Konya Mühendislik Bilimleri Dergisi, c. 13, s. 1, 1-10, 2025
Konya Journal of Engineering Sciences, v. 13, n. 1, 1-10, 2025
ISSN: 2667-8055 (Electronic)
DOI: 10.36306/konjes.1530104

MA-OFDM-SPM: A NEW MULTIPLE ACCESS TECHNIQUE FOR 3GPP-DEFINED REDCAP IOT DEVICES

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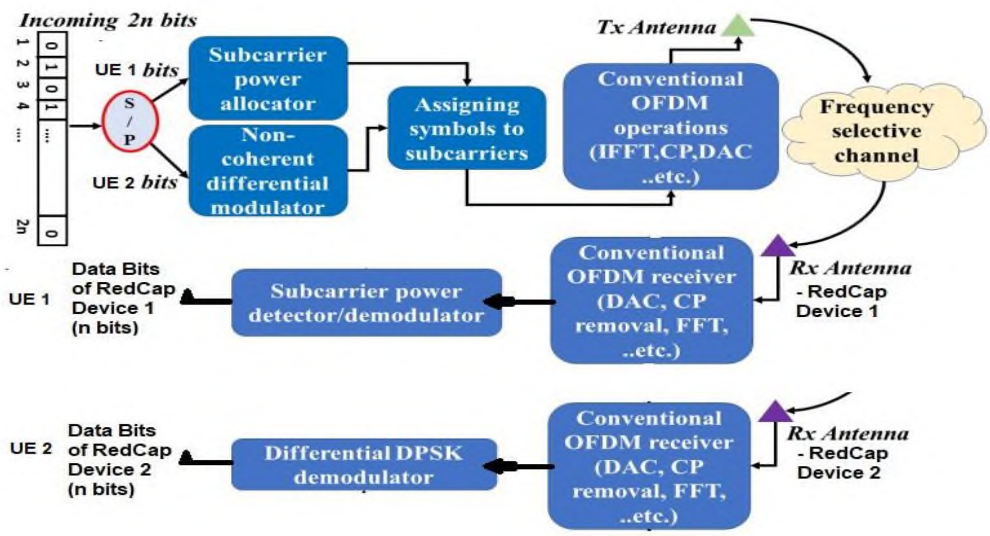
Highlights

- Non-coherent OFDM based a new multiple user waveform has been studied for 6g and beyond wireless communications.
- The performance of this new technique that is called MA-OFDM-SPM is compared with conventional OFDMA.
- The BER and throughput of this waveform are found to work well for RedCap devices and IOT.

Graphical Abstract



Transmitter/Receiver of the proposed MA-OFDM-SPM. Unlike conventional OFDM, the proposed technique employs two separate modulations where half the incoming bit stream is modulated by DPSK and the other half is modulated through the power level (i.e., high and low pattern).

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(Received: 08.08.2024; Accepted in Revised Form: 04.12.2024)

ABSTRACT: RedCap devices face challenges related to efficient multiple access techniques that can fully leverage their potential while adhering to their constraints. There are many multiple access techniques proposed in the literature recently, but none of them is deemed a good fit for the multi-facet requirements of RedCap devices. Motivated by that, this paper introduces a new multiple-access technique designed to address these challenges, aiming to optimize the performance and efficiency of RedCap devices in various application scenarios. The proposed technique seeks to enhance data rates, reduce latency, and extend battery life while maintaining the cost-effectiveness and simplicity essential for RedCap devices. Consequently, the proposed design effectively overcomes prior challenges and boosts system throughput by leveraging the power domain to transmit supplementary data bits, all while preserving a streamlined and uncomplicated transceiver design. In summary, with the same time, frequency, space, and power resources, it can be served an additional user with a stream of data bits equal to that of the main user, thus resulting in doubling the system's spectral efficiency.

Keywords: 6G, Coherent Transmission, IOT, Non-Coherent OFDM, Subcarrier Power Modulation, Wireless Communications

1. INTRODUCTION

Reduced Capability (RedCap) devices, as delineated by the 3rd Generation Partnership Project (3GPP) standards, represent a middle ground between high-end, full-featured 5G devices and low-power, low-complexity IoT devices. These devices are engineered to support use cases such as industrial IoT and remote drone control that necessitate moderate data rates and latency, while also benefiting from lower device complexity and extended battery life. RedCap devices are particularly relevant for applications where performance requirements are more demanding than those of low-end IoT devices but do not necessitate the full capabilities of 5G [1].

The main specifications of RedCap Devices include: 1) reduced peak data rates; 2) simplified and lower-order modulation and coding schemes; 3) reduced bandwidth with support for sub 6G Hz spectrum; 4) simplified MIMO configurations limited to 2x2 MIMO or single-antenna systems; 5) lower complexity with fewer receive and transmit chains and simplified RF design and baseband processing; 6) extended battery life with enhanced power-saving features and Support for extended DRX cycles and power-saving modes; 7) support for 5G core features including compatibility with key 5G core network features such as network slicing, service-based architecture, and edge computing.

The advantages of RedCap Devices include cost effectiveness due to reduced complexity which leads to lower production costs, extended battery life that is optimized for low power consumption, moderate performance suitable for applications requiring better performance than basic IoT but not the full capabilities of high-end 5G devices, and seamless integration that is compatible with existing 5G infrastructure, leveraging 5G's advanced features.

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Despite these advantages, RedCap devices face challenges related to efficient multiple-access techniques that can fully leverage their potential while adhering to their constraints. There are many multiple access techniques both orthogonal and non-orthogonal proposed in the literature recently [2], [3], but none of them is deemed a good fit for the multifaceted requirements of RedCap devices, especially the one related to reducing complexity while improving efficiency. Motivated by that, this paper introduces a new multiple-access technique designed to address these challenges, aiming to optimize the performance and efficiency of RedCap devices in various application scenarios. The proposed technique seeks to reduce complexity, enhance data rates, reduce latency, and extend battery life while maintaining the cost-effectiveness and simplicity essential for RedCap devices.

The use of non-coherent-based multiple access approaches allows the use of low complexity detectors, which can reduce complexity remarkably and thus make it a better fit for RedCap devices. Although non-coherent-based multiple schemes and systems reduce complexity significantly, their performance in terms of reliability and throughput is usually suboptimal compared to their coherent counterparts [4]. To address the dilemma between coherent and non-coherent designs, the authors have proposed a solution involving Orthogonal Frequency-Division Multiplexing with Subcarrier Power Modulation (OFDM-SPM), and Differential Phase Shift Keying (DPSK) as initially introduced in references [5] and [6]. In [7], OFDM-SPM was generalized to quadrature signal constellations. A non-coherent adaptation of Orthogonal Frequency-Division Multiplexing (OFDM) with Subcarrier Power Modulation (OFDM-SPM) was proposed in [8] where the receiver complexity was reduced further using differential phase shift keying (DPSK) instead of coherent BPSK. OFDM-SPM exploits the power of the subcarriers within an OFDM block as an additional dimension to transmit extra information bits, resulting in reduced complexity and latency compared to conventional approaches. Furthermore, it was shown in [8] that OFDM-SPM operates under different power modes including power saving and power reassignment. This latter mode includes two policies, namely an optimized and a non-optimized reassignment mode. This publication comes under the scope of non-optimized power reassignment where it was found that, under this mode, the scheme achieves the same performance as coherent OFDM-BPSK. Motivated by this, the key contributions of this paper are outlined as follows:

• Presenting a novel non-coherent multiple access design that attains a bit error rate (BER) performance equivalent to that of coherent OFDMA.

• The power level is explored as an extra data dimension; thus, an additional data stream can be transmitted to serve an additional user by changing the subcarriers' power levels according to the user's data bits.

• Achieving twice the spectral efficiency of the overall system relative to conventional OFDMA, due to the inclusion of the two-dimensional data modulation aspects of the scheme.

The subsequent sections of this paper are outlined as follows: Section II provides a detailed description of the system model. Section III examines the performance characteristics of the proposed scheme. Section IV presents the simulation results, and Section V delineates the concluding remarks.

2. SYSTEM MODEL OF MA-OFDM-SPM SYSTEM

The transceiver structure of the proposed MA-OFDM-SPM system is illustrated in Figure 1. In the transmitter, the incoming stream of length 2n bits is partitioned into two branches of n bits each, which are modulated independently afterwards to serve two distinct user equipment (UE1 and UE2) of RedCap-type devices. To serve UE1, the power allocation block determines the power levels for the subcarriers, with the ith bit indicating the power value assigned to the ith subcarrier used for data transmission. In other words, a bit '1' signifies that the subcarrier power is set to high (represented as H), whereas a bit '0' indicates that the subcarrier power is set to low (represented as L). The second n bits are modulated using classical DPSK modulation to serve UE2.

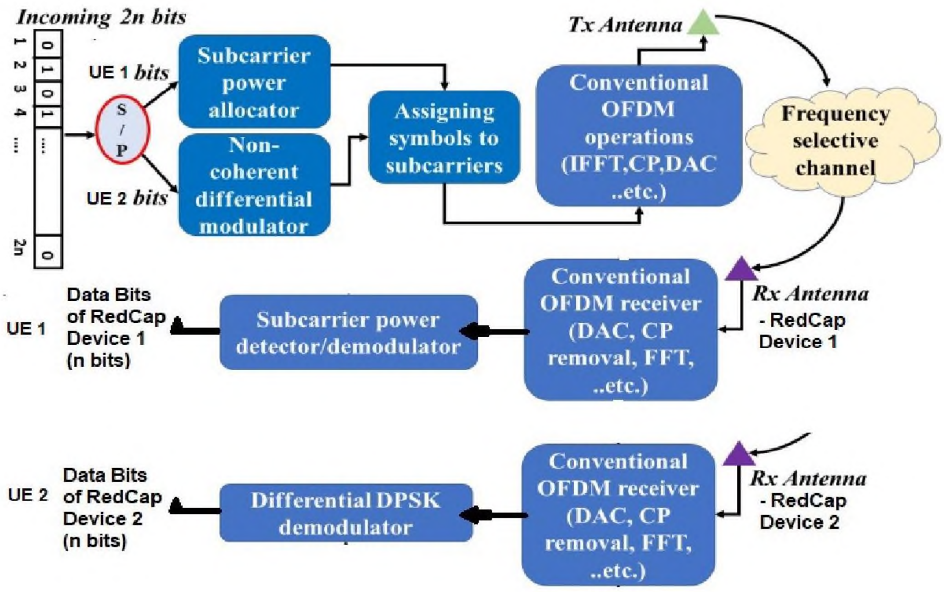

Figure 1. Transmitter/Receiver of the proposed MA-OFDM-SPM. In contrast to conventional OFDMA, the proposed approach uses two distinct modulations: one half of the incoming bit stream is modulated using DPSK, while the other half is modulated based on the power levels (i.e., high and low values).

At the receiving RedCap Device 1 (UE1), the power bits are detected from the incoming combined stream. More specifically, the values essentially the levels of power detection are performed by straightforwardly comparing each subcarrier's received power level with a pre-determined optimal threshold T defined as the power level corresponding exactly to the central point between the high (H) and low (L) power values.

$$T = \left(\frac{H+L}{2}\right)^2 \tag{1}$$

On the other hand, at the receiving RedCap Device 2 (UE2), conventional DPSK demodulation is performed for the data symbols according to the difference of the symbols' phases and applying differential decoding for the bits having DPSK modulation. It is crucial to emphasize that the minor complexity in the detection of the power block through thresholding comparison, which is regarded as a non-coherent detection approach, makes the proposed scheme an excellent fit for Redcap device requirements. The resulting simplicity in the detection process of the proposed design makes it surpass existing methodologies such as OFDM-IM, OFDM-SNM, and SIM-OFDM, which commonly rely on either maximum likelihood (ML) detection for optimal performance or log-likelihood ratio (LLR) detection for decreased complexity [9].

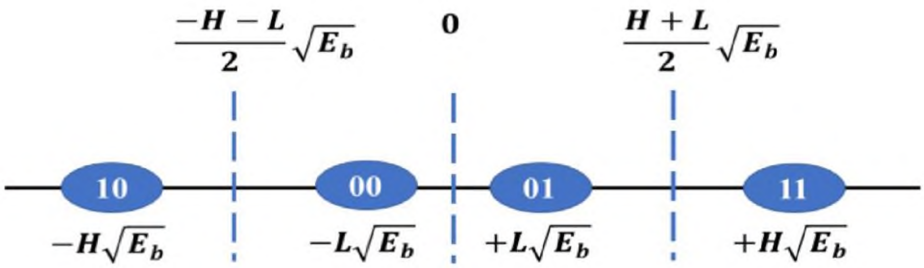

Figure 2. Constellation diagram of MA-OFDM-SPM, where the bit pair 'ij' is mapped to a subcarrier with power modulation (high if 'i' = 1 and low if 'i' = 0) and carries a bit 'j' modulated using two-bit (2)-DPSK

3. PERFORMANCE ANALYSIS OF THE PROPOSED MULTI-USER SYSTEM: MA-OFDM-SPM

Unlike conventional OFDMA, MA-OFDM-SPM combines two modulations to serve two different users. As shown in the receiver in Fig.1, an error can occur during the power levels' detection for UE1 or DPSK symbols demodulation for UE2. This results from multipath channel fading and noise impact, which can either increase or decrease the subcarrier power. Consequently, a high-power subcarrier may be misinterpreted as a low-power subcarrier, and vice versa. This results in four constellation points as shown in the constellation diagram of Fig.2. Consequently, the aggregated bit error rate of the system supporting two users simultaneously is characterized as the average of the bit error rates for the power component associated with UE1 and the DPSK component linked to UE2:

$$BER_{MA} = \frac{1}{2}(BER_{DPSK-UE2} + BER_{Power-UE1}) \quad (2)$$

Particularly, the bit error rate expression for 2-DPSK in a Rayleigh fading environment, under the assumption that the channel phase remains relatively stable over the duration of a bit sequence, is as follows [10]:

$$BER_{DPSK,Conventional} = \frac{1}{2\left(1+\frac{E_b}{N_0}\right)} \quad (3)$$

where E_b/N_0 shows the signal to noise ratio. The derivation of the expression $BER_{DPSK-UE2}$ can be computed by considering the variations resulting from high and low power levels. As such, the bit error rate of the bit stream modulated through DPSK follows the following expression:

$$BER_{DPSK-UE2} = \frac{1}{2}\left(BER_{DPSK|H} + BER_{DPSK|L}\right) \quad (4)$$

where

$$BER_{DPSK|H=}\frac{1}{2\left(1+H^2\frac{E_b}{N_0}\right)} \quad (5)$$

and

$$BER_{DPSK|L=}\frac{1}{2\left(1+L^2\frac{E_b}{N_0}\right)} \quad (6)$$

show the impact of the high and low power levels on the bit stream modulated by DPSK respectively.

For the bit stream modulated by the power levels, the BER can be expressed as follows:

$$BER_{Power-UE1} = \frac{1}{4}P_1 + \frac{1}{4}P_2 + \frac{1}{4}P_3 + \frac{1}{4}P_4 \tag{7}$$

where

$$P_1 = \frac{1}{2\left(1+\left(\frac{H-L}{2}\right)^2\frac{E_b}{N_0}\right)} \tag{8}$$

$$P_2 = \frac{1}{2\left(1+\left(\frac{H+3L}{2}\right)^2\frac{E_b}{N_0}\right)} \tag{9}$$

$$P_3 = \frac{1}{2\left(1+\left(\frac{H-L}{2}\right)^2\frac{E_b}{N_0}\right)} \tag{10}$$

$$P_4 = \frac{1}{2\left(1+(H+L)^2\frac{E_b}{N_0}\right)} \tag{11}$$

For the case of non-optimized power reassignment, through a successive series of exhaustive trial-and-error experiments, the values of high and low power were determined to be:

$$H = \sqrt{3}, L = 1 \tag{12}$$

By substituting the specific values of H and L identified in equation (12) into equation (4),
It was found that this expression approaches the bit error rate of coherent conventional OFDM-BPSK very closely as confirmed by the bit error rate simulation results. The expression for conventional OFDM with BPSK used in the simulations is as follows:

$$BER_{Coherent-BPSK} = \frac{1}{2}\left(1 - \sqrt{\frac{\frac{E_b}{N_0}}{1+\frac{E_b}{N_0}}}\right) \tag{13}$$

4. SIMULATION RESULTS

Simulation results displaying the performance of the proposed multiple access technique named MA-OFDM-SPM are exhibited. In the simulator, non-coherent subcarrier power modulation is used to serve UE 1, and non-coherent differential phase shift keying is used to serve UE2. The evaluation is expressed as bit error rate (BER) and throughput of the system. Table 1 shows a complete list of the simulation parameters.

Figure 3 illustrates the results of the simulations for BER for both U2 and U1 which are served by bit sequences modulated by DPSK and power level of the subcarriers respectively. Besides, the derived BER curve for the DPSK-UE2 is plotted. Furthermore, theoretical BER curves for conventional OFDM with DPSK and conventional OFDM with BPSK are displayed for comparison purposes. As shown in this plot, the BER curve for UE2 as a result of using MA-OFDM-SPM surpasses conventional OFDM with DPSK and achieves almost the same performance as coherent OFDM-BPSK.

Table 1: Parameters of Simulations with Rayleigh Channel Model

Modulation Parameters	**Values**
IFFT / FFT size	64
Number of subcarriers for data n	52
Number of symbols for CP	16
Number of inactive sub-carriers for OOBE	12
Number of OFDM symbols	10^4
Delay samples positions (Multipath channel)	[0 3 5 6 8]
Multipath channel tap power profile (dBm)	[0 -8 -17 -21 -25]

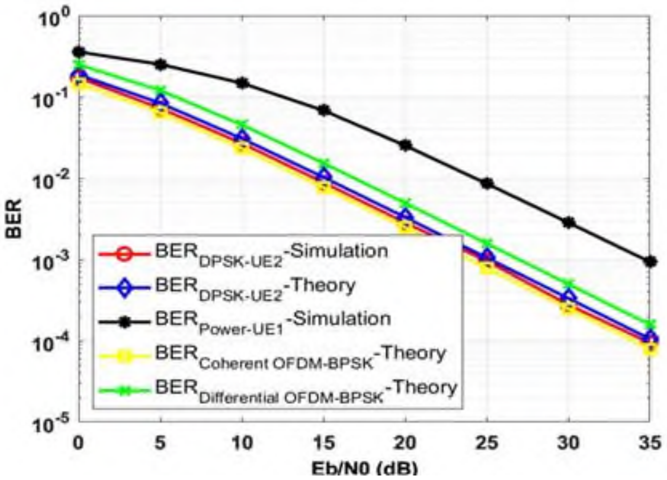

Figure 3. BER (Bit error rate) of MA-OFDM-SPM method. As observed, the bit error rate for groups of bits modulated with DPSK approaches the curve of coherent OFDM-BPSK very closely.

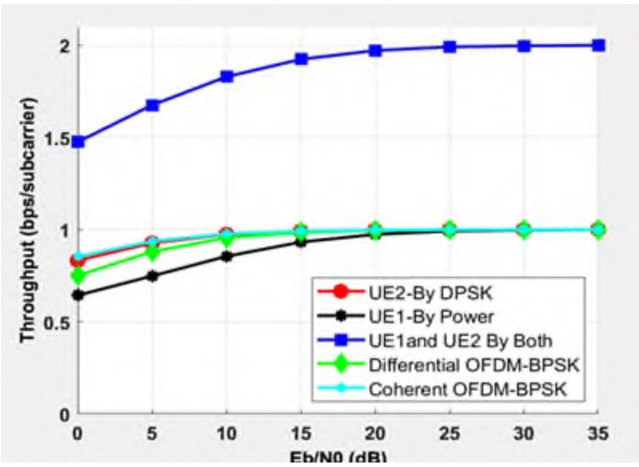

Figure 4. Throughput of MA-OFDM-SPM relative to conventional OFDM with coherent BPSK and non-coherent BPSK (i.e. DPSK). The 2-D modulation aspect (i.e., the DPSK dimension and the power dimension) of MA-OFDM-SPM gives it the benefit of doubling the system throughput compared to conventional OFDM with BPSK or DPSK

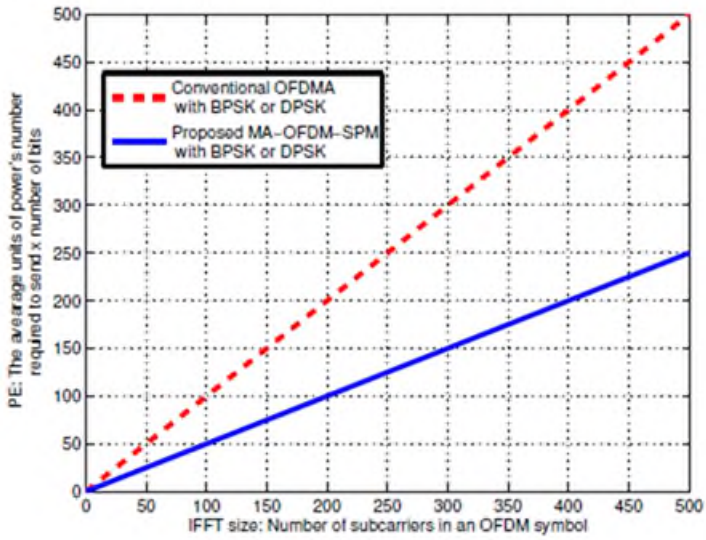

Figure 5: MA-OFDM-SPM compared to OFDM in terms of Power Efficiency (PE) versus number of subcarriers in an OFDM symbol (IFFT size).

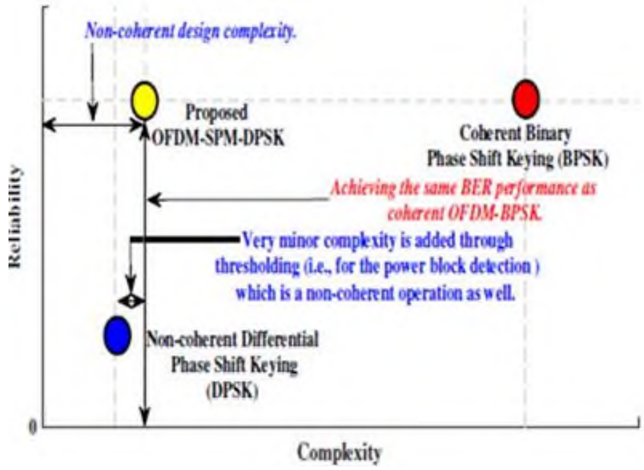

Figure 6: OFDM-SPM-DPSK compared to coherent and noncoherent BPSK in terms of design complexity and reliability. The figure shows that OFDM-SPM-DPSK combines the benefits of both non-coherent modulations (i.e., low-complexity) and coherent modulations (i.e., high performance).

Moreover, since MA-OFDM-SPM explores the power characteristic of the subcarriers as an additional data-carrying dimension, it allows for the transmission of an extra bit sequence using the power levels of the subcarriers. However, as shown in Figure 3, the detection of this additional stream is less reliable compared to conventional OFDM-DPSK. This erroneous bit sequence can be allocated to some user applications such as audio or video streaming services that don't demand ultra-reliability.

In Figure 4, the throughput of MA-OFDM-SPM is displayed individually and collectively for both UE1 and UE2. It is clear that, at high SNR values, the aggregated data rate of the scheme is twice as high as that of conventional OFDMA with DPSK/BPSK. This is due to the fact that MA-OFDMSPM utilized the power of subcarriers in OFDM as an extra dimension to serve an additional user, thus outperforming conventional OFDMA in terms of data rate. It is known in the literature, coherent schemes are recognized as surpassing non-coherent systems in terms of reliability; however, non-coherent schemes are less complex in terms of receiver design because of the absence of phase estimation.

In Fig. 5, the power efficiency[1] of MA-OFDM-SPM is compared with coherent and non-coherent OFDMA modulations considering the use of binary phase shift keying with different number of subcarriers (i.e., IFFT size)[1]. This plot represents the huge benefits that MA-OFDM-SPM offers, as being a non-coherent multi-access design which can provide twice the performance in terms of power efficiency as that of conventional coherent or non-coherent OFDMA based designs, which are currently being used in LTE, 5G, and WiFi networks. In other words, MA-OFDM-SPM needs half the power as that of OFDMA to send the same number of bits. This is with the benefit of having an additional stream that can be transmitted through the power subcarriers.

It is known in the literature that coherent systems surpass non-coherent systems in terms of reliability; however, noncoherent schemes are less complex in terms of receiver design because of the absence of phase estimation [11]–[14]. In Fig.6, OFDM-SPM-DPSK is compared with coherent and noncoherent binary phase shift keying modulations in terms of complexity and reliability. This plot is a presentation for the great benefits which OFDM-SPM-DPSK offers, in the nonoptimized power reassignment mode, as being a non-coherent design with the same performance as coherent OFDM with BPSK. This is with the benefit of having an additional stream that can be transmitted through the power subcarriers. As such, OFDM-SPM-DPSK is a good fit for applications requiring low-complexity, ultra-reliability and high data rate.

In addition, we used logical numerical and theoretical analysis to investigate the effect of the number of users on the amount of spectrum measured in IFFT size, which is required to be allocated among users so that similar spectral efficiency can be achieved, and noticed that MA-OFDM-SPM is twice superior than that of conventional OFDMA. It's also anticipated by logic that the BER performance to remain the same regardless of the number of users in the system because the new additional users can be allocated different new resources. Also, the system spectral efficiency of MA-OFDMSPM will stay twice or double that of conventional OFDMA based systems even when the number of users increases in the system setup. Moreover, future studies will conduct actual practical implementation of MA-OFDM-SPM to verify and solidify its superiority against competitive schemes in real life network setups. Given the above detailed analysis of the results, it is shown that MA-OFDM-SPM can be a good fit for applications requiring low complexity, ultra-reliability, and high spectral efficiency performance. Future studies will focus on improving the performance of MA-OFDM-SPM further using AI/ML based methods and techniques like deep learning and neural networks in a way that is similar to what has been done in [15], [16].

5. CONCLUSION

RedCap devices face significant challenges in achieving efficient multiple access techniques that fully leverage their potential while adhering to their constraints. Despite numerous proposed techniques in recent literature, none have satisfactorily met the multi-faceted requirements of RedCap devices. This paper introduced a novel multiple-access technique designed specifically to address these challenges, optimizing the performance and efficiency of RedCap devices across various application scenarios. The proposed technique enhances data rates, reduces latency, and extends battery life while maintaining the cost-effectiveness and simplicity crucial for RedCap devices. By utilizing the power domain as an extra dimension for delivering additional data bits, the design not only overcomes previous challenges but also provides higher system throughput. This approach effectively doubles the system's spectral efficiency, allowing an additional user to be served with a stream of data bits equal to that of the main user, without increasing transceiver design complexity.

[1] Power efficiency (PE) is measured as the average units of power's number required to send x number of bits; and this is equal to the number of sucarriers in an OFDM symbol (the IFFT size) times the the unit of power in average per subcarrier divided by the number of bits per symbols per subcarrier that can be sent by OFDMA or MA-OFDMA-SPM.

Declaration of Ethical Standards

The authors declare that all ethical guidelines including authorship, citation, data reporting, and publishing original research are followed.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

Funding / Acknowledgements

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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