

Non-coherent OFDM-Subcarrier Power Modulation for Low Complexity and High Throughput IoT Applications

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The matlab simulation codes used to generate the results in this paper can be found at [https://researcherstore.com/SimulationCodes/Non-coherent OFDM-SPM](https://researcherstore.com/SimulationCodes/Non-coherent%20OFDM-SPM)

ABSTRACT Aiming to reduce the transceiver complexity and power consumption of communication systems dedicated to serving future Internet of Things (IoT) applications, researchers have taken many approaches with varying degrees of success. A promising candidate solution that can reduce complexity significantly and thus also enhance power-saving is the use of non-coherent modulation-based schemes. Utilizing a non-coherent structure rids the system of any dependency on the knowledge of the phase of the transmitted signal during demodulation. However, although most of the available non-coherent techniques in the literature reduce the complexity of the system, they, unfortunately, suffer from a drawback of some sort, especially in reducing the overall spectral efficiency of the system. To address this problem, we propose a new non-coherent modulation scheme called orthogonal frequency division multiplexing with subcarrier power modulation and differential phase-shift keying (OFDM-SPM-DPSK), as an effective modulation technique for future 6G and beyond systems. The proposed technique has the potential to reduce complexity, enhance power-saving while improving spectral efficiency significantly, resulting in a spectral efficiency performance twice that of a conventional OFDM system. Furthermore, receive diversity is implemented through maximal ratio combining to overcome the bit error degradation brought by the adoption of a non-coherent structure. Additionally, the computational complexity is discussed and shown to be as efficient as OFDM, where the proposed scheme does not add further complexity over conventional OFDM.

INDEX TERMS IoT, Low complexity, Modulation, Non-coherent, OFDM, Spectral efficiency, Wireless communication.

I. INTRODUCTION

THE Internet of Things (IoT) is a newly emerging phenomenon by which every object can be equipped with computing, sensing, control, and communication capabilities. Ericsson estimates that by the year 2022, a total of approximately 1.5 billion devices will be connected to the network. The IoT then naturally brings its own requirements to the research and technological fields. As such, it has been given an extensive interest in the field of research and is one of the critical technologies (seen as a use case), which the upcoming 6G communication systems will fully accommodate.

As the IoT consists of a vast number of devices/appliances/sensors communicating with one another, communication systems serving the IoT devices should be characterized by two main properties: low complexity, and

low power consumption. This is to maintain prolonged battery lives and to accommodate the small sizes of these sensors and devices which make up the IoT applications. Furthermore, future projections estimate that most data transfer related to the IoT will be that of short messages of an irregular or aperiodic nature [1]. This is rather dissimilar to the applications of previous 4G and 4.5G communication systems, and further emphasizes the need for communication systems specifically tailored to the IoT requirements.

Aiming to reduce the complexity and power consumption of communication systems to be used in IoT applications, researchers have taken many approaches with varying degrees of success. A promising candidate solution that can reduce complexity significantly and thus also enhance power-saving is the use of non-coherent modulation-based systems [2]. Utilizing a non-coherent structure rids the system of

any dependency on the knowledge of the channel state information from one side and the phase of the transmitted symbols of the signal during demodulation from another side. The dependency on CSI and symbols' phases is the basis of detection in coherent systems and is one of the main sources of complexity and overhead in the transceiver design of coherent systems. Furthermore, when dealing with short, sporadic messages, conventional channel estimation uses vast resources and results in a significant amount of overhead [3]. This overhead can dominate the data exchange relative to the size of the data intended to be delivered, and thus reducing the total system throughput and efficiency, especially for those applications that require low latency as the symbol duration is shorter in this case. In [4], it was shown that while coherent structures experience a considerable capacity loss due to the overhead and the CSI estimation error, non-coherent schemes can achieve higher capacity in high-mobility environments. This fact implies that a coherent scheme requires higher bandwidth than its non-coherent equivalent to achieving a target data rate in a practical wireless network so that the capacity loss of using the pilot overhead can be compensated. Another benefit for non-coherent schemes is providing the reliability of mission-critical control links in high-mobility environments such as satellites in space, manned/unmanned aircraft in the air as well as high-speed trains and cars on the ground [5], [6].

In current communication systems, orthogonal frequency division multiplexing (OFDM) is the technique of preference as it offers great spectral efficiency and flexibility. Unlike earlier schemes like frequency division multiplexing (FDM), where a frequency guard band is inserted between every two consecutive FDM carriers, OFDM transmits data on orthogonal closely spaced (overlapping) subcarriers, thus saving a good amount of bandwidth. OFDM has been established and used in many of the currently deployed communication systems (e.g. LTE, WiFi, WiMax, WiGig, LiFi, DVB, DSL, 5G, etc.), and is well suited to frequency-selective channels, which offer a good model for practical multipath wireless channels.

In the literature, several OFDM based non-coherent schemes have been proposed. The proposed schemes can be classified into two main categories, namely non-coherent unipolar OFDM and non-coherent non-linear OFDM techniques. The former is mostly developed for optical communication systems, while the latter is generally used in wireless communication setups.

In unipolar OFDM, the transmitter and the receiver use non-coherent modulation and non-coherent demodulation respectively. This type of communication system is known as intensity modulation/direct detection (IM/DD) system since the phase of the subcarrier is completely ignored in the information encoding and the subcarrier amplitude or intensity is used instead. In this family, firstly DC-offset OFDM (DCO-OFDM) was proposed in [7]. DCO-OFDM uses the Hermitian symmetry property with a DC-bias to generate a

real and positive time-domain signal. This DC-bias depends on the peak-to-average-power ratio (PAPR) of the OFDM symbol and since OFDM has a considerably high PAPR, the DC bias is significantly high. As such, the main problem with DCO-OFDM is the selection of a suitable DC-bias as a large DC-bias was proven to make the communication power-inefficient [8] while smaller DC-bias enhances inter-carrier-interference (ICI) and creates out-of-band signal power [9].

Asymmetrically clipped optical OFDM (ACO-OFDM) was proposed in [11], which unlike DCO-OFDM does not use any DC-bias at the expense of half the data rate [9]. In ACO-OFDM only odd subcarriers are used to transmit data symbols and any negative time samples of the ACO-OFDM symbol are clipped at the transmitter.

Another scheme termed Flip-OFDM with the same performance as ACO-OFDM and saving 50% in hardware complexity at the receiver was presented in [10]. In Flip-OFDM, the output of the IFFT is decomposed into two streams, a positive and a negative part and are separately transmitted over two successive OFDM symbols. Flip-OFDM suffers from the noise power problem as it is doubled during the recombination of the positive and negative OFDM subframes.

The second class of non-coherent OFDM schemes is non-linear OFDMs. Unlike unipolar OFDMs, non-linear OFDM systems employ coherent modulation at the transmitter and non-linear signal direct detection (DD) at the receiver. It is clear in this scenario that the transmitter design for non-linear OFDMs is more complex than unipolar OFDM systems, however, the adoption of this design for the transmitter/receiver of the non-linear OFDM improves the spectral efficiency of the overall communication system when compared with unipolar systems [9].

Particularly, self-heterodyne OFDM (self-het OFDM) [12] has been proposed as a non-coherent OFDM technique that provides immunity to frequency offset and phase noise, thus attaining a non-coherent structure and reducing complexity. The performance analysis for self-het OFDM was carried out in additive white Gaussian (AWGN) environment as well as in frequency selective channels and the following disadvantages were concluded: (1) in terms of spectral efficiency, it allows maximum utilization of only 50% of the spectrum for communication; (2) the local carrier transmission uses almost half of the transmit power; (3) during the self-mixing process, inter-modulation distortions are exhibited at the receiver [9].

Another technique termed as self-coherent OFDM [13] was proposed, which also adopts a non-coherent design. In [13], it was shown that the additional phase noise (PN) introduced by under-sampling down-conversion in self-het OFDM can be substantially reduced with self-coherent demodulation. Although self-coherent OFDM provides both a better bit error rate and spectral efficiency than self-het OFDM, the maximum utilization of the available spectrum is approximately 80%.

Non-coherent OFDM with index modulation (OFDM-IM) [14] has also been proposed as a non-coherent technique that conveys data only through the indices of the active

subcarriers of the OFDM symbol; however, this scheme has also provided worse spectral efficiency than conventional OFDM-IM, depending on the coherence time of the channel.

As can be seen from the above examples of non-coherent OFDM schemes in the literature, generally the adoption of non-coherent transceivers reduces the system complexity, but this always comes at the expense of some reduction in the system's overall spectral efficiency.

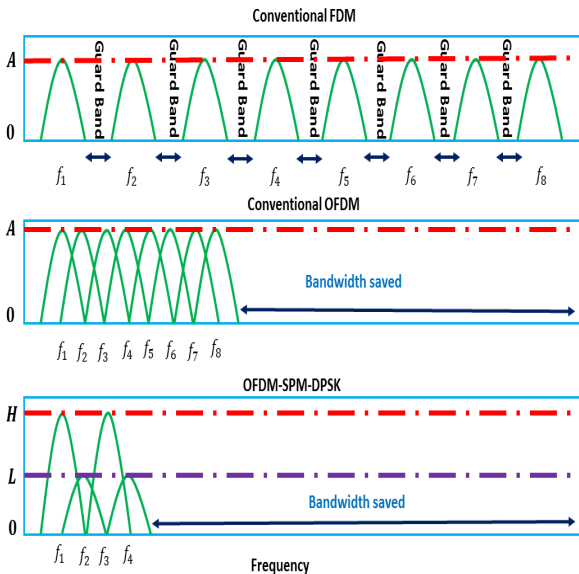


FIGURE 1. OFDM-SPM vs FDM and OFDM

To address this challenge, we propose a new non-coherent modulation scheme called non-coherent OFDM-subcarrier power modulation with differential phase-shift keying (OFDM-SPM-DPSK), as a modulation technique for future wireless communication systems. Such a novel non-coherent modulation scheme has great potential in achieving the following merits: 1) reduce complexity, 2) enhance power-saving, and 3) improve the spectral efficiency by at least twice as that offered by conventional OFDM-based schemes. It should be mentioned that OFDM with subcarrier power modulation (OFDM-SPM) [15], [21] is a recently proposed novel modulation scheme that vastly increases the spectral efficiency of the system. This is done by introducing a third dimension through which data can be conveyed. The pattern of the subcarriers' power in an OFDM block is used to send extra data bits.

An explanatory schematic showing the differences between OFDM-SPM and conventional OFDM subcarriers is depicted in Figure 1. From this figure, it can be seen that unlike conventional OFDM where all the subcarriers have the same power level A , OFDM-SPM subcarriers have two different power levels H , and L . A subcarrier corresponding to the larger power is called a 'high power subcarrier' and a subcarrier with the smaller power is termed as a 'low power

subcarrier'. This pattern of high and low levels in the power spectrum is exploited as a new dimension to convey extra information bits. From the figure (i.e., Fig. 1), the merits that OFDM-SPM introduces in terms of spectral gain are very clear as it achieves a significant saving in the system bandwidth since exactly half the number of subcarriers required by an OFDM system is used by OFDM-SPM-DPSK for transmitting the same amount of data. This saving comes from the manipulation of the power of the subcarriers as half of the data bits can be sent just through the power pattern.

Simulation results and theoretical analysis of OFDM-SPM with binary phase-shift keying (BPSK), which is a coherent modulation scheme, showed that OFDM-SPM increases spectral efficiency greatly, and saves power. This is achieved at the cost of a certain degradation in the BER. With these merits, OFDM-SPM fits the needs of IoT-based applications as it reduces power consumption, reduces delay, and improves spectral efficiency. However, the complexity of the system still needs to be simplified. Therefore, a non-coherent version of OFDM-SPM is proposed in this study.

In this new version of OFDM-SPM, the differential phase (through using DPSK as a modulation format) is used jointly with the power of the subcarriers to detect the information data symbols non-coherently, while maintaining the spectral efficiency merits of the original scheme (OFDM-SPM) [15] as well as reducing complexity and signaling overhead. Particularly, OFDM-SPM-DPSK is proposed as a modulation technique to be used for applications requiring high throughput, low complexity, and low power such as those in the domain of IoT. Furthermore, its performance is demonstrated by theoretical derivations and verified by numerical simulations in terms of both bit error rate (BER) and throughput over a wireless multipath Rayleigh fading channel.

However, it is known that coherent schemes exhibit a better bit error rate than non-coherent modulation schemes [16]. To compensate for this unavoidable degradation in the BER introduced by the use of a non-coherent scheme, we use receive diversity and specifically maximal ratio combining (MRC) by employing two antennas at the receiver. Simulations show that receive diversity improves the degraded bit error of OFDM-SPM-DPSK greatly.

The specific contributions of this paper are summarized as follows:

- The complexity of the original OFDM-SPM transceiver is reduced through the use of a non-coherent modulation format, namely differential binary phase-shift keying (DPSK). The originally proposed scheme (i.e., OFDM-SPM) is a low-power technique which suits very well IoT applications, however, the complexity of the transceiver needed to be reduced further to fit the low-complexity requirement of the IoT domain. OFDM-

SPM-DPSK is the new variant of OFDM-SPM proposed in this paper where the complexity of the original OFDM-SPM system is solved through the use of a non-coherent transceiver. Detailed theoretical and simulated bit error rate and throughput results are provided.

- Although non-coherent schemes provide less-complex transceiver designs than coherent schemes, it is estimated that the BER for non-coherent detection is about two times worse than the BER for coherent detection [16]. To deal with this degradation due to non-coherent detection, receive diversity through MRC (maximal ratio combining) is used. OFDM-SPM-DPSK is studied and simulated under receive diversity.

It should be noted that even though the implementation of MRC needs perfect CSI, it provides the best performance, in terms of bit error rate, among all other known combining schemes.

- The computational complexity of OFDM-SPM-DPSK is discussed.

The remaining sections of this paper are organized as follows. Section II illustrates and explains the OFDM-SPM-DPSK system model. In Section III, the performance analysis is carried out. Section IV provides simulation results. Finally, Section V presents the conclusion and future possible works related to the introduced scheme.

II. SYSTEM DESIGN CONCEPT

A. TRANSMITTING SIDE OF THE PROPOSED NON-COHERENT OFDM-SPM-DPSK

OFDM-SPM-DPSK alternates the power of OFDM subcarriers, which also carry DPSK modulated data symbols, to transmit extra data bits per subcarrier. Since the power is manipulated, non-coherent detection that does not require the phase information of the carrier or channel is possible and feasible. Besides, DPSK is also a non-coherent modulation scheme that does not require the information of the phase of the transmitted symbols at the receiving side, thus rendering the whole transmission process of OFDM-SPM-DPSK as a complete, non-coherent modulation process.

DPSK encodes and decodes data by the relative phase difference between two successive symbols, thus using the previous symbol as a reference and eliminating the need for the knowledge of the absolute phase of the current transmitted symbol and the need for the channel estimation process. This, in effect, greatly reduces the complexity of the transceiver structure of the system, which is very useful for low complexity IoT applications.

The basic structural system model of the introduced OFDM-SPM-DPSK modulation process at the transmitter side is displayed in Figure 2. As shown from the figure, the incoming data bits, which are assumed to have a length of $2n$ bits, are split into two groups of n number of bits each, where n represents the subcarriers' number in a single OFDM block. The first n bits specify the power levels of the subcarriers, where the i_{th} bit identifies the power value of the i_{th} subcarrier used to carry data. A bit "1" therefore

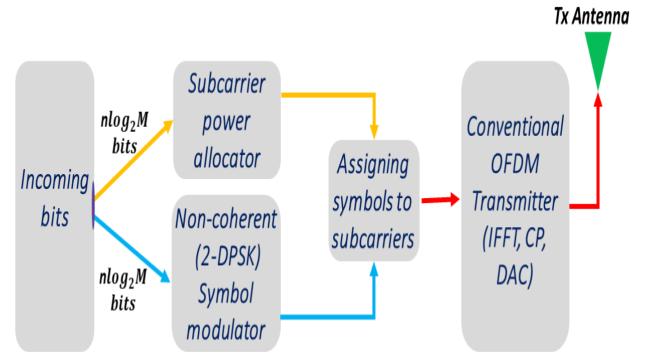


FIGURE 2. Transmitter structure of OFDM-SPM with DPSK.

corresponds (or maps) to setting the subcarrier power to high, and a bit "0" corresponds to setting it to low. The second n bits, which are coming from the other stream, are the bits to be modulated using 2-DPSK modulation. Thus, these bits go through the differential encoding process and then the phase of each symbol is changed with reference to its previous symbol. The 2-DPSK symbols are then assigned to their respective subcarriers. This mapping mechanism results in four different possible constellation points, namely 00 which maps to a low power subcarrier carrying a "0" modulated by 2-DPSK, 11 which maps to a high-power subcarrier carrying a "1" modulated by 2-DPSK, 01 which maps to a low power subcarrier carrying a "1" modulated by 2-DPSK, and vice versa. The resulting mapping points are presented in Figure 3, where E_b represents the energy per bit, and L and H indicate the low and high amplitudes corresponding to the different power levels. Finally, this OFDM symbol proceeds through the other processing steps of the classical OFDM transmission including taking IFFT, adding CP, performing DAC, etc. until the signal is transmitted from the antenna to the wireless channel [17].

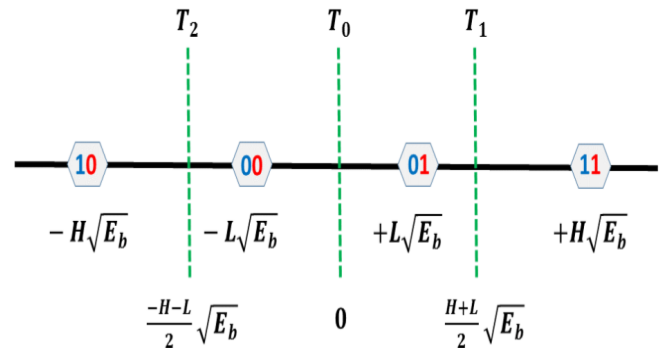


FIGURE 3. Constellation diagram of OFDM-SPM-DPSK where the bits pair " $i'j'$ " maps to a power subcarrier (i.e., low if ' i' ' = 0 and high if ' i' ' = 1) carrying a bit ' j' ' modulated by 2-DPSK.

The power levels of the subcarriers are carefully determined to minimize the overall BER of the scheme while guaranteeing that the average energy per sub-carrier does not

go beyond that of classical OFDM with 2-DPSK modulation. This assures that the proposed OFDM-SPM-DPSK scheme not only improves the spectral efficiency by double but also saves half of the transmit power for achieving the same data rate when compared to conventional OFDM with 2-DPSK. This is so while delivering non-coherent, low complexity detection, thus making it a very attractive scheme for IoT applications. All these merits come at the cost of some increase in the BER performance when power-saving policy (PSP) is used, which is the case where the scheme uses only half the power that conventional OFDM would need to transmit the same amount of data. However, if an application requires a lower BER, then the saved power can be reassigned to the subcarriers using power reassignment policy (PRP), thus resulting in a much more improved BER.

A detailed explanation for the power reassignment policies is presented in D. It should be mentioned that the optimal low and high-power levels that minimize the overall resulting BER of the system are calculated by means of a successive process of exhaustive trial and error experiments. In particular, when defining the low and high amplitude values of the subcarriers, their power levels at any time are conditioned by the following equations under the use of power-saving policy (PSP) and power reassignment policy (PRP), respectively.

$$L^2 + H^2 = 2E_b \quad (1)$$

$$L^2 + H^2 = 4E_b \quad (2)$$

By setting or assuming a numerical value for H , we obtain L for PSP and PRP, respectively, as given below:

$$L = \sqrt{2E_b - H^2} \quad (3)$$

$$L = \sqrt{4E_b - H^2} \quad (4)$$

B. RECEIVING SIDE OF THE PROPOSED NON-COHERENT OFDM-SPM-DPSK

The receiver side of the proposed OFDM-SPM-DPSK modulation scheme, which is presented in Figure 4, is featured by its simplicity as one of its most prominent advantages. As can be noticed, the received signal passes first through the normal, classical OFDM processes in the receiving end (i.e., performing ADC, removing CP, performing FFT, ... etc.). However, at the symbol demodulation stage, the signal is passed into two different blocks of demodulation processes. The first is responsible for the detection of the bits carried or conveyed by the power levels of the subcarriers, where this is attained by simply comparing the received power level of each subcarrier with a given optimal threshold T . This threshold is identified as the power level corresponding exactly to the midpoint between the low and high-level of the subcarriers. In case the power of the subcarrier is higher than the threshold, it is considered as a high-power subcarrier; namely a "1" and vice versa. Note that the midpoint and threshold T adopted for comparison with the power of the received subcarriers are given as:

$$midpoint = \left(\frac{L + H}{2} \right) \quad (5)$$

$$T = \left(\frac{L + H}{2} \right)^2 \quad (6)$$

The other demodulator performs conventional DPSK demodulation to the data symbols carried by subcarriers according to the phase difference between them and then differentially decodes the modulated bits.

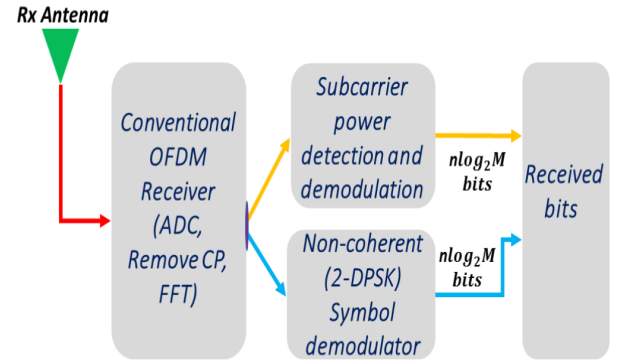


FIGURE 4. Receiver structure of OFDM-SPM with DPSK.

C. OFDM-SPM-DPSK WITH RECEIVE DIVERSITY

Receive diversity (RD) is a method used to improve the BER performance of the system by increasing the number of antennas at the receiving end. Without the use of diversity, fading due to the fluctuations in the channel may result in an unreliable received signal. However, if diversity is employed, the impact of fading is reduced as the probability that all the copies experience a deep fade is small since every transmitted signal passes through a channel with different characteristics. In diversity combining, since the power of the received noise is decreased, the SNR of the signal is effectively increased, thus resulting in less erroneously detected bits, and consequently producing a better BER for the system.

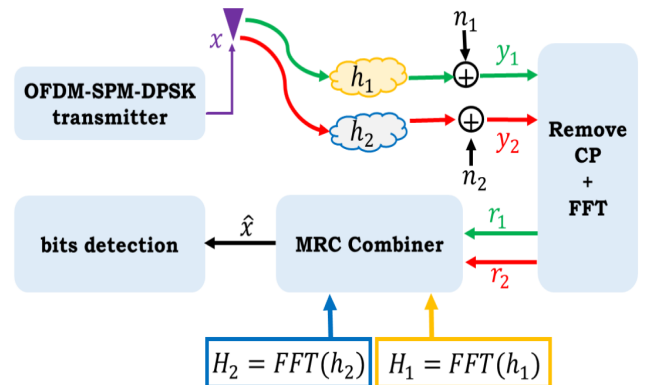


FIGURE 5. OFDM-SPM-DPSK transceiver with receive diversity

Among classical diversity schemes, maximal ratio combining (MRC) is the optimal one in terms of SNR as the best (optimal) weights are found such that the output SNR is maximized.

In the presence of a channel h_i , the instantaneous signal to noise ratio (SNR) at the i_{th} receive antenna is given by:

$$\gamma_i = |h_i|^2 \frac{E_b}{N_0}. \quad (7)$$

When employing N antennas at the receiver, the effective SNR at the receiver is found as the summation of the instantaneous SNR values given as

$$\gamma = \sum_{i=1}^N \gamma_i = N \times \gamma_i \quad (8)$$

In our scenario, the need for diversity usage is coming from the bit error rate degradation, resulting from the adoption of a non-coherent design for the system. This choice is for simplifying the receiver structure of the original coherent OFDM-SPM scheme. The use of diversity in our current version (OFDM-SPM-DPSK) greatly simplifies, through the use of differential modulation (DPSK), the complexity of the original OFDM-SPM system and overcomes, through the use of maximal ratio combining, the degradation in the system's bit error rate due to the use of a non-coherent modulation scheme such as DPSK.

A schematic of the OFDM-SPM-DPSK transceiver with receive diversity is presented in Fig.5. The setup consists of a single transmit antenna and two receive antennas. The transmitter structure is the same as the transmitter of OFDM-SPM-DPSK depicted in Fig.2. The same transmit signal x experiences two different channels with different fading amplitudes h_1 and h_2 with two different levels of noise n_1 and n_2 . The received copies of the same signal x , at the input of the FFT, are expressed as follows:

$$y_1 = x * h_1 + n_1 \quad (9)$$

$$y_2 = x * h_2 + n_2 \quad (10)$$

where, $(*)$ stands for the convolution operation.

As shown in Fig.5, the MRC combiner needs the received signals r_1 and r_2 along with the perfect knowledge of the channels to compute the estimate \hat{x} of the transmitted signal x . To compensate for the phase shift in the channel, each received signal is multiplied by the conjugate transpose of the corresponding channel.

At the output of the maximal ratio combiner, the estimate of the transmitted signal x is given by the equation below [20]:

$$\hat{x} = \frac{H_1^H \times r_1 + H_2^H \times r_2}{H_1 \times H_1^H + H_2 \times H_2^H} \quad (11)$$

$$= \frac{H_1^H \times r_1 + H_2^H \times r_2}{|H_1|^2 + |H_2|^2} \quad (12)$$

where, $H_i = FFT(h_i)$. $(.)^H$ and $|.|$ denote the conjugate transpose and the absolute value, respectively.

The above equation can be rewritten in the following form, to show the fact that each of the received signals is multiplied by the corresponding optimal weight:

$$\hat{x} = \frac{H_1^H}{|H_1|^2 + |H_2|^2} \times r_1 + \frac{H_2^H}{|H_1|^2 + |H_2|^2} \times r_2 \quad (13)$$

Although this implementation of maximal ratio combining is coherent and results in slight design complexity, it is completely resistant to phase changes of the channels and provides the best bit error rate performance among all diversity schemes.

A thorough analysis of the system performance, in terms of bit error rate, under the use of receive diversity through MRC is presented in section III.

D. POWER POLICIES

To clearly explain the power policies, the illustrative example depicted in Fig.6 is considered where the same sequence of bits is transmitted using both conventional OFDM and the proposed OFDM-SPM-DPSK. As from Fig.6, it is clear that OFDM-SPM-DPSK doubles the spectral efficiency when compared with conventional OFDM as for the same number of data bits OFDM-SPM-DPSK uses exactly half the number of subcarriers required by conventional OFDM. This doubling provides the scheme with some flexibility in terms of the power of the subcarriers. This power can be saved (Power saving policy) or reassigned to the transmit subcarriers (Power reassignment policy) to enhance the reliability of the scheme as, in this case, a larger separation between the symbols (see subplot 3 in Fig.6) is kept and thus making the detection less prone to be in error.

1) Power saving policy

In this mode, OFDM-SPM uses only half the number of subcarriers required by OFDM to transmit the same amount of data bits as depicted in Fig.6. In this scenario, it is clear that half the power is being saved. This mode suits low-power applications very well, however, it is shown that, in this mode, the scheme's overall bit error rate exhibits a slight degradation when compared with conventional OFDM with 2-DPSK.

2) Power reassignment policy

The second policy is the power reassignment mode where the saved power (i.e, due to using only half the number of subcarriers when compared with conventional OFDM) can be reassigned to the transmit subcarriers to overcome the degradation problem in the bit error rate. This reassignment makes the detection mechanism much easier as the power of the signal is amplified making it more robust to channel noise

and fading.

Two cases of power reassignment are considered: the non-optimal and optimal power reassignment variants. Each reassignment policy involves an optimization constrained on the bit error rate.

As discussed in the transceiver design, OFDM-SPM-DPSK is a scheme that is composed of two data streams: the power stream and the 2-DPSK stream. The non-optimized reassignment denotes the case where the optimization problem goal is finding the power levels for which the 2-DPSK stream is better, in terms of bit error rate, than the conventional OFDM with 2-DPSK. Corresponding consequences on the power curve are discussed in the simulations part.

In the optimal power reassignment policy case, the goal is to find the power levels such that the average stream (average of the power stream and the 2-DPSK stream) attains the best possible bit error rate.

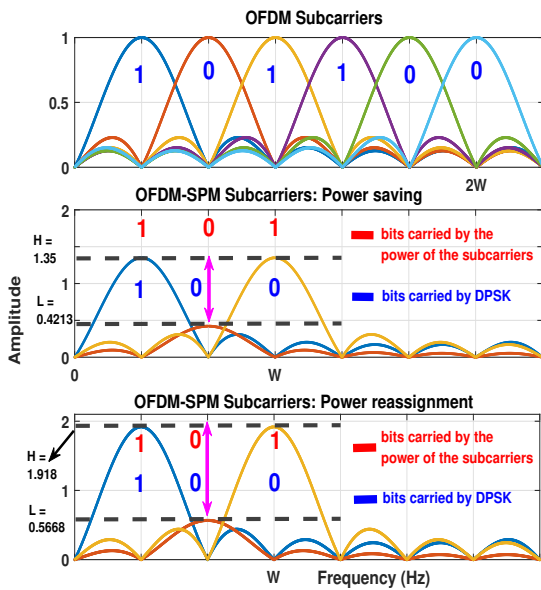


FIGURE 6. An exemplary transmission: OFDM-SPM vs Conventional OFDM to clearly illustrate the power policies.

III. PERFORMANCE ANALYSIS

A. BIT ERROR RATE (BER) ANALYSIS WITHOUT RECEIVE DIVERSITY

Since OFDM-SPM-DPSK employs an extra data-carrying dimension (i.e., power) compared to conventional OFDM with 2-DPSK modulation, there are two general sources for receiving a sent symbol in error. In other words, a bit can be received erroneously during the demodulation of 2-DPSK symbols or while decoding the power levels of the subcarriers. Multipath channel fading and the effects of the noise can either amplify or attenuate the power of the subcarriers, causing a high power subcarrier to be detected as a low power sub-carrier or vice versa.

From the constellation diagram presented in Fig.3, it is clear that the probability of error of a given DPSK symbol

is related to its corresponding power subcarrier. Furthermore, the constellation shows that low power subcarriers are more prone to error due to the smaller Euclidean distance separating them. Although this result affects the overall bit error rate of the scheme, this is compensated by the fact that high power subcarriers are less prone to erroneous detection due to the far separation between them.

As clarified above, two estimation processes are involved in our case. Let P and D denote, respectively, the power and the 2-DPSK estimations and E stands for the estimation of the overall error probability of the system. Since the power and the 2-DPSK streams are always of equal length, the respective probabilities for P and D are equal. That is:

$$p(P) = p(D) = \frac{1}{2} \quad (14)$$

Using the law of total probability, the overall error rate is given by:

$$p(E) = p(E|P)p(P) + p(E|D)p(D) \quad (15)$$

$p(\cdot)$ and $p(\cdot|\cdot)$ in the equations, denote the marginal and conditional probabilities respectively.

Expressed in terms of bit error rate (BER), Eq.(15) can be written as:

$$BER_{OFDM-SPM} = \frac{1}{2}BER_{2-DPSK} + \frac{1}{2}BER_{Power} \quad (16)$$

where BER_{Power} denotes the errors resulting from the detection of the subcarriers' power levels and BER_{2-DPSK} stands for the errors encountered in the detection of the 2-DPSK received symbols. The terms of Eq.(16) can be easily derived based on the expression of the bit error rate of the conventional OFDM with 2-DPSK modulation in a Rayleigh channel by multiplying the SNR in the original expression with the suitable multiplication factor to account for the distance changes introduced by the high and low power levels in the detection scenario.

The bit error rate expression for 2-DPSK in a Rayleigh environment assuming the channel phase is relatively constant over a symbol time is given by [18]:

$$BER_{2-DPSK,Conventional} = \frac{1}{2(1 + \frac{E_b}{N_0})} \quad (17)$$

Errors encountered in the detection of the 2-DPSK symbols at the receiver of OFDM-SPM-DPSK are the average of the errors caused by the low and high power levels. The expression for this first term in the overall error rate presented in Eq.(16) is as follows:

$$BER_{2-DPSK|H} = \frac{1}{2(1 + H^2 \frac{E_b}{N_0})} \quad (18)$$

$$BER_{2-DPSK|L} = \frac{1}{2(1 + L^2 \frac{E_b}{N_0})} \quad (19)$$

$$BER_{2-DPSK} = \frac{BER_{2-DPSK|H} + BER_{2-DPSK|L}}{2} \quad (20)$$

It can be noticed that the constellation diagram for OFDM-SPM-DPSK resembles that of 4-PAM since in our case the amplitude of the power spectrum is exploited. The only necessary addition in the BER derivation is to include the effect of the power levels on the Euclidean distances between the symbols.

Due to its symmetry, throughout the derivation, we carry out the analysis on the right half-plane of the constellation diagram.

Regarding the detection of the power levels, two main cases are to be analyzed, namely the error of detecting a low power symbol as a high power symbol or vice versa.

Firstly, we consider the case where a low power symbol is being detected as a high power symbol. Let E_1 stand for this event. E_1 can happen in one of two ways depending on the sign of the amplitude of the destination power subcarrier. Mainly, a low power symbol can be detected as a high power symbol with amplitude equal to either $(+H\sqrt{E_b})$ or $(-H\sqrt{E_b})$.

The first transition corresponds to crossing the threshold T_1 in the positive direction with a minimum distance of $\frac{H-L}{2}$ and the second corresponds to crossing the threshold T_2 in the opposite direction, which is equivalent to traveling a minimum total euclidean distance of $\frac{H+3L}{2}$. This transition is less probable to happen but is not impossible in the case of high channel noise or fading environment. Individual conditional probabilities for both transition types composing the event E_1 are given by Eq.(21) and (22).

$$P_1 = \frac{1}{2(1 + (\frac{H-L}{2})^2 \frac{E_b}{N_0})} \quad (21)$$

$$P_2 = \frac{1}{2(1 + (\frac{H+3L}{2})^2 \frac{E_b}{N_0})} \quad (22)$$

Secondly, we analyze the situation where a high power symbol is detected as a low power symbol. Let's denote this event by E_2 . The high power symbol can be detected as a low power symbol with a positive amplitude or a negative amplitude corresponding to a minimum Euclidean distance of $\frac{H-L}{2}$ and $H+L$, respectively.

Respective individual conditional probabilities for the event E_2 are:

$$P_3 = \frac{1}{2(1 + (\frac{H-L}{2})^2 \frac{E_b}{N_0})} \quad (23)$$

$$P_4 = \frac{1}{2(1 + (H+L)^2 \frac{E_b}{N_0})} \quad (24)$$

Since all the above transitions corresponding to P_1, P_2, P_3 and P_4 are equally likely to happen, we have:

$$p(P_1) = p(P_2) = p(P_3) = p(P_4) = \frac{1}{4} \quad (25)$$

Using the law of total probability, the overall bit error rate due to the detection of the power block is given by the following equation:

$$BER_{Power} = \frac{1}{4}P_1 + \frac{1}{4}P_2 + \frac{1}{4}P_3 + \frac{1}{4}P_4 \quad (26)$$

1) BER analysis under receive diversity

Diversity combining through maximal ratio combining was employed at the receiver to further improve the bit error rate performance of the OFDM-SPM-DPSK system. Since the power reassignment policy is the case where the system provides the best performance in terms of bit error rate, MRC is implemented upon this case.

Since the system was studied and simulated under a Rayleigh fading channel model, h_i in Eq.(7) is a Rayleigh distributed random variable and this implies that $|h_i|^2$ is a chi-squared random variable with two degrees of freedom [19]. The pdf of γ_i is then given by:

$$p(\gamma_i) = \frac{1}{\frac{E_b}{N_0}} e^{-\frac{\gamma_i}{\frac{E_b}{N_0}}} \quad (27)$$

As from Eq.(8), the effective SNR is the sum of N such random variables which implies that the pdf of γ follows a chi-squared distribution with $2 \times N$ degrees of freedom as expressed in the following equation:

$$p(\gamma) = \frac{1}{(N-1)! (\frac{E_b}{N_0})^N} (\gamma^{N-1}) e^{-\frac{\gamma}{\frac{E_b}{N_0}}}, \gamma \geq 0 \quad (28)$$

For two receive antennas, the pdf of the effective SNR is found by setting $N = 2$ in Eq.(28):

$$p(\gamma) = \frac{1}{(\frac{E_b}{N_0})^2} \gamma e^{-\frac{\gamma}{\frac{E_b}{N_0}}}, \gamma \geq 0 \quad (29)$$

Furthermore, the total bit error for a conventional OFDM system using 2-DPSK modulation and employing receive diversity through MRC (with 2 branches) is found by averaging over the channel distribution:

$$BER_{DPSK,MRC} = \int_0^{\infty} (BER_{DPSK,AWGN})(p(\gamma))d\gamma \quad (30)$$

The term $BER_{DPSK,AWGN}$ denotes the bit error rate for 2-DPSK in AWGN and is given by the equation below [18]:

$$BER_{DPSK,AWGN} = \frac{1}{2}e^{-\gamma} \quad (31)$$

By substituting Eq.(29) and Eq.(31) in the total bit error rate expression given by Eq.(30) and solving for the integral through the integration by parts method, the resulting bit error rate for a 2-DPSK modulated OFDM system using maximal ratio combining with $N = 2$ branches is found as:

$$BER_{DPSK,MRC} = \frac{1}{2(1 + \frac{E_b}{N_0})^2} \quad (32)$$

Particularly, the bit error rate of the OFDM-SPM-DPSK system using receive diversity can be derived based on

this last equation by accounting for the Euclidean distance changes introduced by the effect of the high and low power levels in the detection of the combined stream. Similar to Eq.(16), the final expression for the bit error rate of OFDM-SPM-DPSK under the use of maximal ratio combining employing 2 receive antennas can be written as follows:

$$BER_{SPM-DPSK,MRC} = \frac{1}{2}BER_H + \frac{1}{2}BER_L$$

where

$$BER_H = \frac{1}{2(1 + H^2 \frac{E_b}{N_0})^2} \quad (33)$$

$$BER_L = \frac{1}{2(1 + L^2 \frac{E_b}{N_0})^2} \quad (34)$$

B. COMPLEXITY ANALYSIS

The complexity of OFDM-based schemes is computed as the number of complex operations performed on an individual subcarrier [17]. This reduces to the estimation of the number of operations required by the IFFT and FFT in the transmitter and receiver respectively. Similar to conventional OFDM, the number of FFT/IFFT operations used in the proposed scheme is $N \log(N)$. OFDM-SPM is computationally efficient as it does not add further complexity over conventional OFDM since the only complex operations are due to FFT/IFFT computations. Furthermore, the computational complexity increases with the modulation order.

IV. SIMULATIONS RESULTS

Simulations displaying the performance results for the overall BER and the throughput of OFDM-SPM-DPSK are conducted using the MATLAB simulation environment and shown for both cases when the power is saved (i.e., under PSP) and when the power is reassigned to the subcarriers (i.e., under PRP).

Furthermore, the use of receive diversity with two receiving antennas through the maximal ratio combining technique is simulated as a means for improving the overall bit error rate of the system. The corresponding throughput is simulated as well.

Simulations are conducted assuming a slowly-varying multipath Rayleigh fading channel. The channel is assumed to be constant for one OFDM block duration.

The list of all simulation parameters is displayed in Table 1.

A. POWER SAVING POLICY

As shown in the explanatory diagram in Fig.1 and Fig.6, OFDM-SPM-DPSK uses exactly half the number of subcarriers normally needed to send the same amount of data using conventional OFDM. This implies that OFDM-SPM needs only half the required power by a conventional OFDM system to transmit the same number of data bits.

OFDM-SPM-DPSK with power-saving is a good candidate scheme for low-power IoT applications.

The high and low power levels used in the simulation of

this case are defined as in Eq. (1), and were found as $H = 1.35, L = 0.4213$.

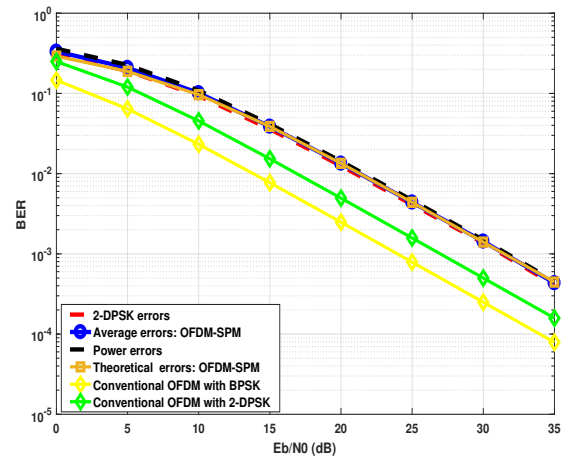


FIGURE 7. BER of OFDM-SPM-DPSK with power-saving policy, where half of the transmit power is saved by OFDM-SPM-DPSK.

As can be seen from Fig.7, the system exhibits some degradation in the BER in this case when compared with the conventional OFDM with 2-DPSK (the green curve). However, OFDM-SPM-DPSK with power-saving surpasses OFDM in terms of power-saving as it reduces the transmission power to half and achieves a doubling in the overall data rate as displayed in Fig.8. Individual data rates of the power and 2-DPSK streams achieve the same rate as the conventional OFDM with 2-DPSK.

TABLE 1. Simulation Parameters

Modulation type	DPSK ($M = 2$)
IFFT / FFT size	64
Subcarriers for data n	52
Symbols allocated for cyclic prefix	16
Number of inactive sub-carriers for out of band emission	12
Number of OFDM symbols	2×10^4
Multipath channel delay samples locations	[0 3 5 6 8]
Multipath channel tap power profile (dBm)	[0 -8 -17 -21 -25]

B. POWER REASSIGNMENT POLICY

As discussed in the power policies, the saved power in the power-saving mode can be used to the advantage of the scheme as it can be reassigned to the transmit subcarriers, thus inducing a great improvement in the bit error rate of either the individual streams of the scheme or the overall average stream depending on the reassignment mechanism. Two cases of the reassignment mechanism are simulated and discussed in the following subsections.

1) Non-optimized power reassignment

In this case of the power reassignment, the power levels are chosen in such a way that the error rate performance of the 2-DPSK is not degraded but rather exhibiting an error rate

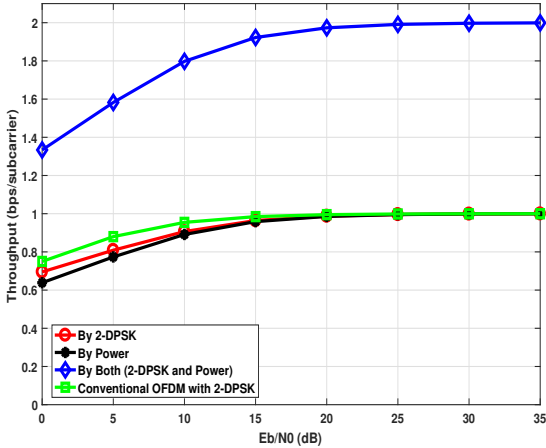


FIGURE 8. Throughput of OFDM-SPM-DPSK with power-saving policy, where half of the transmit power is saved by OFDM-SPM-DPSK.

much better than that of the conventional OFDM with 2-DPSK. In this mode, the saved power is reassigned to the high power subcarriers while the low power subcarriers are set to unity. The corresponding power levels were found as $H = 1.732, L = 1$.

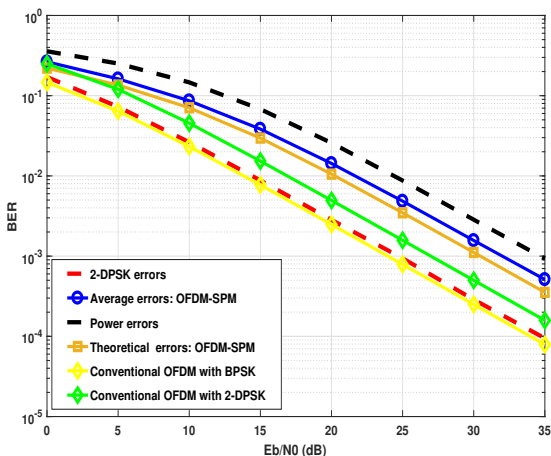


FIGURE 9. BER of OFDM-SPM-DPSK with non-optimized power reassignment policy, where the saved power is reassigned to high-power subcarriers, whereas low-power subcarriers are set with unity power levels. As can be seen, there is about 3dB improvement in the BER of the bits' stream modulated by 2-DPSK, while having another additional bits' stream modulated by SPM.

As displayed in Fig.9, a gain of 2 to 3 dB in terms of the bit error rate is achieved through this reassignment mechanism when compared to the error performance of the conventional OFDM with 2-DPSK in a Rayleigh environment. Furthermore, an additional stream that can carry half the information bits through the high and low power pattern is provided. Although under this mechanism, this latter curve exhibits a degradation in the BER this can be regarded as an extra gain over the optimized 2-DPSK curve and can still be useful in

the case of a user or application where ultra-reliability is not the main concern as in video streaming services.

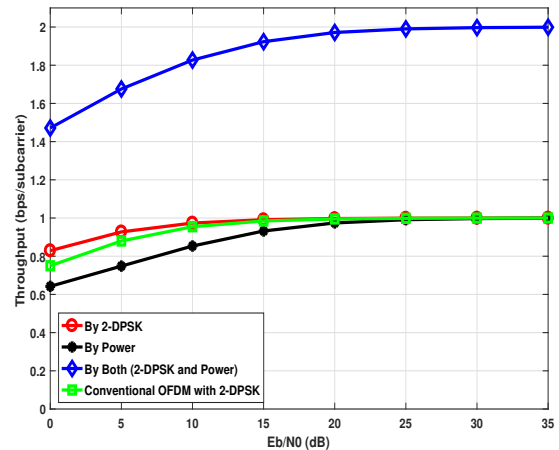


FIGURE 10. Throughput of OFDM-SPM-DPSK with non-optimized power reassignment policy, where the saved power is reassigned to high-power subcarriers, whereas low-power sub-carriers are set with unity power levels.

The schemes' gains in terms of spectral efficiency are displayed in Fig.10 where it is shown that the transmission data rate is being doubled. It can be noticed that the power curve exhibits a spectral efficiency less than the 2-DPSK curve at low SNR values which is an expected result as the optimization is constrained on the 2-DPSK curve. However, at High SNR values, both streams have the same data rate as the conventional OFDM with 2-DPSK in a Rayleigh channel.

2) Optimized power reassignment

In this case, the saved power is reassigned to the subcarriers such that the average errors (i.e., an average of the 2-DPSK stream errors and the power stream errors) attain the minimum possible values.

The optimal high and low power levels were obtained using exhaustive trials and errors based on Eq.(2) and were found: $H = 1.918, L = 0.5668$.

Although the resulting BER with the optimized levels suffers from a slight degradation (1 dB loss) when compared with conventional OFDM with 2-DPSK in a Rayleigh fading channel (green curve), the benefits that OFDM-SPM-DPSK offers in terms of spectral gain can outrank this very slight degradation. Throughput simulations for this case are as displayed in Fig.12 where a data rate value of 1.956 bps/Hz is achieved at 15 dB. For SNR values greater than or equal to 20 dB the schemes' overall data rate is double that of conventional OFDM with 2-DPSK as shown in Fig.12. It can also be seen that the individual streams provide the same spectral efficiency as conventional OFDM with 2-DPSK.

C. RECEIVE DIVERSITY

Fig.13 displays the results of the scheme in a Rayleigh fading channel in the case of power reassignment and receive diver-

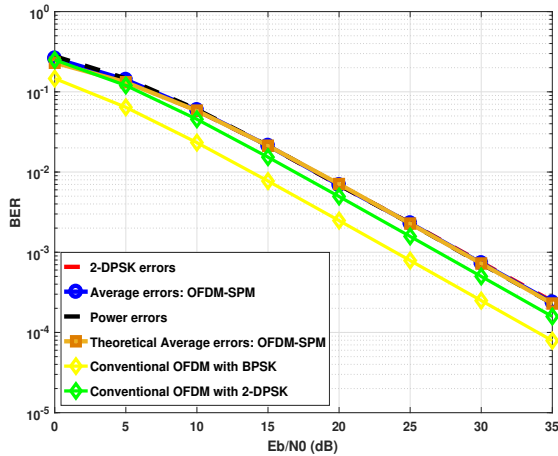


FIGURE 11. BER of OFDM-SPM-DPSK with optimized power reassignment policy, where the optimal power levels that minimize the overall average error rates are used.

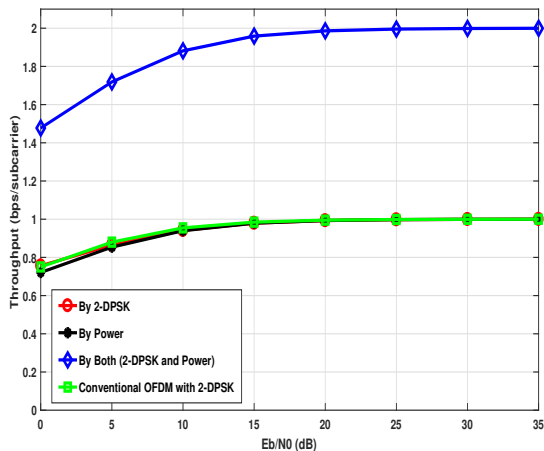


FIGURE 12. Throughput of OFDM-SPM with optimized power reassignment policy, where the optimal power levels that minimize the overall error rates are used.

sity implemented in this case. Conventional OFDM-BPSK (solid pink curve), OFDM with 2-DPSK (green), OFDM-BPSK using MRC (dashed pink curve), and OFDM-DPSK using MRC (dashed green curve) are graphed as well for comparison purposes.

Note that when optimized power levels are chosen, then the bit errors due to power detection, which is represented by the black curve, and errors due to 2-DPSK detection, which is represented by the red curve are equal to each other and thus equivalent to the overall, averaged BER of the OFDM-SPM-DPSK scheme (the blue curve).

As seen from the figure, the scheme's performance under the power reassignment mode closely approaches that of conventional OFDM with 2-DPSK. To improve the BER of the system, power reassignment policy (PRP) and receive diversity (RD) with two antennas are used, the BER is

improved by almost 8 dB.

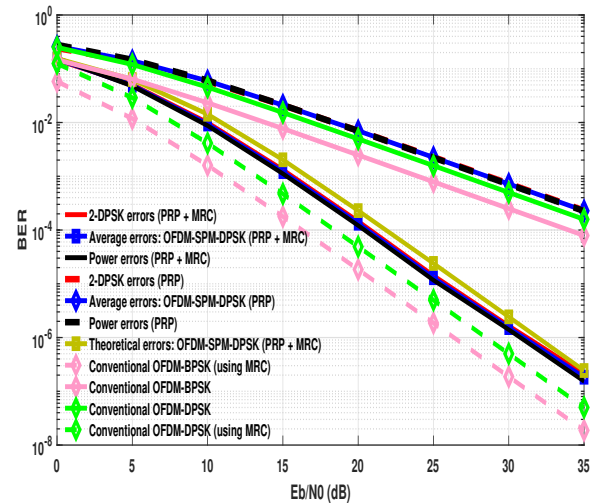


FIGURE 13. BER of OFDM-SPM-DPSK with optimized power reassignment policy and receive diversity.

Furthermore, the throughput performance of OFDM-SPM-DPSK, in this case, is illustrated by the blue diamond curve in Fig. 14 where it is effectively doubled compared to conventional OFDM-DPSK. Note that the throughput due to power subcarrier modulation, which is represented by the black curve in Fig. 14, and the throughput due to DPSK modulation, which is represented by the red curve are equal to unity, and thus the total throughput of the OFDM-SPM-DPSK scheme becomes double.

Even though the coherent implementation of MRC introduces slight complexity, *OFDM-SPM-DPSK is still a good candidate for high throughput wireless communication systems as it can achieve a good BER, reduce the power by half, reduce the complexity greatly (i.e., in the case of no diversity) and double the spectral efficiency.*

V. CONCLUSION

In this paper, a novel non-coherent modulation technique known as OFDM-SPM-DPSK was introduced to meet the requirements of future IoT applications that require low complexity with high data throughput. In this scheme, the data bits are transmitted not only by the differential phase of the symbol but also by the power levels of the subcarriers of the OFDM block. When compared to conventional OFDM with DPSK, OFDM-SPM-DPSK doubles the spectral efficiency as it uses only half the number of subcarriers which conventional OFDM with 2-DPSK would require and thus saving half the transmission power. This saved power can either be saved or reassigned to enhance the BER performance of the scheme.

As the adoption of non-coherent design naturally brings a degradation in the bit error rate, receive diversity through maximal ratio combining was used by employing two an-

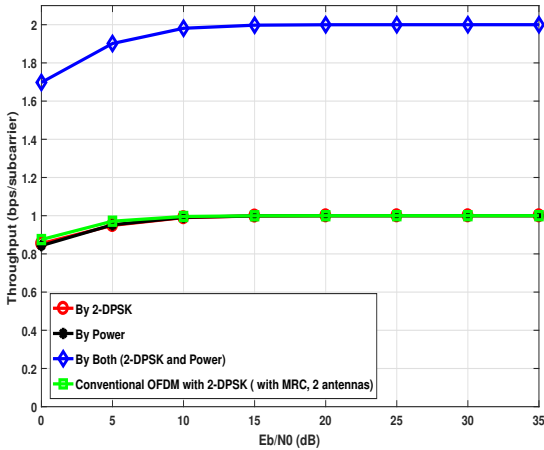


FIGURE 14. Throughput of OFDM-SPM-DPSK with optimized power reassigment policy and receive diversity.

tennas at the receiver to enhance the overall bit error rate of the scheme. Although the coherent implementation of MRC brings slight complexity in the receiver design, it provides the best bit error rate performance as it compensates for the channels phase shifts.

In short, all the aforementioned key merits of OFDM-SPM-DPSK clearly emphasize the high potential of this scheme being a strong candidate that could be adopted in future communication systems and particularly in the IoT domain due to its high throughput and low-complexity design properties.

APPENDIX. THE DIFFERENCE BETWEEN OFDM-SPM AND 4-PAM

The constellation diagram of figure 3 reveals a close similarity between the proposed OFDM-SPM and pulse amplitude modulation (PAM).

To further clarify this ambiguity raised by the similarity of both constellations, we consider figure 15 for highlighting the structural difference that exists between both schemes.

First, as explained in the system model of OFDM-SPM and shown in the simulation results, the OFDM-SPM waveform results from the combination of two main operations: conventional OFDM with DPSK modulation and power (or amplitude) modulation which corresponds to manipulating the power level of the transmit subcarriers by setting it to high (H) or low (L). The power allocator block in the transmitter diagram of figure 2 is the unit responsible for this latter operation. In other words, the power of the subcarriers is used as an extra dimension for conveying extra data bits.

In figure 15, we clarify this misconception by showing that even though any pair of bits " ij " appears to be in the same position of the constellation diagram of both SPM and PAM, this pair is a result of different operations in both cases. That's, in the case of OFDM-SPM, the pair " ij " corresponds to a power subcarrier (i.e, low if ' i ' = 0 and high if ' i ' = 1)

carrying a bit ' j ' modulated by 2-DPSK. On the other hand, in the upper subplot where PAM is represented all the pairs are colored with the same color because they are all resulting from simple PAM modulation and, unlike OFDM-SPM, no extra dimension is explored to convey extra data bits.

Moreover, exploring the subcarriers' power is the same principle employed in index modulation (OFDM-IM) where the positions (indices) of the active subcarriers can be selected according to a look-up table for conveying extra data bits. In fact, the difference between OFDM-SPM and PAM is the same as the difference between OFDM-IM and pulse position modulation (PPM).

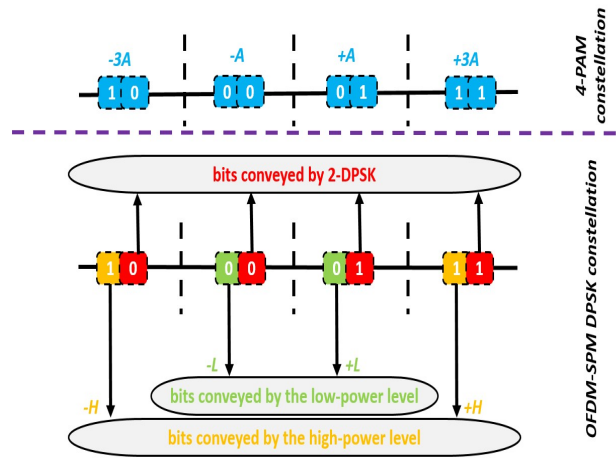
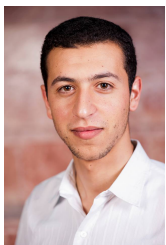


FIGURE 15. Comparison between the constellation diagram of OFDM-SPM and 4-PAM.

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