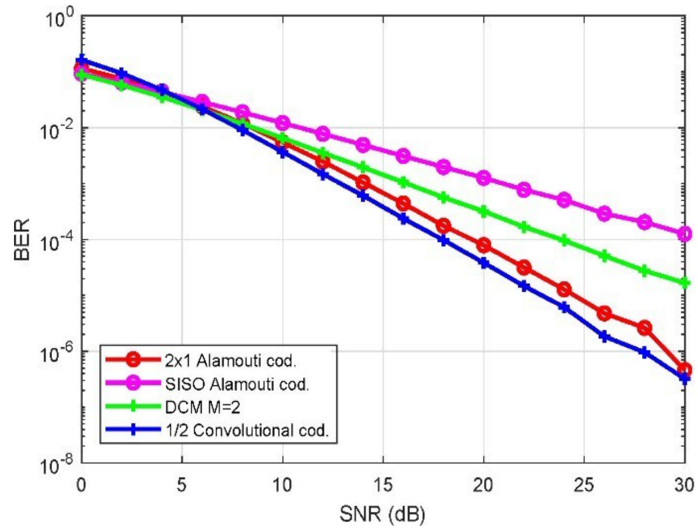


Fig. 8. Comparisons in BPSK modulation.

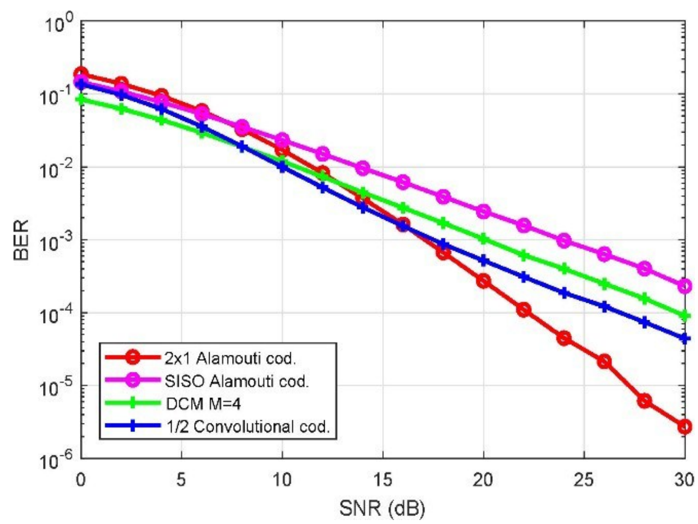


Fig. 9. Comparisons in QPSK modulation.

Figure 10 shows the simulations realized in 16QAM. Alamouti STBC seems to be inferior to DCM performance in 16QAM modulation. Even the Alamouti SISO version seems to outperform the MISO version. The output power is kept the same for all simulations, therefore, the amplitude is halved in Alamouti STBC. Since symbols are more close in 16QAM and halved amplitude, Alamouti STBC performance falls from others.

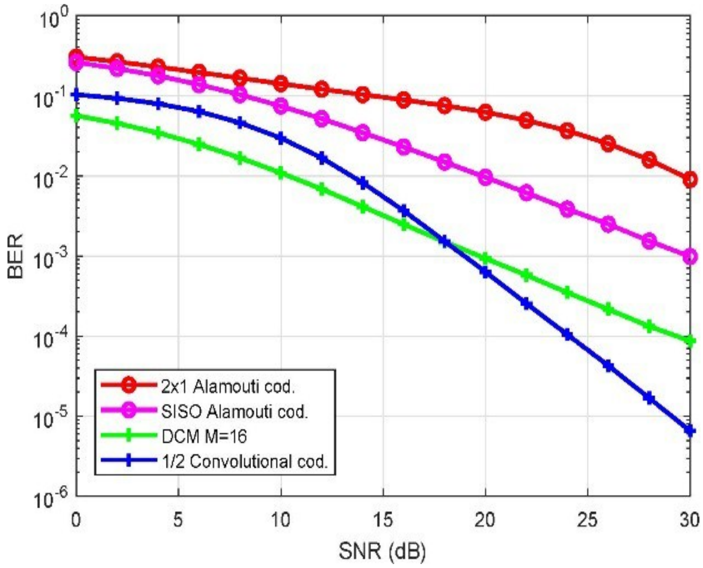


Fig. 10. Comparisons in 16QAM modulation.

According to these graphs, it is seen that DCM gives better results than Alamouti coding in high-level (M=16) modulation. Here the SISO adapted Alamouti is better than the MISO version. However, in this case, the data rate is halved. It is seen that MISO Alamouti coding gives better results than DCM in low-level (M=4, M=2) modulation. However, it is seen that the performance of SISO Alamouti coding is lower than that of DCM. In a single tap channel, ½ convolution coding generally appears to perform slightly better than Alamouti SISO and DCM. However, the receiving part of the convolution coding is more complex than other methods. At low-level modulation, Alamouti MISO gives better performance. However, in some applications such as body area networks, it is thought that using multiple antennas would not be ideal since size will be important.

4. CONCLUSION

In this study, the comparative analysis reveals that DCM offers improved performance over convolution channel coding at high modulation levels in WBAN channels. When compared with Alamouti STBC, DCM performs better in high-level modulations, while Alamouti STBC is advantageous in low-level modulations. The SISO adaptation of Alamouti coding falls behind DCM in terms of performance, albeit with a reduced data rate. These findings contribute to the understanding of the benefits and trade-offs associated with DCM and provide valuable insights for optimizing communication systems in WBAN scenarios. DCM's ability to achieve superior performance at high modulation levels positions it as a promising candidate for robust data transmission in WBANs, enabling seamless communication in healthcare and wearable applications. Future research can delve deeper into optimizing DCM for specific WBAN scenarios and extending its benefits to other wireless communication systems.

References

[1] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications,* 16(8), pp. 1451-1458, 1998.

[2] A. Batra and J. Balakrishnan, "Improvements to the multi-band OFDM physical layer," *in Proceedings of the 3rd IEEE Consumer Communications and Networking Conference*, 08-10 Jan. 2006, Las Vegas, USA [Online]. Available: IEEE Xplore, http://www.ieee.org. [Accessed:16.06.2018].

[3] Ecma International, Ecma-368 high rate ultra-wideband PHY and MAC standard, *IEEE Std*, Geneva, 2008.

[4] K. H. Park, H. K. Sung and Y. C. Ko, "BER analysis of dual carrier modulation based on ML decoding," *in Proceedings of the Asia-Pacific Conference on Communications,* 31 Aug. 2006, Busan, South Korea [Online]. Available: IEEE Xplore, http://www.ieee.org. [Accessed:21.06.2018].

[5] T. Wu and T. Chen, "Dual carrier modulation in channel aggregation for 60GHz WLAN system," *IEEE Wireless Communications Letters*, 7(5), pp. 792-795, 2018.

[6] S. K. Kondoju, V. V. Mani and R. Bose, "Exact BER analysis of DCM for multiband OFDM-UWB system over uncorrelated Nakagami-M fading channels," *in Proceedings of the IEEE International Conference on Ultra-WideBand (ICUWB)*, 01-03 Sept. 2014, Paris, France [Online]. Available: IEEE Xplore, http://www.ieee.org. [Accessed:16.06.2019].

[7] S. K. Kondoju and V. V. Mani, "Outage and BER analysis of dual-carrier modulation over frequency-selective Nakagami-m fading channels," *International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, 36(1), pp. 90-107, 2017.

[8] Y. Feng, B. Zhang, C. Zhi, K. Liu, W. Liu, F. Shen, C. Qiao, J. Zhang, Y. Fan and X. Yang, "A 20.8-Gbps dual-carrier wireless communication link in 220-GHz band," *China Communications*, 18(5), pp. 210-220, 2021.

[9] A. R. Ferdous, "Bit error rate performance evaluation of an ultra-wideband communication system with dual carrier modulation and space diversity," MS Thesis, Bangladesh University of Engineering and Technology, Dhaka, 2019.

[10] Y. Qian, L. Xiao and T. Jiang, "SM-STBC aided orthogonal time frequency space modulation," *in IEEE Wireless Communications and Networking Conference (WCNC)*, 10-13 April 2022, Austin, TX, USA [Online]. Available: IEEE Xplore, http://www.ieee.org. [Accessed: 07 May 2021].

[11] U. I. Hamouda, M. J. Bendaw, T. M. Buzid and M. M. Eddaghel, "Comparison of BER performance of SISO, MISO and MIMO systems based on OSTBC and EO-STBC techniques," *in Third Conference for Engineering Sciences and Technology (CEST- 2020)*, 1-3 Dec. 2020, Alkhoms, Libya.

[12] Y. Karan and S. Kahveci, "QPSK-dual carrier modulation for ultra-wideband communication in body area network channels," *Turkish Journal of Electrical Engineering & Computer Sciences*, 27(4), pp. 2526-2540, 2019.

[13] IEEE Standards Association, IEEE Standard for Local and Metropolitan Area Networks - Part 15.6: Wireless Body Area Networks. *IEEE Std*, New York, 2012.

[14] Y. Karan and S. Kahveci, “Performance comparison of wireless body area network protocol with dual carrier modulations,” *Journal of Communications Technology and Electronics*, 68(5), pp. 527–539, 2023.
[15] R. Yang and R. S. Sherratt, *Novel Applications of the UWB Technologies, (Chapter:1) Multiband OFDM Modulation and Demodulation for Ultra Wideband Communications*, First Edition, IntechOpen, Rijeka, 2011.
[16] J. Meyer, “Convolution decoder using the viterbi algorithm,” *U.S. Patent and Trademark Office. U.S. Patent No 5,802,115*, Washington DC, 1998.
[17] F. Huang, “Evaluation of soft output decoding for turbo codes,” Master Thesis, Virginia Polytechnic Institute and State University, Virginia, 1997
[18] J. Jootar, J. R. Zeidler and J. G. Proakis, “Performance of Alamouti space-time code in time-varying channels with noisy channel estimates,” *in Proceedings of the IEEE Wireless Communications and Networking Conference*, 13-17 March 2005, New Orleans, LA, USA, [Online]. Available: IEEE Xplore, http://www.ieee.org. [Accessed: 21 June 2019].
[19] A. Çalhan, C. Çeken and İ. Ertürk, "A teaching demo application of convolutional coding techniques for wireless communications," *in 2009 IEEE International Conference on Application of Information and Communication Technologies*, 14-16 October 2009, Baku, Azerbaijan [Online]. Available: IEEE Xplore, http://www.ieee.org. [Accessed: 07 Sept. 2022].
[20] K. Takizawa, T. Aoyagi, J. I. Takada, N. Katayama, K. Yekeh, Y. Takehiko and K. R. Kohno, “Channel models for wireless body area networks,” *in Proceedings of the 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 20-25 Aug. 2008 Vancouver, BC, Canada [Online]. Available: IEEE Xplore, http://www.ieee.org. [Accessed: 13 Oct. 2019].
[21] K. Sankar, “DSPLOG signal processing for communication,” [Online]. Available: *http://www.dsplog.com/2008/10/16/alamouti-stbc/* [Accessed: April 23, 2021].
[22] R. K. Roy and T. K. Roy, “BER analysis of MIMO-OFDM system using Alamouti STBC and MRC diversity scheme over Rayleigh multipath channel,” *Global Journal of Research in Engineering*, 13(13), pp. 14-24, 2013.
[23] S. Nandi, A. Nandi and N. N. Pathak, “Performance analysis of Alamouti STBC MIMO OFDM for different transceiver system,” *in Proceedings of the International Conference on Intelligent Sustainable Systems (ICISS)*, 07-08 Dec. 2017, Austin, Palladam, India [Online]. Available: IEEE Xplore, http://www.ieee.org. [Accessed: 07 May 2021].
[24] R. Qomarrullah, I. W. Mustika and S. Dharmanto, “Performance comparison of SISO and MIMO-OFDM based on SDR platform,” *in 3rd International Conference on Science and Technology-Computer (ICST)*, Yogyakarta, Indonesia, 2017.

Biographies

Yasin Karan was born in İstanbul, Türkiye. He received his B.Sc. degree in Electronics and Communication Engineering from Kocaeli University, M.Sc. degree from the University of Rochester, NY, USA and Ph. D. degree in Electrical-Electronics Engineering from the Karadeniz Technical University, Trabzon, Türkiye, in 2006, 2009, and 2021, respectively. He is currently an Assistant Prof. at Recep Tayyip Erdogan University. His main research areas include wireless communications, body area networks, microcontrollers, sensors and embedded control systems.
E-mail: yasin.karan@erdogan.edu.tr

Salim Kahveci was born in Trabzon, Türkiye, on January 05, 1975. He received the B. Sc., M. Sc., and Ph. D. degrees in Electrical & Electrical Engineering from the Karadeniz Technical University, Tabzon, Türkiye, in 1996, 1999, and 2006, respectively. From September 2010 to June 2011, he has been a Postdoctoral Researcher, with the Signal Processing Laboratory, Department of Electrical Engineering, Columbia University, New York, USA. He is now a Full Prof. at Karadeniz Technical University. His main research areas include wireless communications, signal processing, information theory, 5G and channel codes.
E-mail: salim@ktu.edu.tr