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NC-OFDM-SPM: A Two-Dimensional Non-Coherent Modulation Scheme for Achieving the Coherent Performance of OFDM along with Sending an Additional Data-stream

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The Matlab simulation codes used to generate the results in this paper can be found at researcherstore.com.

ABSTRACT A promising candidate solution for reducing complexity in future wireless systems is the use of non-coherent designs; however, it is very well known in the literature that non-coherent schemes perform worse than their coherent counterparts. To address this longstanding challenging trade-off, we demonstrate and prove in this work the ability of the proposed two-dimensional modulation scheme termed as non-coherent orthogonal frequency division multiplexing with subcarrier power modulation and differential phase shift keying in achieving the performance of a coherent design, while reducing complexity. Although the proposed design is non-coherent (i.e., it uses differential phase shift keying and power difference to convey information), it achieves the same bit error rate (BER) performance as conventional OFDM with coherent BPSK. Furthermore, since the proposed scheme employs two-dimensional modulations simultaneously (i.e., DPSK and subcarrier power levels), an additional data stream can be transmitted through the power subcarriers' levels. Thus, the proposed design not only solves the trade-off between coherent and non-coherent modulations in terms of reliability by achieving the same BER, but also provides higher data rates by exploring the power domain as an additional dimension for conveying extra data bits, while maintaining low complexity transceiver design, thus making it very appealing for IoT applications.

INDEX TERMS Non-coherent, Internet of Things, IoT, non-coherent OFDM, subcarrier power modulation, OFDM-SPM, wireless communication.

I. INTRODUCTION

A. MOTIVATION

The field of the internet of things (IoT) is a new emerging domain where billions of devices are being interconnected. This massive inter-connectivity shaping the future wireless world imposes the combination of very harsh design requirements such as high spectral efficiency, low-complexity and high reliability. Regarding the spectral efficiency requirement, the designer is facing a massive interconnection of data-hungry devices, while being restricted with the scarcity of the frequency spectrum allocated for wireless communications.

Another crucial concern in the design of future wireless communication systems is reducing the complexity and thus the latency of the communication, while guaranteeing a sufficient level of the transmission reliability.

In order to meet the requirements of future wireless systems mentioned above, we investigate two research directions which gained much investigation in the communications' literature over the past years. We argue that the combination of these two directions can solve this harsh set of requirements which are to be met at the same time.

From one side, a promising solution for enhancing the

spectral efficiency of future wireless systems is the exploration of an extra dimension related to the transmission setup for conveying extra data bits, without wasting any further bandwidth solely for this introduced dimension. Some of the developed modulation formats of this type include spatial modulation OFDM (SM-OFDM), proposed in [1] where the indices of the transmitting antennas are used to send extra data bits. Particularly, since OFDM is the basis for current wireless communication systems due its robustness against multipath fading, the manipulation of several waveform parameters inside an OFDM block have been studied for the purpose of generating new types of modulations where data is conveyed not only through a classical modulation scheme such as phase shift keying (PSK) or quadrature amplitude modulation (QAM) but also some of the data is transmitted through the new dimension. Examples of schemes which explore an additional dimension related to the OFDM waveform include subcarrier index modulation (SIM-OFDM) proposed in [2] and OFDM with index modulation (OFDM-IM) proposed in [3] where the indices of the active subcarriers inside an OFDM block are manipulated for conveying extra information bits. Also, OFDM with subcarrier number modulation (OFDM-SNM) was developed in [4] where the number of active subcarriers was utilized to convey additional data bits.

From another side, regarding complexity reduction in current communication systems, one of the promising design solutions is the use of non-coherent structures; which unlike coherent systems do not require expensive and complex carrier recovery circuit [5]. In the literature, numerous OFDM-based non-coherent techniques have been developed. Asymmetrically clipped optical OFDM (ACO-OFDM) was proposed in [6]. Another technique called Flip-OFDM achieving the same performance as ACO-OFDM while saving 50% in hardware complexity was proposed in [7]. In [8], self-heterodyne OFDM (self-het OFDM) was proposed as a non-coherent OFDM technique that provides immunity to frequency offset and phase noise; however, it allows maximum utilization of only 50% of the spectrum for communication. Also, self-coherent OFDM was proposed in [9], surpassing self-het in terms of both bit error rate (BER) and spectral efficiency; however, the maximum utilization of the available spectrum is approximately 80%. Non-coherent OFDM with index modulation (OFDM-IM) [10] has 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 attains less spectral efficiency than conventional OFDM-IM, depending on the coherence time of the channel.

B. PROPOSED DESIGN & CONTRIBUTION POINTS

According to the need of future wireless systems, the combination of the design directions mentioned above

presents a powerful way of designing communication algorithms for future wireless systems where low-complexity, higher spectral efficiency and good system reliability requirements are gathered.

In this regard, non-coherent orthogonal frequency division multiplexing with subcarrier power modulation and differential phase shift keying, in short NC-OFDM-SPM-DPSK was developed. In this design, unlike conventional OFDM schemes, the power of the subcarriers in an OFDM block is explored as a new dimension for sending extra data bits. OFDM with subcarrier power modulation (OFDM-SPM) was originally presented in [11] and [12] for providing highly spectral-efficient data transmission for future 6G wireless communication systems. Moreover, the generalization of the OFDM-SPM design to quadrature signal constellations was studied in [13] to demonstrate the fact that OFDM-SPM performance does not degrade compared to its counterparts when higher order modulations are used.

Furthermore, A non-coherent version of OFDM-SPM has recently been introduced in [14], where the basic idea of its design was established. The development of non-coherent OFDM-SPM is motivated by the points discussed in the section above, where its non-coherence ensures low design complexity and the exploration of the power as a second dimension enhances the spectral efficiency of the system, where it is capable of doubling the data rate per device compared to a conventional OFDM system. Unlike OFDM-IM [3], SIM-OFDM [2] and OFDM-SNM [4], the exploration of the power as a dimension allows the usage of all the subcarriers in the OFDM block at the same time; and thus an additional stream of data is sent through the power pattern solely, while a second stream is conveyed through a classical modulation constellation symbols.

OFDM-SPM is featured by its flexibility regarding the allocation of the transmit power where, for the transmitting the same number of data bits, only half the subcarriers required by conventional OFDM are needed for this purpose. This is due to the 2-D format of the modulation where a subcarrier in OFDM-SPM is able to carry two bits while a classical OFDM is capable of carrying only one bit per subcarrier. This lead to the development of different power policies for OFDM-SPM including power saving and power reassignment modes. In the power saving mode, half the power is saved compared to conventional OFDM while in the power reassignment the saved power is reassigned to the transmit subcarriers for enhancing the reliability of the system.

In this manuscript, we treat a specific power reassignment mechanism where we show that the NC-OFDM-SPM-DPSK design can be used to reach the performance of coherent OFDM, under proper power reassignment conditions. The contributions of this paper can be summarized in the following points:

FIGURE 1. Transmitter/Receiver of the proposed NC-OFDM-SPM-DPSK. 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).

- Demonstrating and proving the ability of solving the design trade-off between low-complexity and high reliability, which exists between coherent and non-coherent techniques, through the use of the recently introduced non-coherent OFDM-SPM by finding a setup where the proposed non-coherent scheme achieves the same performance as that of coherent conventional OFDM with BPSK.
- Showing the ability of the proposed non-coherent scheme in doubling the spectral efficiency of the system due to the exploration of the power domain as a second dimension for data transmission.

As such, the demonstrated design in this paper, achieves the combination of three main and harsh requirements of future wireless systems; namely low-complexity, high spectral efficiency and high system reliability.

The remaining sections of this paper are organized as follows. Section II explains the system model of NC-OFDM-SPM-DPSK. In Section III, theoretical performance analysis is carried out. In section IV, simulation results are presented. Finally, Section V presents the conclusion.

II. NC-OFDM-SPM-DPSK: SYSTEM MODEL

A. TRANSMITTER/RECEIVER DESIGN

The system model of NC-OFDM-SPM-DPSK is shown in Fig. 1. As shown in the transmitter depicted in Fig.1., the incoming data stream of length $2n$ bits is divided into two sub-streams of n bits which are modulated separately. One of the sub-streams consisting of n bits is modulated using the classical differential binary phase shift keying (DBPSK). The second sub-stream is modulated using

two-level subcarrier power modulation (SPM), where a bit "1" corresponds to setting the subcarrier power to high (i.e., denoted by H), and a bit "0" corresponds to setting it to low (i.e., denoted by L). After the 2-D modulation setup, the symbols are then assigned to their respective subcarriers. Finally, the symbols go through the remaining steps of the conventional OFDM transmission process, including inverse fast Fourier transform (IFFT), normal cyclic prefix (CP) addition, and digital-to-analog conversion (DAC).

At the receiver, the individual streams (i.e., the stream modulated through SPM and the stream modulated through DBPSK) are demodulated separately from the incoming combined stream. The DBPSK stream is detected using conventional differential demodulation. For the power stream, the detection of the power levels is done by simply comparing the received power level of each subcarrier with a given optimal threshold T , defined as the midpoint between the low (L) and high (H) power levels.

B. SIGNAL CONSTELLATION

The proposed mapping scenario results in the constellation diagram of Fig.2. where the binary pair ' $i'j'$ ' denotes a power subcarrier (i.e., low if ' i' ' = 0 and high if ' i' ' = 1) carrying a bit ' j' ' modulated by differential BPSK.

C. CHANNEL MODEL

The channel model is assumed to be a Rayleigh type frequency selective wireless channel with L multi-path exponentially decaying taps, denoted by $\mathbf{h} = [h_0, h_1, \dots, h_{L-1}]$. As such, the received symbols in time domain are given

FIGURE 2. Constellation diagram of NC-OFDM-SPM-DPSK.

as:

$$y = x \otimes h + n \quad (1)$$

where $\otimes$ represents the convolution operator. x , h and n are vectors representing the transmitted time domain samples, the channel impulse response, and the additive white Gaussian noise, respectively. The noise n samples are drawn from a normal distribution with zero mean and variance equal to N_0 ; $n \sim \mathcal{N}(0, N_0)$. Additionally, the channel is slowly varying in time such that it is assumed to be constant for multiple OFDM symbols duration before it changes independently in the subsequent time intervals.

III. PERFORMANCE ANALYSIS

In this section, first the power policies related to subcarrier power modulation are discussed. Then, the non-coherence of the proposed design is discussed. Finally, we demonstrate how the proposed design can be used for achieving coherent performance of OFDM.

A. POWER POLICIES

Due to the exploration of the high and low power pattern as an extra data-carrying dimension, the proposed scheme combines two streams; a stream of data modulated by DPSK (i.e., *DPSK-stream*) and another modulated by the power levels (i.e., *Power-stream*) as shown in Fig.1. As such, NC-OFDM-SPM-DPSK uses only half the number of subcarriers that conventional OFDM would require to send the same number of data bits. Thus, half the power used by conventional OFDM is unused (i.e., saved) by NC-OFDM-SPM-DPSK. This saved power gives the scheme some flexibility as it can be saved to match the requirements of low-power applications or it can be reassigned to the transmit subcarriers for increasing the reliability of the proposed design.

1) Power Saving

In this policy, half the power is saved compared to OFDM since NC-OFDM-SPM-DPSK uses only half the number of subcarriers required by conventional OFDM for transmitting the same number of bits. The values of

the high and low levels corresponding to this case can be defined with the following equation:

$$\frac{H^2 + L^2}{2} = E_b \quad (2)$$

where it is shown that the high and low levels used for subcarrier power modulation are chosen such that the average energy per bit does exceed that of binary phase shift keying where the bit energy is E_b .

2) Power Reassignment

The saved power can be reassigned to the transmit subcarriers to enhance the reliability performance of the proposed scheme. The reassignment can be done in many ways, where every pair of power levels (H, L) corresponds to some effect on the bit error rate of the individual streams (i.e., *DPSK-stream* & *Power-stream*). The power levels (H, L) corresponding to this reassignment policy are defined using the following equation:

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

This definition expresses the reassignment of the saved power to the transmit subcarriers where the factor 2 in the right side of Eq.(3) expresses the fact that a single subcarrier in NC-OFDM-SPM-DPSK carries two bits, while a conventional OFDM with BPSK is capable of carrying only one bit per subcarrier. This shows that OFDM-SPM doubles the data rate, compared to a conventional OFDM system using BPSK. We direct the reader to [12] for an extended discussion on the reassignment policies of the proposed design.

Particularly, this manuscript is devoted to showing the possibility of reaching the performance of coherent OFDM-BPSK with this non-coherent version of the OFDM-SPM technique, for a special choice of the power levels pair (H, L).

It is important to note that it is well known in the literature that non-coherent systems perform worse than their coherent counterparts ; however, in our case, reaching coherent performance is possible due to the power reassignment used to enhance the bit error rate of the scheme.

In the next sections, after discussing the non-coherence of the proposed design and showing the simplicity of its transceiver, we demonstrate how, under proper power reassignment, the proposed NC-OFDM-SPM-DPSK design can reach the coherent performance of OFDM-BPSK.

B. NON-COHERENCE OF NC-OFDM-SPM-DPSK

As shown in the system model of Fig.1, the receiver of NC-OFDM-SPM-DPSK uses two separate blocks for the detection of the transmitted symbols. The differential DPSK demodulator block uses non-coherent differential detection. Moreover, the subcarrier power detector/demodulator employs a threshold for the detection

of the power bits as mentioned in the previous section. As such, both detection mechanisms employed are non-coherent and thus NC-OFDM-SPM-DPSK is a completely non-coherent scheme with low-design complexity.

It is important to note that with this simple transceiver design, NC-OFDM-SPM-DPSK surpasses some of the known schemes, which explore an extra dimension for data transmission such as subcarrier number (OFDM-SNM), subcarrier index (OFDM-IM, SIM-OFDM) which usually employ either a maximum likelihood (ML) detector for optimum performance, or a log likelihood ratio (LLR) detector for reduced complexity [15].

C. ACHIEVING COHERENT PERFORMANCE WITH NC-OFDM-SPM-DPSK

The power reassignment mechanism can be treated as an optimization problem where the goal is to find the high and low power levels pair (H, L) which satisfy some constraints on the individual curves (i.e., *DPSK-stream* and *Power-stream*) of NC-OFDM-SPM-DPSK. Particularly, for reaching the performance of coherent OFDM, the values of (H, L) which satisfy the following system of equations (S) can be used.

$$(S) \begin{cases} BER_{DPSK-stream} = BER_{Coherent\ OFDM-BPSK} \\ \text{No constraint on } BER_{Power-stream} \end{cases} \quad (4)$$

, where the first equation in (S) corresponds to setting the DPSK stream (i.e., *DPSK-stream*) to match the performance of coherent OFDM-BPSK, while the second equation corresponds to setting the power curve (i.e., *Power-stream*) constraint-free for allowing a degree of freedom in the optimization.

In the following, we will solve the optimization defined in (S) by finding the optimal low (L) and high (H) power levels satisfying (S). Then, it is shown by simulations, that the optimization error corresponding to this choice of (H, L) is negligible.

Let's derive the bit error rates needed for the solution of (S). First, the bit error rate of conventional OFDM with binary DPSK in Rayleigh [16], given in the equation below, can be taken as the basis for the derivation of the expression $BER_{DPSK-stream}$ by accounting for the changes in the Euclidean distance between the DPSK symbols due to the high and low power levels.

$$BER_{Differential\ OFDM-BPSK} = \frac{1}{2 \left(1 + \frac{E_b}{N_0}\right)} \quad (5)$$

where, $\frac{E_b}{N_0}$ denotes the signal to noise ratio. The bit error rate for the bit stream modulated through DPSK (i.e., *DPSK-stream*) can be expressed as follows:

$$BER_{DPSK-stream} = \frac{1}{2} (BER_H + BER_L) \quad (6)$$

where,

$$BER_H = \frac{1}{2 \left(1 + H^2 \frac{E_b}{N_0}\right)} \quad (7)$$

$$BER_L = \frac{1}{2 \left(1 + L^2 \frac{E_b}{N_0}\right)} \quad (8)$$

represent, respectively, the effect of the high and low power levels on the detection of the DPSK-modulated bit stream.

Furthermore, the expression for coherent conventional OFDM-BPSK, in Rayleigh, is given in [16] as:

$$BER_{Coherent\ OFDM-BPSK} = \frac{1}{2} \left(1 - \sqrt{\frac{\frac{E_b}{N_0}}{1 + \frac{E_b}{N_0}}}\right) \quad (9)$$

After the derivation of the BER expressions necessary for the solution of (S), the values of the power levels (L) and (H) satisfying the system (S) were obtained using the following iterative algorithm:

- 1) By setting H to an arbitrary value, the corresponding value for L can be found, by using Eq.(3), as:

$$L = \sqrt{4E_b - H^2} \quad (10)$$

- 2) For every choice of L and H defined according to Eq.(10), the error function corresponding to the difference between the proposed non-coherent stream (i.e., $BER_{DPSK-stream}$ defined in Eq.(6) and the target coherent OFDM-BPSK stream (i.e., $BER_{Coherent\ OFDM-BPSK}$ defined in Eq.(9) is calculated.

$$\epsilon = BER_{DPSK-stream} - BER_{Coherent\ OFDM-BPSK} \quad (11)$$

The goal is to minimize the error between the two curves.

- 3) Steps 1) and 2) were repeated for numerous values. The smallest error was found for the following (H, L) pair:

$$H = 1.732, L = 1 \quad (12)$$

IV. SIMULATION RESULTS

Simulations displaying the performance results of OFDM with subcarrier power modulation and differential phase shift keying (NC-OFDM-SPM-DPSK) in terms of the bit error rate and system spectral efficiency are conducted using the MATLAB simulation environment. The list of all simulation parameters is displayed in TABLE I.

Figure 3 shows the bit error rate expressions for this study. First, let's define the curves related to the proposed design from this figure. Starting with the error rates for the bit stream modulated by DBPSK, we have ($BER_{DPSK-stream}(Simulation)$ which represents the bit error rate of the bit stream modulated by differential phase shift keying, obtained by computer simulations. $BER_{DPSK-stream}(Theory)$ represents the theoretical bit

TABLE 1. Simulation Parameters, channel model = Rayleigh

Modulation type	DPSK (order = 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]

error rate of this DPSK stream, which is derived in Eq.(6). As the graph shows, the two curves are superimposed confirming each other.

Second, in this graph, $BER_{Power-stream}$ corresponds to the error rate of the subcarrier power modulation, obtained through computer simulations. The theoretical BER for the *Power-stream* is not plotted here because this curve is not the at the core of this study where the optimization focuses on the *DPSK-stream* instead. We direct the reader to [14] for a detailed derivation of the theoretical bit error rate expression of this curve.

Third, the curve $BER_{Coherent\ OFDM-BPSK}$ and the curve $BER_{Differential\ OFDM-BPSK}$ are plotted for comparison purposes and they, respectively, denote the theoretical error rate of coherent OFDM with binary phase shift keying (OFDM-BPSK) expressed by Eq.(9), and OFDM with differential binary phase shift keying (OFDM-DBPSK), shown in Eq.(5).

FIGURE 3. Bit error rate of the proposed NC-OFDM-SPM-DPSK. As can be seen, the bit error rate for the bits' block modulated through DPSK (i.e., $DPSK-stream$) attains the performance of conventional OFDM with coherent BPSK with very negligible difference.

As can be seen from the results displayed in Fig.3, the DPSK stream (i.e., $BER_{DPSK-stream}(Simulation)$) proposed in this design surpasses conventional OFDM with differential BPSK (i.e., $BER_{Differential\ OFDM-BPSK}$) and matches the performance of coherent OFDM with

BPSK (i.e., $(BER_{Coherent\ OFDM-BPSK})$) very closely. This result is what we aimed at showing in this paper, as discussed earlier.

Figure 4 plots the error defined in (11), and it is shown that, over all the SNR range, the value of this error is very negligible. Thus, showing the ability of this non-coherent design in reaching the performance of a coherent OFDM system. Moreover, reaching coherent

FIGURE 4. Error plot for the expression given in Eq.(11) with the high and low power levels found in Eq.(12), where it is shown that the proposed non-coherent NC-OFDM-SPM-DPSK design can reach the performance of coherent conventional OFDM-BPSK with a very negligible difference.

performance with the DPSK stream has some side effects on the power stream as can be seen from Fig.3., where $(BER_{Power-stream})$ experiences a degradation amounting to 5dB compared to $BER_{DPSK-stream}$. Note that, since the aim is to achieve a coherent performance with the proposed NC-OFDM-SPM-DPSK scheme, the DPSK-stream was chosen for this purpose while the power stream was kept constraint-free, as defined in the system (S). However, this power stream (i.e., $BER_{Power-stream}$) can be allocated for a user application where ultra-reliability is not a main requirement such as audio streaming services, while the *DPSK-stream* can serve a user application where both low-complexity and high reliability are key requirements.

In Fig.5. the spectral efficiency of NC-OFDM-SPM-DPSK is displayed. It can be seen that, for high SNR values, the overall data rate of the scheme is doubled compared to conventional OFDM with differential BPSK or OFDM with coherent BPSK. This doubling is due to the fact that the proposed NC-OFDM-SPM-DPSK design employs two modulations (i.e., namely differential encoding and the power levels). Thus, a single subcarrier in NC-OFDM-SPM-DPSK is capable of carrying two bits while conventional OFDM with coherent or differential BPSK can only carry a single bit per subcarrier. The spectral efficiency is measured in units of bits/second/subcarrier.

FIGURE 5. Spectral efficiency of the proposed NC-OFDM-SPM-DPSK. As shown, the proposed design doubles the spectral efficiency compared to conventional OFDM with coherent and differential BPSK.

V. CONCLUSION

Future wireless systems impose the combination of a harsh set of requirements such as high spectral efficiency, low design and computational complexity and high transmission reliability. To meet these set of requirements at the same time, we propose the combination of two promising research directions; namely the use of non-coherent modulation formats and the manipulation of some specific parameters related to the OFDM waveform in order to convey extra data bits through the manipulation of this dimension. We presented OFDM with subcarrier power modulation and differential phase shift keying (i.e., NC-OFDM-SPM-DPSK) as a promising technique of this type where low-complexity is ensured through the choice of a non-coherent structure while subcarrier power modulation results in doubling the spectral efficiency per device due to the use of all the subcarriers in an OFDM block unlike other techniques such as SIM-OFDM, OFDM-IM, OFDM-SNM, SM-OFDM where the index/number of only the active subcarriers/antennas is used for transmitting extra information bits. This allows OFDM-SPM for doubling the spectral efficiency of the communication compared to conventional OFDM. Moreover, the presented design is featured with its flexibility regarding the transmit power where, for the same transmission, half the power can be saved compared to conventional OFDM. The saved power can be reassigned to the transmit subcarriers for enhancing the reliability of the scheme. Particularly, in this manuscript, we designed a specific power reassignment setup where the derived high and low power levels give the scheme the ability to reach the performance of a coherent OFDM system. This is while having an additional stream of data that can be conveyed through the power dimension; however the reliability of this latter stream experiences some degradation in the BER but it can be allocated for a user application where high reliability is not a main

requirement.

In conclusion, NC-OFDM-SPM-DPSK is a competitive modulation design which achieves the combination of three main and harsh requirements of future wireless systems; namely low-complexity, high spectral efficiency and transmission reliability.

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