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D-SEAD: A Novel Multi-Access Multi-Dimensional Transmission Technique for Doubling the Spectral Efficiency per Area and per Device

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ABSTRACT The world of today is characterized by a very huge inter-connectivity of data-hungry devices. This imposes on wireless system designers not only developing techniques that are spectrally efficient at the area level where many users are served with the same resources simultaneously but also developing techniques that are spectrally efficient at the device level as well. For addressing this problem, we propose in this paper a technique that is capable of doubling the spectral efficiency per area and per device by modulating a recently developed multiple access design called multi-user auxiliary signal superposition transmission(MU-AS-ST) through a multi-dimensional OFDM technique termed OFDM with subcarrier power modulation (OFDM-SPM). This integration results in the technique proposed in this manuscript and yields, with doubling the spectral efficiency, merits such as robust security, low complexity, and enhanced transmission reliability.

INDEX TERMS B5G, Low complexity, Modulation, Multiple access, NOMA, OFDM, Spectral efficiency, Wireless communication, 6G.

I. INTRODUCTION

A. MOTIVATION

Future wireless communication systems are characterized by a set of challenging requirements due to the rise of a variety of applications such as connected autonomous cars, smart appliances, the Internet of Things (IoT), and the ever-increasing data demand of the mobile phone industry [1]. This massive connectivity and data demand places spectral efficiency at the top of the wireless design requirements where there are two categories of spectral gain that need to be considered in the design of future wireless techniques to respond to the massive demand of future wireless networks.

- Spectral efficiency per area: Due to the massive connectivity that characterizes future wireless networks, there is a need for developing techniques that take spectral efficiency per area into account. This spectral efficiency approach focus is on serving many users in the same coverage area simultaneously with the limited spectrum resources available.
- Spectral efficiency per device: Besides enhancing the spectral efficiency per area where many users are served simultaneously using the same set of resources, the data rate per user needs to be enhanced as well. This is due to the rise of a massive number of applications per device serving various purposes in the life of their users such as bank account applications, social media applications, gaming, ...etc.

For addressing the spectral efficiency need of this dense network of data-hungry devices, the wireless community has proposed a set of techniques with various levels of success; however, among the proposed techniques two directions of research have gained particular interest from the wireless community as a means of improving both types of spectral efficiency related to the coverage, or the data demand per device.

From one side, for enhancing the spectral efficiency per area (coverage) multiple access techniques have been the choice of preference for the recent 5G systems where many multiple access designs have been proposed from both the wireless academia and the wireless industry.

Among the proposed designs, the most critical technique is power domain NOMA which was proposed and studied in many releases of the 3rd Generation Partnership Project (3GPP) under the name MUST (Multi-User Superposition Transmission) since it offers many desirable benefits including great spectral efficiency where superposition coding is used at the transmitter and successive interference cancellation (SIC) is used at the receiver [2], [3].

However, after a deep investigation from the part of the 3GPP community, power domain NOMA was excluded from the study items of release 17 of 3GPP, due to many reasons including risks of security and receiver complexity due to the cost of SIC [4].

On the other side, for enhancing the spectral efficiency per device, multi-dimensional OFDM modulation formats constitute a field of wireless research that gained too much interest in recent years.

Many novel modulation formats of this type were developed by exploring an additional dimension related to the OFDM waveform for sending more information bits by manipulating the index of the transmit subcarriers, their number, gap, power, or other characteristics. Examples of the developed multi-dimensional OFDM modulation techniques include but are not limited to the following set:

- Index as a dimension: Many techniques which explore the index of the transmitting antennas or explore the indices of the active subcarriers inside the OFDM waveform were proposed such as Spatial Modulation OFDM (SM-OFDM) proposed in [5] where the indices of the active transmitting antenna are used to convey additional data bits, SIM-OFDM (Subcarrier Index Modulation OFDM) proposed in [6], and OFDM-IM (OFDM with Index Modulation) proposed in [7] where the Index of the active subcarriers in an OFDM block is used.
- Number as a dimension: This set Utilizes the number of the active subcarriers in the OFDM block for sending extra information such as in OFDM-SNM (OFDM with Subcarrier Number Modulation) proposed in [8] where the authors have studied the use of the number of the active subcarriers, rather than the index, as a new dimension for sending more data bits.
- Gap as a dimension: The gap between the active subcarriers in the OFDM block was explored as an additional dimension for transmitting extra information bits as in [8], where the authors proposed a technique called OFDM-SGM (OFDM with Subcarrier Gap Modulation) where they studied the gap between active subcarriers in the OFDM waveform for enhancing the data rate per device.

Reference [10] provides a very comprehensive and detailed survey on the state-of-the-art related to multi-dimensional modulation formats.

B. CONTRIBUTIONS OF THE PROPOSED DESIGN

As can be seen from the literature review above, there are two trials at enhancing the spectral efficiency either at the area level where many users are served using the same set of resources simultaneously or at the device level using multi-dimensional OFDM modulation formats, for example.

The contribution of this paper lies in bridging the gap between the two fields of spectral gain enhancement where the technique developed, in this paper, is capable of enhancing the spectral gain at both the area level and at the device level.

The proposed design is a hybrid design where a recently developed multiple access technique termed as Multi-User Auxiliary Signal Superposition Transmission (MU-AS-ST) is modulated through a multi-dimensional OFDM modulation format called OFDM with Subcarrier Power Modulation (OFDM-SPM).

MU-AS-ST was proposed with other designs in [11] as novel non-orthogonal transmission schemes for achieving highly efficient, reliable, and secure multi-user communications. Motivated by the need to address the limitations of the existing power domain NOMA schemes, authors in [11] presented four novel NOMA-inspired communication schemes for enhancing security and reliability of low complexity massive machine-type communications in future wireless networks. Each of the proposed techniques was studied separately in detail as in [12]–[15].

Particularly, MU-AS-ST was studied in [16] where its performance was analyzed in detail using mathematical derivations and computer simulations. MU-AS-ST was shown to surpass power domain NOMA in terms of BER performance and security due to the use of specially designed auxiliary signals superimposed on top of the users' data. Moreover, the receiver of MU-AS-ST is a typical OFDM receiver and does not use SIC.

The proposed design is modulated through a multi-dimensional OFDM modulation technique called OFDM-SPM [18], in which the subcarriers' power is explored as another dimension for sending more data bits. Unlike NOMA which aims at enhancing the spectral efficiency per area, this technique focuses on the data rate per device where it is capable of doubling it, compared to a conventional OFDM system. Besides, OFDM-SPM is a very low-complex design with the merits of power efficiency and low latency. Note that the exploration of the power as an additional dimension is a mere signal processing operation for enhancing the use of

the available spectrum as this manipulation does not use any spectrum resources (bandwidth).
Particularly, the choice of the modulation technique OFDM-SPM allows doubling the spectral efficiency per device since all the subcarriers in the OFDM waveform are used. Other multi-dimensional OFDM techniques that explore other waveform dimensions such as the index, number, gap, ...etc. contribute only with a partial enhancement due to de-activating some of the transmit subcarriers.

The hybrid design presented in this paper aims at enhancing both the area spectral efficiency and the data rate per device while keeping the original merits of its component schemes. Besides the spectral gain it offers, D-SEAD has the following set of merits:

- Achieving robust security against external and internal eavesdroppers.
- Having a simple design especially by carrying all of the processing at the transmitter and freeing the receiver from complex tasks where only a classical OFDM receiver is used.
- Achieving better error rates compared to conventional power domain NOMA.

The remaining sections of this paper are organized as follows. Section II explains the system model of the proposed design / D-SEAD. In Section III, the theoretical analysis is discussed. In section IV, simulation results are presented. Finally, Section V presents the conclusion.

II. SYSTEM MODEL

The general system model of the proposed scheme is shown in Fig. 1 where its main philosophy is revealed. Fig. 1 tells the story of the general landscape of wireless in today's world which is characterized by the connectivity of a massive number of devices in each of which there are many applications installed for serving various purposes in the life of their users.

In this regard, the idea of the proposed technique is developing a single design that addresses the spectral efficiency need at the area level and at the device level where it can serve various users using the same set of resources but also takes into account the need for enhancing the data rate per user.

As can be seen, to each user end a data stream is transmitted. In the transmitted data stream two streams of data are embedded due to the use of the multi-dimensional OFDM modulation technique OFDM-SPM which uses two separate modulations for transmitting data where half of the data bits is transmitted using the conventional BPSK modulation while the other half is transmitted through the manipulation of the power of the subcarriers in the OFDM waveform.

A. TRANSMITTER DESIGN

For explaining the internal architecture of the transmitter and the receiver of D-SEAD, let's consider Fig. 2 where the case of two users is studied.
The presented downlink setup consists of a base station of two antennas $\mathbf{A_1}$ (sending signal $\mathbf{u_1}$) and $\mathbf{A_2}$ (sending signal $\mathbf{u_2}$) trying to communicate with two legitimate user devices UE_1 and UE_2. Furthermore, we assume the presence of a passive eavesdropper UE_X trying to listen to the data of the legitimate users.
At the transmitter, the following set of operations are carried out:

1) First, the data of each user is modulated using two different modulators, where:
    - A BPSK modulator performs the classical Binary Phase Shift Keying (BPSK) to the incoming data stream.
    - A Subcarrier Power Modulator (SPM) sets the power of the transmit subcarriers in the OFDM waveform to high and low values according to the incoming data bit where a bit 1 corresponds to setting the power to a value high H and a bit 0 corresponds to setting it to low L.
      The pair (H, L) is found such that the overall BER (Bit Error Rate) of the scheme is the minimum possible. This produces two streams of data for each user. Let's call $\mathbf{p_1}, \mathbf{p_2}$ the power streams for UE_1 and UE_2, respectively. Similarly $\mathbf{b_1}, \mathbf{b_2}$ are the BPSK streams for the two legitimate user devices.
2) After the modulations, a joint stream for each user is constructed where the power stream and the BPSK stream are integrated into one stream. Let us call this stream the joint stream.
3) The joint streams of UE_1 and UE_2 are superimposed, then the combined signal $\mathbf{x_1} + \mathbf{x_2}$ is fed into a block that adds specifically designed auxiliary signals $\mathbf{r_1}, \mathbf{r_2}$ and performs conventional OFDM operations such as taking the IFFT (Inverse Fast Fourier Transform), adding CP (Cyclic Prefix) and performing DAC (Digital to Analog Conversion).

4) Finally, the transmitted signals can be written as:

$$\mathbf{u_1} = \mathbf{x_1} + \mathbf{x_2} + \mathbf{r_1} \tag{1}$$

$$\mathbf{u_2} = \mathbf{x_1} + \mathbf{x_2} + \mathbf{r_2} \tag{2}$$

where $\mathbf{u_1}$ and $\mathbf{u_2}$ are sent from two different antennas $\mathbf{A_1}$ and $\mathbf{A_2}$, simultaneously.

B. CHANNEL MODEL

The channel between the transmitter and any receiver is assumed to be a slowly-varying, frequency selective Rayleigh type channel with L multi-path exponentially decaying taps, denoted by $\mathbf{h} = [\mathbf{h_0}, \mathbf{h_1}, ..., \mathbf{h_{L-1}}]$.

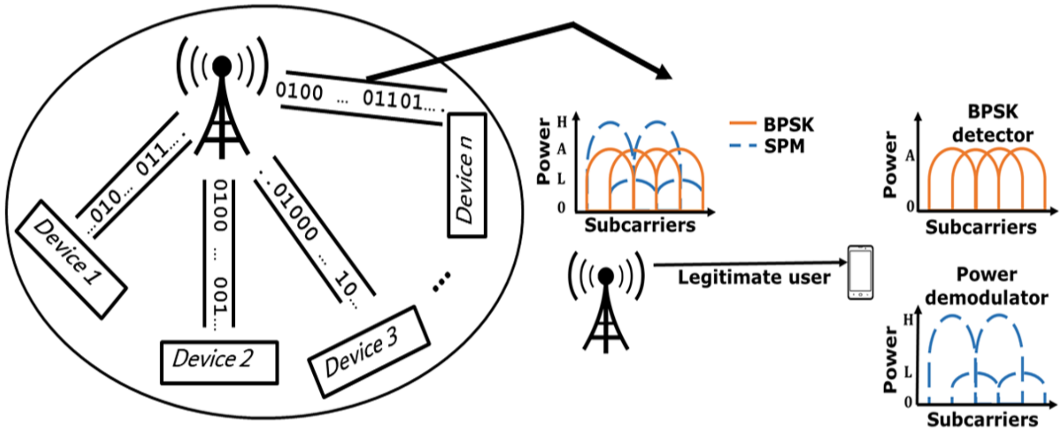

FIGURE 1. The generic system model of the proposed transmission design called D-SEAD.

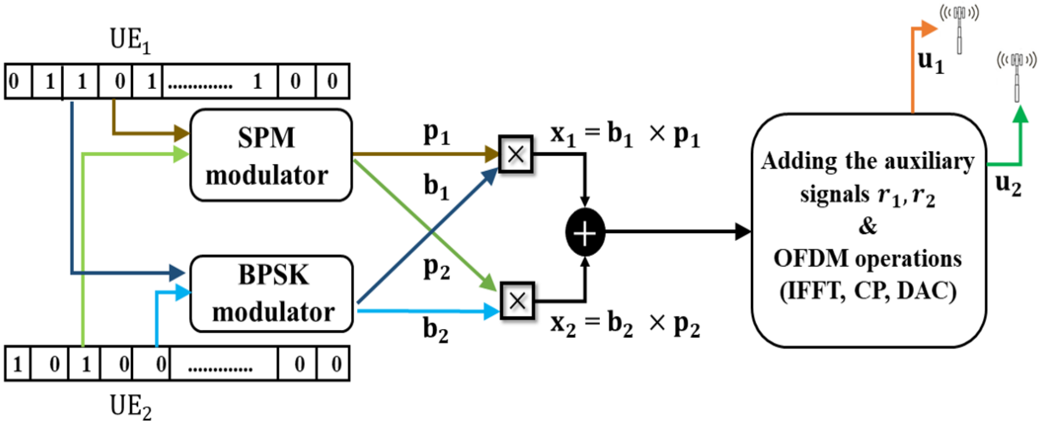

FIGURE 2. The transmitter design of the proposed D-SEAD transmission method.

TABLE 1. Channels between antennas and users.

	$\mathbf{A_1}$	$\mathbf{A_2}$
UE_1	$\mathbf{H_{11}}$	$\mathbf{H_{12}}$
UE_2	$\mathbf{H_{21}}$	$\mathbf{H_{22}}$
UE_X	$\mathbf{H_{X1}}$	$\mathbf{H_{X2}}$

Considering the scenario of two legitimate users (UE_1, UE_2) and a passive eavesdropper (UE_X), the channels between the transmit antennas and each receiving node, in the frequency domain, are denoted as in TABLE 1.

Moreover, it is assumed that the transmitter does not know the channel of a passive eavesdropper. Let $\mathbf{n_j}$ denote the additive white gaussian noise at UE_j, where the samples are drawn from a normal distribution with zero mean and variance equal to N_0; $\mathbf{n_j} \sim \mathcal{N}(0, N_0)$.

C. RECEIVER DESIGN

The receiver of the proposed design is shown in Fig. 3 where a conventional OFDM receiver is used. The only difference between the receiver of the proposed technique and conventional OFDM is that, since this design uses two modulation dimensions, there are two separate detectors for detecting each type of received data including the BPSK data and the subcarrier power modulated data.

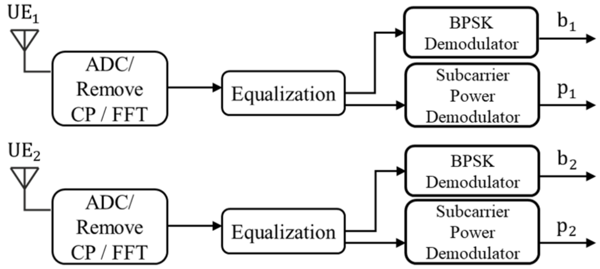

FIGURE 3. Receiver of D-SEAD

1) Received signal at the legitimate node, UE_1

The received signal at any legitimate user can be written as the sum of the signals received from the two transmit antennas $\mathbf{A_1}$ and $\mathbf{A_2}$. Thus, the received signal at UE_1 can be written as:

$$\mathbf{y_1} = \mathbf{H_{11}}\mathbf{u_1} + \mathbf{H_{12}}\mathbf{u_2} + \mathbf{n_1} \tag{3}$$

By replacing $\mathbf{u_1}$ and $\mathbf{u_2}$ by their values as in Eq.1, Eq.2, we can write:

$$\mathbf{y_1} = \mathbf{H_{11}}(\mathbf{x_1} + \mathbf{x_2} + \mathbf{r_1}) + \mathbf{H_{12}}(\mathbf{x_1} + \mathbf{x_2} + \mathbf{r_2}) + \mathbf{n_1} \tag{4}$$

Then, by grouping the terms of the above equation based on the users' data $\mathbf{x_1}, \mathbf{x_2}$, the following equation can be written:

$$\mathbf{y_1} = (\mathbf{H_{11}} + \mathbf{H_{12}})\mathbf{x_1} + (\mathbf{H_{11}} + \mathbf{H_{12}})\mathbf{x_2} + \mathbf{H_{11}}\mathbf{r_1} + \mathbf{H_{12}}\mathbf{r_2} + \mathbf{n_1} \tag{5}$$

2) Received signal at the legitimate node, UE_2

Similarly, the received signal at UE_2 can be written as:

$$\mathbf{y_2} = \mathbf{H_{21}}\mathbf{u_1} + \mathbf{H_{22}}\mathbf{u_2} + \mathbf{n_2} \tag{6}$$

$$\mathbf{y_2} = \mathbf{H_{21}}(\mathbf{x_1} + \mathbf{x_2} + \mathbf{r_1}) + \mathbf{H_{22}}(\mathbf{x_1} + \mathbf{x_2} + \mathbf{r_2}) + \mathbf{n_2} \tag{7}$$

$$\mathbf{y_2} = (\mathbf{H_{21}} + \mathbf{H_{22}})\mathbf{x_1} + (\mathbf{H_{21}} + \mathbf{H_{22}})\mathbf{x_2} + \mathbf{H_{21}}\mathbf{r_1} + \mathbf{H_{22}}\mathbf{r_2} + \mathbf{n_2} \tag{8}$$

III. PERFORMANCE ANALYSIS

A. BER ANALYSIS

1) Optimal Power Levels (H, L)

As the assigned H and L power factors affect the overall bit error rate of the scheme, these values were chosen optimally to minimize this error. This optimization was done under a constraint that ensures the average energy of an OFDM subcarrier in OFDM-SPM can not exceed that of a subcarrier in conventional OFDM using BPSK symbol modulation. This allows a fair comparison between both schemes and ascertains that OFDM-SPM achieves a great gain in spectral efficiency without requiring additional power.
Moreover, as shown in the system model in Fig. 1, a subcarrier in OFDM-SPM with BPSK is capable of carrying two bits since it uses two dimensions: BPSK and Power. Thus, the power levels H, L are chosen such that the following equation is satisfied:

$$\frac{H^2 + L^2}{2} = 2 \times E_b \tag{9}$$

In other words, this equation expresses the fact that the average energy per bit in the proposed technique is double that of conventional OFDM with BPSK.

The optimal values of the low and high power levels L and H were found by an exhaustive process of trial and error, with small-sized increments to ensure that all the possible values of L and H were spanned, and their resulting performances compared.

After experiments of exhaustive trial and error, the best pair that guarantees the minimum BER was found as $(H, L) = (1.98, 0.5668)$.

2) D-SEAD Theoretical BER Analysis

As was mentioned, the proposed scheme is a hybrid design where it is an integration of the multiple access design MU-AS-ST and the multi-dimensional OFDM modulation technique OFDM-SPM and as such, it is clear that its overall performance would be related to the performance of its components.

In publications [16] and [18], the authors have detailed the analysis on the performance of both techniques where it can be seen that MU-AS-ST performs better than OFDM-SPM in terms of reliability due to its merits of interference cancellation through the special design of the auxiliary signals and transmit diversity. On the other hand, OFDM-SPM was designed to enhance the spectral efficiency by exploring the power of the subcarriers as an extra dimension, however; this power exploration puts a limitation on the reliability performance where it has sufficient transmission reliability but it is not to the level of MU-AS-ST where, in this latter, very low transmission errors are encountered due to the mentioned reasons above.

As such, concerning the performance of the proposed hybrid technique D-SEAD, we can argue that:

1) The use of transmit diversity and inter-user interference cancellation will enhance the detection of the received signal and thus, the reliability performance of the hybrid design (D-SEAD) will be better than that of OFDM-SPM.

$$\mathbf{BER_{D-SEAD}} \geq \mathbf{BER_{OFDM-SPM}} \tag{10}$$

2) The performance of D-SEAD can never reach the performance of MU-AS-ST since the MU-AS-ST signal $\mathbf{x_1}$ for example embeds the power and the BPSK dimensions (i.e., $\mathbf{x_1} = \mathbf{p_1} \times \mathbf{b_1}$) in the hybrid design while it is only a BPSK vector in the conventional MU-AS-ST design. This allows us to write the following:

$$\mathbf{BER_{D-SEAD}} \leq \mathbf{BER_{MU-AS-ST}} \tag{11}$$

Equations 10 and 11 give lower and upper bounds on the performance of the hybrid design D-SEAD.

$$\mathbf{BER_{OFDM-SPM}} \leq \mathbf{BER_{D-SEAD}} \leq \mathbf{BER_{MU-AS-ST}} \tag{12}$$

TABLE 2. BER vs SNR for D-SEAD, MU-AS-ST and OFDM-SPM

BER	10^{0}	10^{-1}	10^{-2}	10^{-3}	10^{-4}
SNR (OFDM-SPM)	×	5	16	26	36
SNR (MU-AS-ST)	×	×	10	20	30
SNR (D-SEAD)	×	×	13	23	33

In TABLE 2, BER data was collected for various SNR values for each of the techniques OFDM-SPM, MU-AS-ST and the hybrid design D-SEAD. As we can see, the D-SEAD data is the average of its components (MU-AS-ST, OFDM-SPM). This point is explained by the fact that half of the transmitted bits are sent by using MU-AS-ST, whereas the other half is sent by OFDM-SPM. As such, the overall final performance would be the average of the two individual techniques.

B. SECURITY

1) Internal Security

Fig. 4 displays the received signals at the legitimate users expressed in Eq. 5 and Eq. 8. As can be seen, the received signal at the legitimate nodes can be segmented into the following terms:

- The desired term, which is the term that holds the data of the user node in question,
- An undesired term which constitutes the interference caused by the other superimposed user and the effect of the addition of the auxiliary signals,
- A noise term which simulates the AWGN noise.

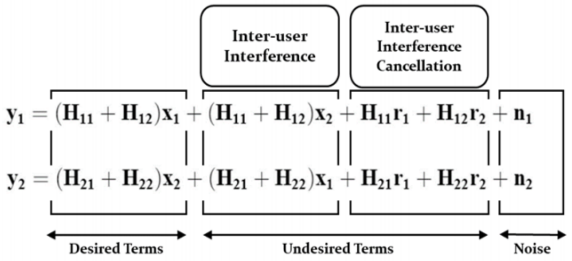

FIGURE 4. Segmentation of the received signals at UE_1, UE_2

Based on this segmentation, for ensuring that each user receives only its desired data without interference, we can write the following system of equations:

$$(S_{r_1,r_2}) \begin{cases} (\mathbf{H_{11}} + \mathbf{H_{12}})\mathbf{x_2} + \mathbf{H_{11}}\mathbf{r_1} + \mathbf{H_{12}}\mathbf{r_2} = \mathbf{0} \\ (\mathbf{H_{21}} + \mathbf{H_{22}})\mathbf{x_1} + \mathbf{H_{21}}\mathbf{r_1} + \mathbf{H_{22}}\mathbf{r_2} = \mathbf{0} \end{cases} \tag{13}$$

Solving the system S_{r_1,r_2} yields the following values for $\mathbf{r_1}$ and $\mathbf{r_2}$:

$$\mathbf{F} = \mathbf{H_{22}} - \mathbf{H_{21}}\mathbf{H_{11}^{-1}}\mathbf{H_{12}} \tag{14}$$

$$\mathbf{g} = -(\mathbf{H_{21}} + \mathbf{H_{22}})\mathbf{x_1} + \mathbf{H_{21}}(\mathbf{I_{64}} + \mathbf{H_{11}^{-1}}\mathbf{H_{12}})\mathbf{x_2} \tag{15}$$

$$\mathbf{r_2} = \mathbf{F^{-1}}\mathbf{g} \tag{16}$$

$$\mathbf{r_1} = (\mathbf{I_{64}} + \mathbf{H_{11}^{-1}}\mathbf{H_{12}})\mathbf{x_2} - (\mathbf{H_{11}^{-1}}\mathbf{H_{12}}\mathbf{r_2}) \tag{17}$$

Replacing these values back in Eq. 5 and Eq. 8, we have the following signals at UE_1 and UE_2, respectively:

$$\mathbf{y_1} = (\mathbf{H_{11}} + \mathbf{H_{12}})\mathbf{x_1} + \mathbf{n_1} \tag{18}$$

$$\mathbf{y_2} = (\mathbf{H_{21}} + \mathbf{H_{22}})\mathbf{x_1} + \mathbf{n_2} \tag{19}$$

The above equations represent the signals that are received at each legitimate node and thus the proposed design has no risk of internal eavesdropping as each user receives its own data without any interference from the other users. After reception, equalization is performed and the transmitted signals $\mathbf{x_1}, \mathbf{x_2}$ are recovered.

2) External Security

The eavesdropper / UE_X receives the broadcasted signals from antenna $\mathbf{A_1}$ and antenna $\mathbf{A_2}$. As such, the received signal at the eavesdropper device can be written as follows:

$$\mathbf{y_X} = \mathbf{H_{X1}}\mathbf{u_1} + \mathbf{H_{X2}}\mathbf{u_2} + \mathbf{n_X} \tag{20}$$

$$\mathbf{y_X} = \mathbf{H_{X1}}(\mathbf{x_1} + \mathbf{x_2} + \mathbf{r_1}) + \mathbf{H_{X2}}(\mathbf{x_1} + \mathbf{x_2} + \mathbf{r_2}) + \mathbf{n_X} \tag{21}$$

$$\mathbf{y_X} = (\mathbf{H_{X1}} + \mathbf{H_{X2}})\mathbf{x_1} + (\mathbf{H_{X1}} + \mathbf{H_{X2}})\mathbf{x_2} + \mathbf{H_{X1}}\mathbf{r_1} + \mathbf{H_{X2}}\mathbf{r_2} + \mathbf{n_X} \tag{22}$$

We can see, from the above subsection on the design of the auxiliary signals, that the designed auxiliary signals are functions of the users channels and users' data and as such the external eavesdropper is extremely challenged in this case since it has no knowledge about the users' channels ($\mathbf{H_{11}}, \mathbf{H_{12}}, \mathbf{H_{21}}, \mathbf{H_{22}}$), users' data (i.e., $\mathbf{x_1}, \mathbf{x_2}$) and the auxiliary signals (i.e., $\mathbf{r_1}, \mathbf{r_2}$).

Due to this, the eavesdropper experiences severe performance degradation when trying to decode the legitimate users' data.

C. DESIGN COMPLEXITY & LATENCY

1) OFDM-SPM

OFDM-SPM uses two modulations including conventional BPSK for detecting the bits modulated through BPSK and the subcarrier power modulator which detects the bits which are modulated through the manipulation of the power of the transmit subcarriers. The BPSK demodulator performs the classical BPSK process to the incoming bits for recovering the BPSK stream while the power demodulator compares the power of the incoming symbols to a pre-defined threshold defined as the midpoint between the high and low power levels.

$$T = \left(\frac{H + L}{2}\right)^2 \tag{23}$$

2) MU-AS-ST

Since MU-AS-ST is a downlink multiple access technique, the philosophy of its design is based on keeping minimal processing at the receiver by doing most of the required processing at the base station, and in the receiver, an OFDM-BPSK receiver is used making from it a very low-complex receiver. Moreover, most of the processing at the transmitter is based on the auxiliary signals which are in turn computed using diagonal matrices for a fast computational process at the transmitter base station.

3) D-SEAD as integration of MU-AS-ST and OFDM-SPM

D-SEAD takes advantage of the individual merits of its components and its overall design is structured such that the complexity is kept minimal especially at the receiver. Due to the nature of this integration, the transmitter of D-SEAD is heavily impacted by the design of MU-AST while its receiver is similar to that of OFDM-SPM. At the transmitter, the only operation that is additional to MU-AS-ST is the construction of the joint streams $\mathbf{x_1}$ and $\mathbf{x_2}$ which embed both the power and the BPSK streams. The receiver is a typical OFDM-SPM receiver.

Overall, the design is much simpler at the receiver where very simple operations are used (BPSK, Power / threshold-based detection) unlike many multi-dimensional OFDM techniques 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 [17].

IV. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed technique in terms of computer simulations. TABLE 3 holds the simulation parameters' list.

TABLE 3. Simulation Parameters

Parameter Name	Value
Modulation type	BPSK
IFFT / FFT size	64
data subcarriers n	52
Symbols for cyclic prefix	16
inactive sub-carriers / out of band emission	12
Number of OFDM symbols	2×10^4
Channel model	Rayleigh
Multipath channel delay samples locations	[0 3 5 6 8]
Multipath channel tap power profile (dBm)	[0 -8 -17 -21 -25]

A. BIT ERROR RATE

Since the proposed design embeds two modulation dimensions, two detectors are involved at each receiving node including the BPSK demodulator for detecting the BPSK stream, and the subcarrier power demodulator for detecting the power modulated stream.

In Figure 5, the bit error rates for UE_1 and UE_2 are presented where it can be seen that the power stream exhibits slightly more errors than the BPSK stream. Moreover, the overall performance of the proposed design can be measured, for each user, through the average stream defined as the average between the BPSK and the power errors.

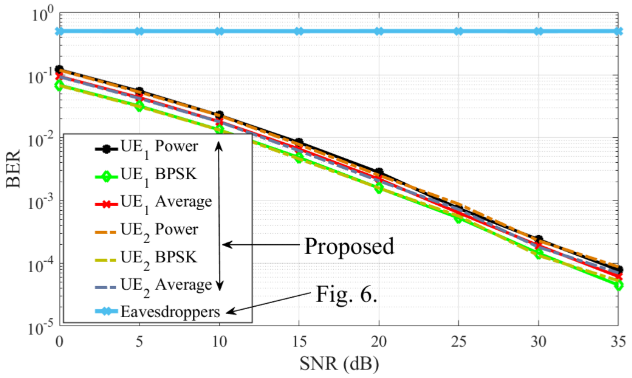

FIGURE 5. Bit error rates for UE_1, UE_2

B. SECURITY

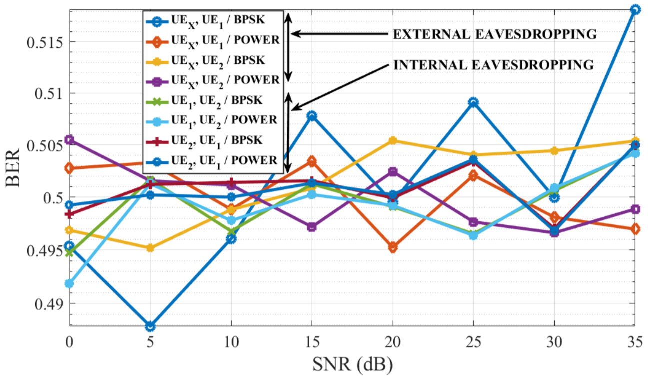

FIGURE 6. Bit error rates of the eavesdroppers

In Fig. 6, the degradation in the bit error rate curves for the internal and external eavesdropping cases is presented in detail where a considerable level of error is found. This means that the probability of the eavesdroppers in decoding the received signals is extremely low due to the incapability of getting rid of the interference that is added by the auxiliary signals r_1 and r_2 and the users' channels.

External eavesdropping refers to the case of an external device trying to listen to the legitimate users' data while internal eavesdropping refers to the legitimate users trying to eavesdrop on each other data.

C. COMPARISON TO CONVENTIONAL NOMA AND OFDM-BPSK

Since the proposed technique is an OFDM-based multiple access technique, we compared its performance with two reference techniques: power domain NOMA and conventional OFDM. Simulation results of this comparison are shown in Fig. 7, where it can be observed that the proposed design surpasses power domain NOMA and slightly outperforms conventional OFDM with BPSK.

This result is due to the specific design of the auxiliary signals employed in the proposed technique where they ensure complete inter-user interference removal and thus enhance the detection of the signal compared to the reference techniques. It is to be mentioned that OFDM-SPM by itself does not pass the performance of conventional OFDM, but its combination with MU-AS-ST in this design leads to a performance enhancement due to the complete removal of the interference and transmit diversity offered by MU-AS-ST and this resulted in better signal reception.

This simulation assumes 0.25 and 0.75 power share ratios

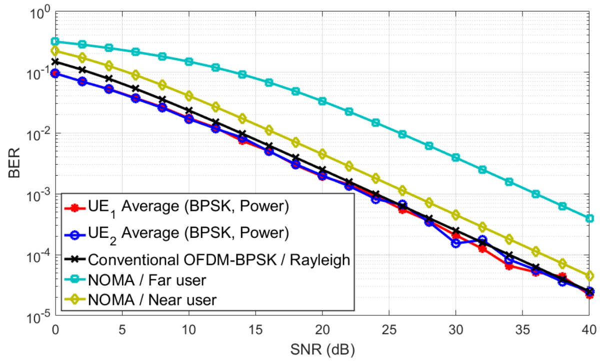

FIGURE 7. The proposed design compared to conventional NOMA and OFDM.

for the near and the far users in the case of power domain NOMA.

D. SPECTRAL EFFICIENCY

In Fig. 8, the data rates for the proposed design are presented where it is shown that the proposed technique doubles the spectral efficiency per device through the two-dimensional modulation format as in the transmitted stream, both BPSK and the power data are embedded. OFDM-SPM is capable of doubling the spectral efficiency compared to plain OFDM since a transmit subcarrier in OFDM-SPM is capable of carrying two data bits while in a conventional OFDM system modulated with BPSK, a subcarrier carries only one bit. Moreover, the design achieves doubling the spectral efficiency per area due to the use of the multiple access technique where we have investigated the case of two users in this paper. Thus, the proposed technique presents a way of enhancing the spectral efficiency per area and per device without treating each enhancement separately.

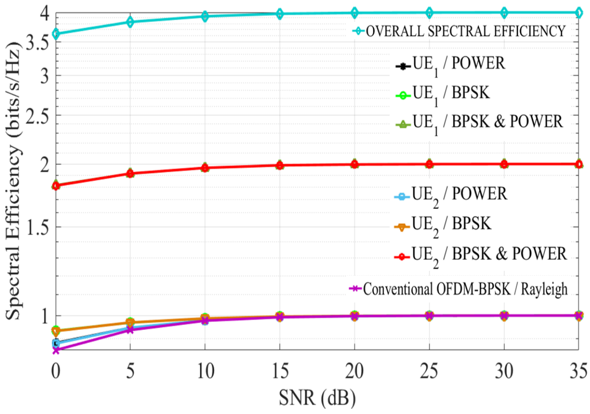

FIGURE 8. Data rates of the proposed design

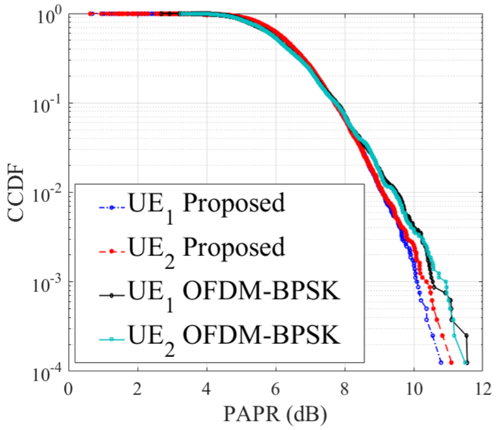

FIGURE 9. Peak to Average Power Ratio (PAPR): D-SEAD vs OFDM-BPSK

E. PEAK TO AVERAGE POWER RATIO

In Fig.9, simulation results of the peak to average power ratio (PAPR) are displayed where the proposed design is compared to conventional OFDM with BPSK.

As can be seen from this figure, D-SEAD achieves lower PAPR values compared to conventional OFDM with BPSK which is a desirable feature for OFDM-based systems.

V. CONCLUSION

In this paper, a new technique is proposed for future wireless systems. The proposed design termed D-SEAD is a hybrid technique that was born from the integration of two recently developed designs namely a multiple access design called multi-user auxiliary signal superposition transmission (MU-AS-ST) and a multi-dimensional modulation format called OFDM-SPM (OFDM with subcarrier power modulation).

Unlike many other techniques which enhance the spectral efficiency at only the area level or the user level, D-SEAD enhances the spectral efficiency both per coverage area and per user/device. Besides the spectral gain, the proposed technique offers many other merits such as robust security of the waveform against internal and external eavesdropping, simplicity of the receiver's design, lower PAPR compared to OFDM, and enhanced transmission reliability.

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