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Modulation Options for OFDM-Based Waveforms: Classification, Comparison, and Future Directions

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ABSTRACT This paper provides a comparative study on the performance of different modulation options for orthogonal frequency division multiplexing (OFDM) in terms of their spectral efficiency, reliability, peak-to-average power ratio, power efficiency, out-of-band emission, and computational complexity. The modulation candidates are classified into two main categories based on the signal plane dimension they exploit. These categories are: 1) 2-D signal plane category including conventional OFDM with classical fixed or adaptive QAM modulation and OFDM with differential modulation, where information is conveyed in changes between two successive symbols in the same subcarrier or between two consecutive subcarriers in the same OFDM symbol and 2) 3-D signal plane category encompassing: a) index-based OFDM modulation schemes which include: i) spatial modulation OFDM, where information is sent by the indices of antennas along with conventional modulated symbols and ii) OFDM with index modulation, where the subcarriers' indices are used to send additional information; b) number-based OFDM modulation schemes which include OFDM with subcarrier number modulation, in which number of subcarriers is exploited to convey additional information; and c) shape-based OFDM modulation schemes which include OFDM with pulse superposition modulation, where the shape of pulses is introduced as a third new dimension to convey additional information. Based on the provided comparative study, the relationship and interaction between these different modulation options and the requirements of future 5G networks are discussed and explained. This paper is then concluded with some recommendations and future research directions.

INDEX TERMS OFDM, OFDM-SNM, index-based OFDM family, shape-based OFDM family, 3-D signal plane, modulation options, PAPR, OOBE, 5G, spatial domain, spectral efficiency, URLLC, mMTC, eMBB, complexity, differential modulation.

I. INTRODUCTION

Higher data rate and better spectral efficiency have great importance in next generation communication systems. So far, orthogonal frequency division multiplexing (OFDM) has been at the heart of a broad range of communication systems such as Long Term Evolution (LTE), Digital Audio and Video Broadcasting (DAB/DVB), IEEE 802.11a/n/ax/ah [1], IEEE 802.16a metropolitan area network (MAN), and the local area standard (LAN) [2]. Although it is promising, conventional technology can hardly meet the requirements of the next generation networks (5G and Beyond). Fifth generation networks should address an increasingly wide range of applications with varying requirements and characteristics [3]. Therefore, determining the right modulation for a given application is very critical, especially for stringent requirements such as latency, energy efficiency, and data rates. The adopted modulation scheme impacts different 5G strategies including millimeter-Wave (mmWave) communications [4].

Traditionally, single-carrier digital modulation techniques including M-PSK, M-QAM, etc. are designed in a way that they map information bits to some constellation points of the used modulation technique in the complex, 2-D signal plane. The OFDM system, as a multi-carrier transmission scheme, is capable of achieving high data rate with the possibility of eliminating intersymbol interference over single-carrier modulation schemes [5]. Each conventional OFDM subcarrier

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carries one symbol modulated using one of the aforementioned single-carrier modulation techniques.

On the other hand, the differential digital modulation non-coherent techniques (for example, DPSK or DQPSK) could be applied to each OFDM subcarrier. These techniques are insensitive to slowly changing amplitude and phase distortion, in which equalization can be completely omitted. For the differential modulation in OFDM (OFDM-DM), the transmitted data is conveyed either in the difference between two successive symbols in the same subcarrier, or between two consecutive subcarriers in the same OFDM symbol [6], which is also represented by 2-D signal plane.

Moreover, there are other modulation techniques that can exploit a third dimension alongside the two dimensional signal plane with the main purpose of sending additional information. The exploited third dimension depends on the application, its requirements and capabilities. Examples of these types of new emerging modulation schemes are spatial modulation orthogonal frequency division multiplexing (SM-OFDM), OFDM with index modulation (OFDM-IM), OFDM with subcarrier number modulation (OFDM-SNM), and OFDM with pulse superposition modulation (OFDM-PSM).

The SM-OFDM and OFDM-IM modulation schemes can be classified under the category of index modulation (IM) family [7]–[10]. These modulation schemes convey additional information with little to no power consumption by embedding information to the index of transmit resource(s) such as transmit antennas as in SM-OFDM, and active subcarriers as in OFDM-IM. Generally speaking, spatial modulation (SM) maps a block of transmitted bits to a symbol and to a certain transmit antenna, in which the same symbol transmitted from different antennas conveys different information bits [11]. The OFDM combined with index modulation (OFDM-IM) [12] is defined as the modulation where part of the information bits are conveyed by the indices (positions) of the active subcarriers that can be chosen by a simple look-up table. In this scheme, a certain fixed number of active subcarriers are selected in each subblock to convey data bits.

Different from OFDM-IM, in OFDM-SNM [13], which belongs to the number-based OFDM modulation schemes, where the number of active subcarriers depends on the data bits. Active subcarriers' number is utilized to convey additional data bits, alongside the conventional modulation symbols in the complex signal constellation plane. One of the advantages in OFDM-SNM scheme, which is not acheived by OFDM-IM, is that the activated subcarriers can be placed in any index within each subblock as the information is sent by the subcarriers' number, and thus they can be made channel-dependent, resulting in even improved reliability.

Another modulation option for OFDM is OFDM-pulse superposition modulation (OFDM-PSM), which belongs to the shape-based OFDM modulation schemes, in which the pulse shape is exploited as an additional degree of freedom for OFDM-based waveforms. In OFDM-PSM, N_p pulses are modulated according to the transmitted data and combined together to construct a structure in which up to N_p data symbols could be transmitted simultaneously in each grid of rectangular time-frequency lattice structure. Consequently, the data rate that can be delivered in this structure would increase and could reach N_p times. Multiple orthogonal Hermite-Gaussian carriers were used with rectangular OFDMA in order to increase the bandwidth efficiency [14]. Pulse superposition approach was also applied to generalized orthogonal frequency division multiplexing (GFDM) [15], and the obtained bandwidth efficiency of superimposed GFDM waveform is almost 2.4 much higher than GFDM with Gaussian pulses [16].

In this paper, we present a unified, inclusive classification framework for different modulation options that can be used with OFDM-based systems. The basic system model of OFDM system and its modulation options is introduced in Section II. In Section III, we provide a comprehensive comparison between modulation options for OFDM in terms of their spectral efficiency, reliability, peak-to-average power ratio (PAPR), power efficiency, out-of-band emission, and computational complexity. Based on the provided comparative evaluation, we explain the interaction between these different modulation options and the requirements of future 5G networks as shown in Section IV. Then, we provide some recommendations and future research directions in Section V. Finally, we conclude the paper in Section VI.[1] [2] [3]

II. BASIC SYSTEM MODEL

A conventional OFDM symbol consists of multiple subcarriers each carrying a single modulated symbol. An OFDM frame refers to a number of consecutive OFDM symbols. Thus, the elements of the Gabor interpretation [17] of a conventional OFDM frame consists of complex-valued symbols placed on the time-frequency plane. The possible modulation options for OFDM-based waveforms can be classified based on whether the modulation option exploits a third dimension alongside the conventional signal plane, as shown in Fig. 1. The signal plane of the differential and conventional OFDM modulation can be interpreted in 2-D plane. It should be noted that two-dimensional differential demodulation is possible in time and frequency direction without changing the transmitter [18]. The remaining modulation options of OFDM have 3-D representation of signal plane classified depending on the type of third dimension which includes index-based [19], number-based [13], and shape-based [14] OFDM modulation schemes. Different domains, such as temporal, frequency, spatial, code,

[1] *Notation*: Bold, lowercase and capital letters are used for column vectors and matrices, respectively. $(.)^T$ and $(.)^H$ represent transposition and Hermitian transposition operator, respectively. det(**A**) denotes the determinant of **A**. $E(.)$ represents the expectation operator. ⊛ denotes a circular convolution operator.

[2] Optical communication OFDM-based modulation techniques are not considered in this paper.

[3] We point out that the modulation options presented in this paper for OFDM waveform are indeed applicable to be used with any OFDM-related waveform such as UFMC, FBMC, GFDM, UW-OFDM, etc.

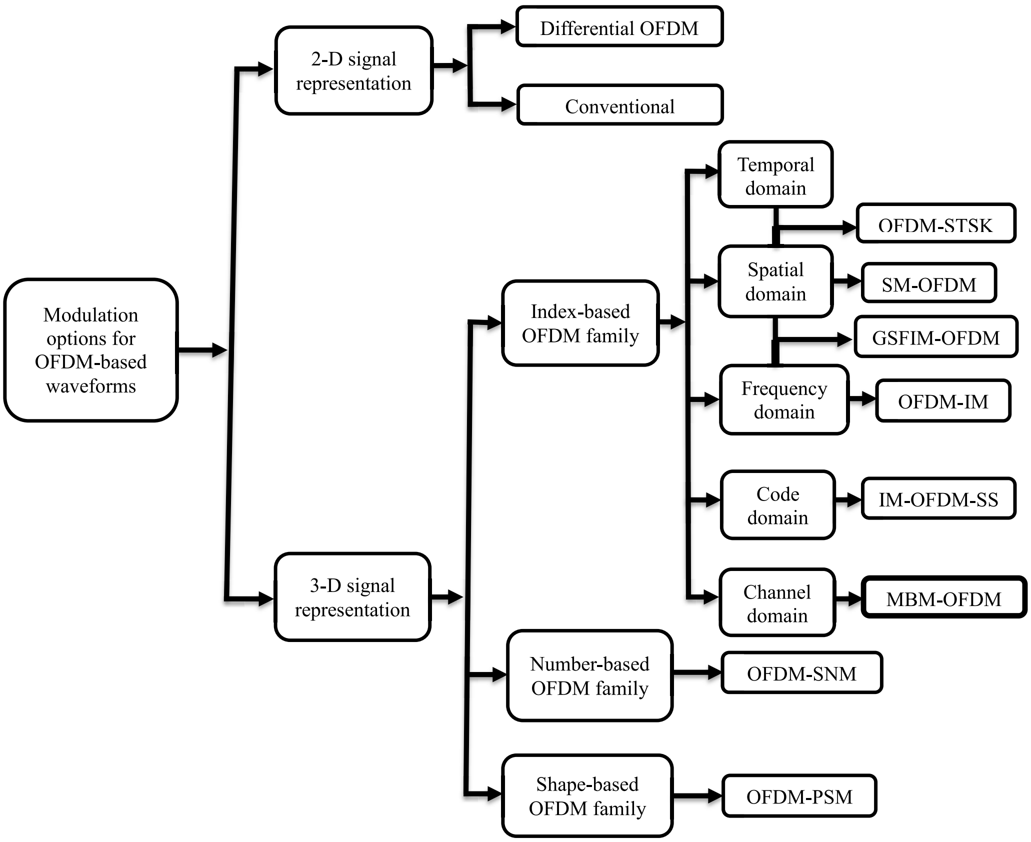

FIGURE 1. A classification of the modulation options for OFDM-based waveforms.

etc. could be exploited individually or combined under the umbrella of the aforementioned OFDM modulation schemes. For instance, by using the index of a transmit entity (or entities) in the temporal and spatial domains, the possible index-based OFDM modulation option is called OFDM-aided space-time shift keying (OFDM-STSK) [20], whereas the possible index-based OFDM modulation scheme, in which indices of both spatial and frequency domains are exploited, is called generalized space frequency index modulation-OFDM (GSFIM-OFDM) [21]. Finally, OFDM-IM, SM-OFDM, index modulated OFDM spread spectrum (IM-OFDM-SS) [22], and media-based modulation [23] schemes exploit index dimension in frequency, space, code, and channel domains, respectively. In the following, the well-known modulation options for OFDM, including conventional and differential OFDM, SM-OFDM, OFDM-IM, OFDM-SNM, and OFDM-PSM, will be discussed in details and a brief description of the others will be introduced.

The transmitted time domain OFDM block with K active subcarriers using any OFDM modulation option shown in Fig. 1 can be represented as::

$$\mathbf{x_T} = \frac{1}{\sqrt{K}} \mathbf{W^H_{N_F}}\ \mathbf{x_F}, \tag{1}$$

where $\mathbf{W_{N_F}}$ is the N_F-point DFT matrix with $\mathbf{W^H_{N_F}} \mathbf{W_{N_F}} = N_F \mathbf{I_{N_F}}$, where $\mathbf{I_{N_F}}$ is the identity matrix with a dimension of $NF \times NF$, and $\mathbf{x_F}$ is the main frequency domain OFDM block of size N_F subcarriers: $\mathbf{x_F} = \left[x_F(1)\ x_F(2)\ \ldots\ x_F(N_F)\right]$. Note that OFDM signals can be modulated in different ways as shown in Table 1. In the following subsections, the structures of the OFDM modulation options featured in this work are explained.

A. CONVENTIONAL OFDM

In conventional OFDM, subcarriers of the OFDM symbol are occupied by complex-valued symbols, that is, $K = N_F - 1$ [24]. So, the main frequency domain block in conventional OFDM is created as: $\mathbf{x_F} = \left[s(1)\ s(2)\ \ldots\ s(N_F)\right]$, where $s(\gamma) \in S$, S is the complex-valued symbols. The basic transmitter structure of conventional OFDM is shown in Fig. 2. In fact, the overall OFDM system can be efficiently realized by FFT and IFFT blocks.

B. DIFFERENTIAL MODULATION OFDM (OFDM-DM)

In differential modulation OFDM (OFDM-DM) scheme, the data bits are encoded in the difference between the consecutive subcarriers within the same OFDM symbol (frequency-domain differential modulation) or in the difference between the adjacent OFDM symbols along the same OFDM subcarrier (time-domain differential modulation) [6]. In OFDM-DM, conventional modulator and demodulator blocks are replaced by differential modulator and demodulator blocks, respectively. OFDM-DM enables low

TABLE 1. Modulation options of OFDM.

OFDM modulation option	*The main frequency domain block of OFDM modulation option* ($\mathbf{x_F}$)
Conventional OFDM [24]	$\mathbf{x_F} = \left[s(1) \quad s(2) \quad \ldots \quad s(N_F) \right]$, where $s(\gamma) \in S$, S is the complex-valued symbols.
OFDM-DM [25]	The information is sent in the difference between subsequent symbols along the same OFDM subcarrier or between subsequent samples within the same OFDM symbol.
SM-OFDM [11]	The frequency domain block for ith transmit antenna: $\mathbf{x_F} = \left[x_i(1) \quad x_i(2) \quad \ldots \quad x_i(N_F) \right]$, which differs from frequency domain blocks for the transmit antennas whose indices are all integer numbers from 1 to N_t except i.
OFDM-IM [12]	$\mathbf{x_F}$ is created based on $\mathbf{s}_\beta$ and I_β where $\mathbf{s}_\beta = \left[s_\beta(1) \quad s_\beta(2) \quad \ldots \quad s_\beta(k) \right]$, where $s_\beta(\gamma) \in S$, S is the complex-valued symbol. $I_\beta = \left\{ i_{\beta,1}, i_{\beta,2}, \ldots, i_{\beta,k} \right\}$ and the number of active subcarriers k is fixed for each subblock.
OFDM-SNM [13]	Same as OFDM-IM expect that the number of active subcarriers (k) varies for each subblock depending on the incoming information bits.
OFDM-PSM [14]	Each one of the orthogonal Hermite-Gaussian pulses is modulated by different data symbol $s(\gamma) \in S$, S is the complex-valued symbols.

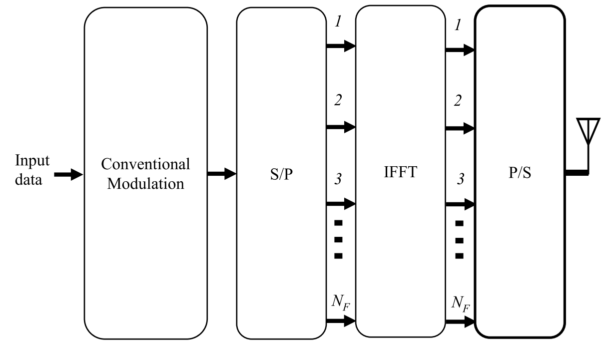

FIGURE 2. Conventional OFDM transmitter.

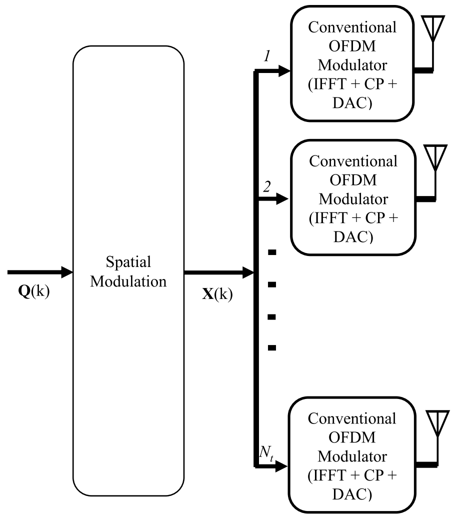

FIGURE 3. SM-OFDM transmitter.

complexity data detection while avoiding channel estimation and equalization. On the other hand, the performance of a differential system is 3 dB worse than the corresponding one for the coherent system with ideal channel knowledge [25]. Moreover, a higher SNR is required in differential modulation to have the same throughput as conventional OFDM system.

C. INDEX-BASED OFDM FAMILY

In the index-based OFDM family, additional information can be transmitted by exploiting a third dimension called index of medium(s). Prevalent index-based OFDM modulation schemes such as SM-OFDM, OFDM-IM, and other additional schemes are explained as follows.

1) SPATIAL MODULATION-OFDM (SM-OFDM)

SM is a novel multiple antenna transmission scheme that utilizes the indices of the transmit antennas in the spatial domain in order to convey additional data bits [26]. The SM scheme takes groups of $M_c + M_a$ bits and maps M_c bits to a constellation point (information symbol) and M_a bits to the location of a specific transmit antenna such that the same symbol transmitted from a different physical location of antennas conveys additional information, where $M_a \leq \log_2(N_t)$, and N_t is the number of transmit antennas [27]. When SM is applied to OFDM, each OFDM subcarrier is mapped to one of the transmitting antennas. Particularly, at each time instant, only the corresponding transmit antenna transmits power on a particular subcarrier, while all other transmit antennas are transmitting zero power on that subcarrier [11].

The main frequency domain block of SM-OFDM for each transmit antenna i is different from that of other transmit antennas blocks. Only one transmit antenna transmits over each subcarrier at a time. The transmitter structure of SM-OFDM is shown in Fig. 3 [11], [28]. Spatial modulation block maps $\mathbf{Q}(k)$ binary matrix of size $n \times N_F$ to another matrix $\mathbf{X}(k)$ of size $N_t \times N_F$, where n is the number of bits per symbol per subcarrier. The data to be transmitted in one subcarrier is shown by the column vectors of $\mathbf{Q}(k)$. Each column vector of $\mathbf{X}(k)$ corresponds to the symbol transmitted per subcarrier and contains one element different from zero at the position of the mapped transmit antenna number. Then, conventional OFDM modulators are used to modulate the N_t row vectors of $\mathbf{X}(k)$. Fig. 4 shows the 3-D signal plane of SM-OFDM where only one out of N_t transmit antennas is active for each subcarrier. It should be noted that a data symbol can be represented as a colored cube with space axis.

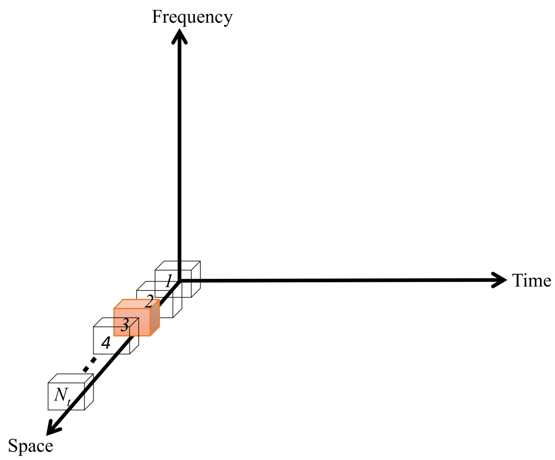

FIGURE 4. 3-D signal plane of the SM-OFDM scheme.

Several new enhanced SM modulation schemes have recently been proposed to enhance its spectral efficiency. For example, generalized SM (GSM) scheme [29] where the same data symbol is transmitted over the selected active transmit antennas, which results in higher spectral efficiency with a much lower number of transmit antennas. In order to further increase the overall spectral efficiency of GSM scheme, GSM was extended to high-rate, low complex MIMO transmission scheme named multiple-active spatial modulation (MA-SM) in which different data symbols from the selected active transmit antennas could be transmitted [30]. A promising form of SM proposed in [31] called enhanced SM (ESM) in which active transmit antennas and signal constellations are jointly selected in order to convey additional information. The ESM scheme transmits one or two additional information bits per channel use as compared to conventional SM scheme. An improved spectral efficiency modified version of SM called quadrature SM (QSM) [32] where the real and imaginary parts of the data symbols are separately sent using the SM principle, so QSM scheme can improve the overall throughput of conventional SM scheme by exploiting an extra new spatial constellation dimension, in which the signal constellation symbol is expanded before transmission to include its in-phase and quadrature components. Detailed, comprehensive information on the recently proposed modulation schemes based on the concept of spatial modulation can be found in [26].

2) OFDM WITH INDEX MODULATION (OFDM-IM)

The basic OFDM-IM transmitter structure conveying m bits is shown in Fig. 5 [12], [33]. In this scheme, the whole OFDM block is divided into g small subblocks (groups), each containing a certain number of subcarriers, from which only a few of these subcarriers are selected as active based on the transmitted information bits. The selected, activated subcarriers are then used to carry conventional modulated QAM symbols. Thus, information bits are sent by the active indices of the subcarriers and the signal constellation points.

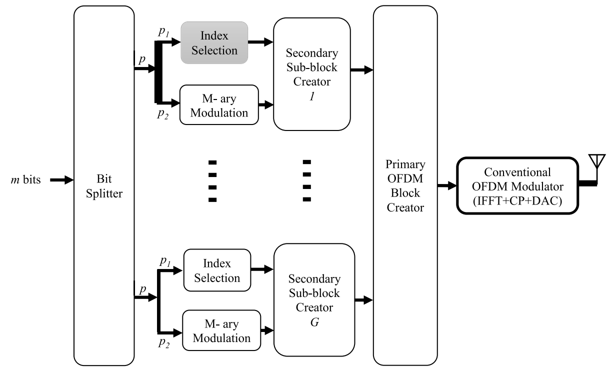

FIGURE 5. OFDM-IM transmitter.

Each subblock contains $p = m/g$ bits, the available p bits are divided into two parts for different purposes. In the first part, the index selector shown in Fig. 5 chooses k out of n active subcarriers. For each subblock β based on the incoming p_1 bits, selected subcarrier indices is sorted in ascending order as: $I_\beta = \{i_{\beta,1}, i_{\beta,2}, \ldots, i_{\beta,k}\}$, where $i_{\beta,\gamma} \in [1, \ldots, n]$ for $\beta = 1, \ldots, g$ and $\gamma = 1, \ldots, k$. In the second part, the p_2 bits of the β subblock are fed to the M-ary modulator in order to select k constellation symbols points ($p_2 = k \log_2(M)$), yielding: $\mathbf{s}_\beta = [s_\beta(1)\ s_\beta(2)\ \ldots\ s_\beta(k)]$, where $s_\beta(\gamma) \in S$, S is the complex-valued symbol to be transmitted over the subcarrier of index $i_{\beta,\gamma}$. Then, the main frequency domain block of OFDM-IM ($\mathbf{x_F}$) is bulit up by taking into account I_β and $\mathbf{s}_\beta$ for all β and concatenating all g groups.

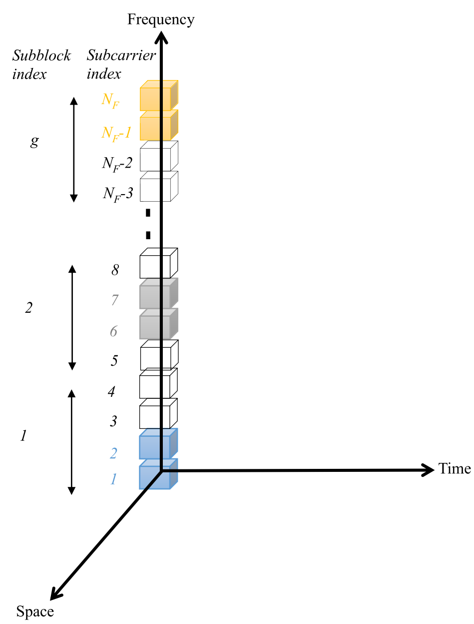

FIGURE 6. 3-D signal plane of the OFDM-IM scheme.

The 3-D signal plane of OFDM-IM is shown in Fig. 6 where k subcarriers are active in each subblock according to the incoming bit stream. For example as shown in Fig. 6, we assume that there are $k = 2$ active subcarriers out of

$n = 4$ subcarriers in each subblock, and the active subcarriers indices correspond to the colored cubes in frequency axis which represent the complex data symbols to be carried over the active subcarriers.

It should be mentioned that several new enhanced modulation schemes inspired by the conventional OFDM-IM scheme have recently been proposed to enhance its spectral efficiency. Among these schemes, we mention OFDM with generalized index modulation (OFDM-GIM) [34], OFDM with dual-mode index modulation (OFDM-DMIM) [35], generalized DM-OFDM (GDM-OFDM) [36], OFDM with multi-mode index modulation (OFDM-MMIM) [37], and two enhanced schemes for OFDM-IM [38], OFDM with hybrid in-phase/quadrature index modulation (OFDM-HIQ-IM) and linear constellation precoded OFDM-I/Q-IM (LP-OFDM-I/Q-IM). In OFDM-GIM [34], more degree of freedom in the selection of active subcarriers has been introduced by using different activation ratios for different subblocks within the whole OFDM block to increase throughput. In OFDM-DMIM [35], the subcarriers in each subblock are divided into two groups and then different signal constellation modes are used for these groups to convey additional information bits, hence all subcarriers are modulated and used to send information bits. In the generalized DM-OFDM (GDM-OFDM) scheme [36], the number of subcarriers modulated by the same constellation alphabet is altered based on the information bits of each OFDM subblock to improve the spectral efficiency of classical DM-OFDM. This dual mode concept is later generalized to a multi-mode structure [37] to further enhance the system performance by transmitting more IM bits with a permutational increase. Moreover, two enhanced OFDM-IM schemes are proposed in [38]. The first scheme called OFDM with hybrid in-phase/quadrature index modulation (OFDM-HIQ-IM) where the IQ dimensions have been explored jointly which doubles the IM bits of OFDM-IM. In the second scheme termed as linear constellation precoded OFDM-I/Q-IM (LP-OFDM-I/Q-IM), a pair of I/Q symbols is linearly combined in order to obtain an additional diversity gain. Detailed, comprehensive surveys on the recently proposed modulation schemes based on the concept of index modulation can be found in [7], [19], [39], and [40].

3) ADDITIONAL INDEX-BASED OFDM MODULATION SCHEMES

Aside from SM-OFDM and OFDM-IM, where index modulation is performed in spatial domain and frequency domain respectively, many different domains could be exploited either individually or jointly in order to convey additional information alongside the conventional symbols. The following are four examples of exploiting joint temporal and spatial domains (OFDM-STSK), joint frequency and spatial domains (GSFIM-OFDM), individual code domain (IM-OFDM-SS) and individual channel domain (MBM). More comprehensive classification of index-based modulation schemes could be found in [19].

- **Spatiotemporal domain**: OFDM-aided space time shift keying (OFDM-STSK) [20] is a modulation option in which both temporal as well as spatial domains are jointly utilized. In OFDM-STSK, J space-time codewords are transmitted simultaneously in one OFDM symbol, every OFDM subcarrier carries a column of each space-time codeword. It should be noted that $J = N_c/T$ (N_c is a multiple of T, T is the number of time slots in a STSK symbol).

  In OFDM-STSK scheme, the available input block of size $p = log_2(Q) + log_2(M)$, is divided into two parts: first part is used to index a dispersion matrix (DM) among Q available DM matrices of size $N_t \times N_r$ for space-time coding, where N_t and N_r are the number of transmit and receive antennas, whereas the second part is modulated into M-QAM symbols to be transmitted over the selected DM [41]. Therefore, OFDM-STSK is an index-based modulation scheme where the index of DM (as a third dimension) is exploited to transmit additional information alongside the 2-D complex M-QAM symbols.
- **Spectrospatial domain**: GSFIM-OFDM scheme [21] uses both subcarriers (frequency domain) in addition to the active antennas (spatial domain) to convey additional information bits through their indices, besides conveying bits through conventional M-ary modulation symbols. At any given time, n_{rf} transmit antennas are active and the remaining n_t-n_{rf} antennas remain silent. The GSFIM encoder takes $\lfloor \log_2 \binom{n_t}{n_{rf}} \rfloor$ bits and maps to n_{rf} out of n_t transmit antennas. Therefore, the GSFIM-OFDM scheme is considered as index-based OFDM modulation scheme where the indices of both active subcarrier and antenna are exploited to transmit additional information bits.
- **Code domain**: In index modulated orthogonal frequency division multiplexing spread spectrum (IM-OFDM-SS) scheme [22], additional information bits are conveyed by the joint exploitation of spreading codes' indices and the conventional M-ary modulated symbols. In this scheme, a selected spreading code is used to spread a data symbol across several OFDM subcarriers to convey additional bits. The spreading code is selected from a predefined set according to the index bits, which results in harvesting additional diversity gain. Therefore, the IM-OFDM-SS belongs to the index-based OFDM modulation family where the indices of a spreading code are utilized to convey additional information.
- **Channel domain**: Channel states domain could be exploited by altering the far-field radiation pattern of reconfigurable antennas, this type of modulation called media-based modulation (MBM) [23]. The MBM scheme belongs to index-based modulation scheme, by means of selecting the index of the corresponding radiation pattern according to the information bits. It should be noted that MBM integration with OFDM could be regarded as a potential candidate transmission scheme for future wireless systems.

D. NUMBER-BASED OFDM FAMILY

In the number-based OFDM family, extra information could be transmitted by exploiting a novel third dimension called number of transmit entity(or entities). The OFDM with subcarrier number modulation (OFDM-SNM) proposed in [13] belongs to number-based OFDM modulation schemes by means of the number of active subcarriers. The active subcarriers are not necessarily adjacent to each other. Also, index-independent subcarrier activation pattern is employed in OFDM-SNM, whereas OFDM-IM utilizes index-dependent pattern. The number of active subcarriers is determined depending on the incoming bits. The new dimension exploited in this novel OFDM-SNM scheme is the number (not index) of specific transmit medium(s), such as the number of active subcarriers in the OFDM-SNM scheme. Therefore, an additional information is sent through number of active subcarriers as well as the conventional two-dimensional QAM symbols.

It should be noted that OFDM-SNM scheme differs from OFDM-IM in that it is based on the number of active subcarrier (k) which varies for each subblock of length n in OFDM-SNM, whereas it is fixed for all subblocks in OFDM-IM. Fig. 7 shows the OFDM-SNM transmitter structure [13].

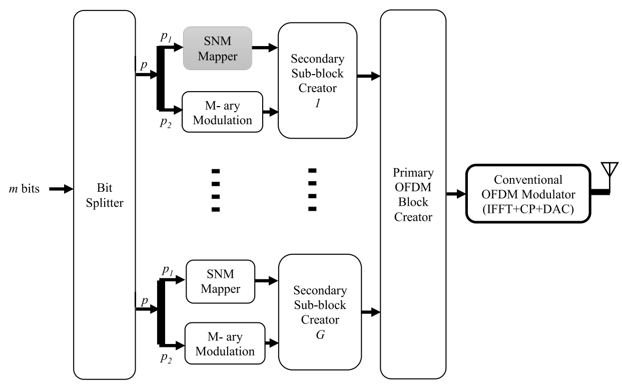

FIGURE 7. OFDM-SNM transmitter [13].

An example of 3-D signal plane of OFDM-SNM is shown in Fig. 8 where the number of adjacent active subcarriers in each subblock is varied according to the incoming bit stream. For example as shown in Fig. 8, there are four possible number of active subcarriers in each subblock of length four, and the width of a subblock is represented by its number of active subcarriers corresponding to the colored cubes in frequency axis which represent the complex data symbols to be carried over that subblock width.

E. SHAPE-BASED OFDM FAMILY

In the shape-based OFDM family, extra information could be implicitly conveyed by a novel third dimension named as the shape of transmit entity (or entities). The OFDM with pulse superposition modulation (OFDM-PSM) is considered as a shape-based OFDM modulation scheme, where data symbols

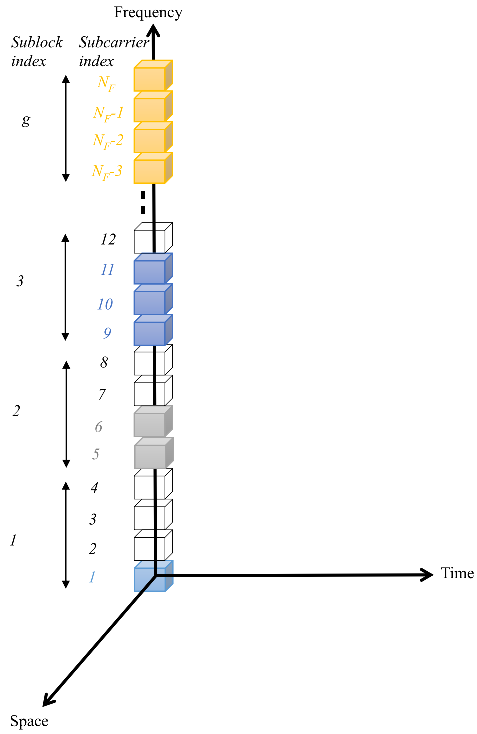

FIGURE 8. 3-D signal plane of the OFDM-SNM scheme.

can be modulated onto time-frequency shifted versions of a transmit pulse. In fact, there are a lot of examples of a transmit pulse in the literature, some of these common pulses can be found in (e.g., [42]–[45]).

In OFDM-PSM modulation scheme [14], each one of orthogonal, fully overlapping pulses is modulated by a different data symbol, and they are then superimposed together within the same time-frequency region in order to increase the transmission spectral efficiency while maintaining a reliability performance comparable to that of basic OFDM waveform.

For instance, in case of superimposing four Hermite-Gaussian pulses, the total spectral efficiency doubles compared to that of the conventional Gaussian-pulse based transmission due to the fact that the third-order pulse covers almost twice the time-frequency region compared to the zeroth-order one as illustrated in Fig. 9.

Accordingly, OFDM-PSM using Hermite-Gaussian pulses outperforms the transmission schemes that utilize single Gaussian pulses as the transmit pulses in terms of spectral efficiency. On the other hand, OFDM-PSM has the same reliability and BER performance as that of OFDM but fewer side lobes due to using localized Hermite-Gaussian pulses instead of the non-localized Sinc pulses.

F. OFDM WITH ADAPTIVE HYBRID MODULATION

Here, a concept differs than the known conventional adaptive QAM scheme will be discussed. In the conventional transmission scheme, different QAM modulation orders are

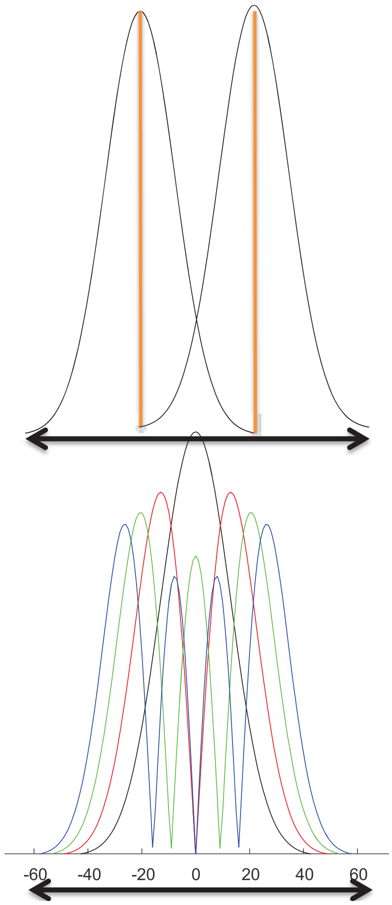

FIGURE 9. Conventional Gaussian transmission (upper part of the figure) vs. pulse superposition modulation using Hermite Gaussian pulses (lower part of the figure). It is noticed that four data symbols can be carried by PSM within a duration (or bandwidth) equal to that occupied by two adjacent Gaussian pulses by which only two data symbols can be carried.

selected and applied to different subcarriers based on their corresponding subchannels' quality and/or the requirements of the service or application being used at the receiver side (i.e., quality of service (QoS) based adaptation). Particularly, given a service with a certain, targeted BER requirement, the modulation orders are adaptively selected to meet the targeted BER while maximizing the transmission spectral efficiency.

Besides the conventional adaptive QAM modulation, there is also the concept of joint adaptive subcarrier switching and adaptive modulation [46]. More specifically, three approaches can be used in this case. 1) OFDM with adaptive index modulation and fixed constellation modulation (OFDM-AIM-FCM), which can be used to enhance secrecy and spectral efficiency. 2) OFDM with joint adaptive index modulation and adaptive constellation modulation (OFDM-AIM-ACM), which can be used to further enhance secrecy and spectral efficiency. 3) OFDM with variable index modulation and variable constellation modulation (OFDM-VIM-VCM) for QoS based communication in order to improve spectral efficiency. In particular, the first two approaches are based on channel based adaptation of subcarrier activation ratios and constellation modulation orders of subblocks in OFDM-IM by utilizing channel reciprocity concept in time division duplex (TDD) mode, whereas the third approach is based on QoS based adaptation. A small degradation in the BER performance is observed while examining the proposed algorithms against imperfect channel estimation [46].

III. PERFORMANCE EVALUATION AND COMPARISON

To analyze the performance of an OFDM system with different modulation options, spectral efficiency (SE), reliability, peak-to-average power ratio (PAPR), power efficiency (PE), out-of-band emission (OOBE), and computational complexity are investigated. The simulation parameters used in the performance analysis of the presented OFDM modulation options are provided in Table 2. To have a fair comparison, single-input and single-output (SISO) transmission with only one user is considered for the featured OFDM modulation options. On the other hand, SM-OFDM as a multi-antenna transmission scheme should be analyzed along with its competitive MIMO transmission schemes including the most popular ones: Vertical Bell Labs Layered Space-Time (V-BLAST) [47] and Alamouti-Coded [48] OFDM systems. The channel used in the simulation is a multi-path Rayleigh slow fading channel. It is assumed that the channel state information is known at the receiver. It should be noted that SNR is defined as $\rho = E_b/N_{o,T}$, where E_b is the average transmitted energy per bit, and $N_{o,T}$ is the noise variance in the time domain.

TABLE 2. Simulation parameters.

Modulation type	BPSK
IFFT/FFT size (N_F)	64
CP Guard Interval (samples)	8
Number of subblocks in each OFDM symbol	16
Number of available subcarriers in each subblock	4
Multipath channel delay samples locations	[0 3 5 6 8]
Multipath channel tap power profile (dBm)	[0 -8 -17 -21 -25]

A. SPECTRAL EFFICIENCY

One of the key figure of merit when assessing the performance of a given modulation system is the spectral efficiency η. The spectral efficiency (bits/s/Hz) of the possible OFDM modulation options is summarized as follows:

$$\eta_{Conventional\ OFDM} = \frac{N_F \log_2(M)}{N_F + N_{CP}}, \quad (2)$$

$$\eta_{OFDM-IM} = \frac{N_F\left(\log_2(M^k) + \lfloor \log_2 \binom{L}{K} \rfloor\right)}{(N_F + N_{CP})L}, \quad (3)$$

$$\eta_{OFDM-SNM} = \frac{\sum_{g=1}^{G}\left(\log_2(N) + K(g)\log_2(M)\right)}{N_F + N_{CP}}, \quad (4)$$

where M is the constellation cardinality, N_{CP} represents the number of guard or cyclic-prefix (CP) samples, L is subblock length and K is the number of active subcarriers in each OFDM-IM subblock of L subcarriers' length, $K(g)$ represents the number of active subcarrier in each OFDM-SNM subblock of N subcarriers' length, and G is the number of OFDM-SNM subblocks (groups). As seen in Fig. 10, the relative loss in throughput is higher in OFDM-DM compared to the conventional OFDM [49]. It should be noted that $K(g)$ varies for each subblock in OFDM-SNM, while it is fixed for all subblocks in OFDM-IM. The spectrum advantage of OFDM-SNM over OFDM-IM holds just for low subblock size cases as implemented in our scenario. However, for more general cases, the spectrum advantage does not hold anymore.

The used two-dimensional constellation diagram and the given number of transmit antennas determine the number of information bits that can be transmitted using SM. The spectral efficiency of SM-OFDM increases logarithmically with the number of transmit antennas (N_t) as follows:

$$\eta_{SM-OFDM} = \frac{N_F \log_2(N_t) + \log_2(M)}{N_F + N_{CP}}. \quad (5)$$

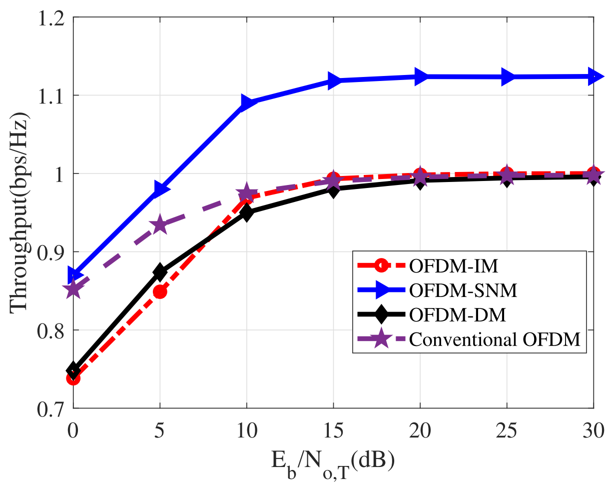

FIGURE 10. Throughput of the featured modulation options of OFDM.

The spectral efficiency of OFDM-PSM using Hermite-Gaussian pulses is better compared to the transmission scheme that utilize only single Gaussian pulses as the transmit base. Fig. 10 shows the throughput comparison between different possible modulation options for OFDM. For the specific simulation parameters presented in Table 2, the throughput performance of OFDM-SNM outperforms all the other modulation options of OFDM. Also, OFDM-IM and OFDM-DM throughput performances converge to that of conventional OFDM at high SNR values. Moreover, conventional OFDM scheme outperforms differential OFDM scheme by about 2.9 dB [49]. It should be mentioned that different throughput values can also be obtained when the design parameters such as the activation ratio and subblock size of a certain modulation option change from one setting to another.

B. BIT ERROR RATE (BER)

The convenient way to compare the reliability of different modulation schemes is through analyzing their BER performances. The BER vs. $E_b/N_{o,T}$ performance for the modulation options of OFDM is shown in Fig. 11. Particularly, Fig. 11 shows that both OFDM-IM and OFDM-SNM schemes have almost similar BER performance which is better than that of conventional OFDM at high SNR region. It should be noted that OFDM-DM has worst BER performance at high SNR region. Besides, OFDM-PSM has almost similar BER performance to that of the classical OFDM [16]. It should be noted that SM-OFDM has better BER performance than the popular V-BLAST and Alamouti-coded OFDM systems at low spectral efficiency. Even though, at high spectral efficiency, its BER performance would be depend on a trade-off between the signal constellation size (M) and spatial constellation size ($N_t \times N_r$) [28].

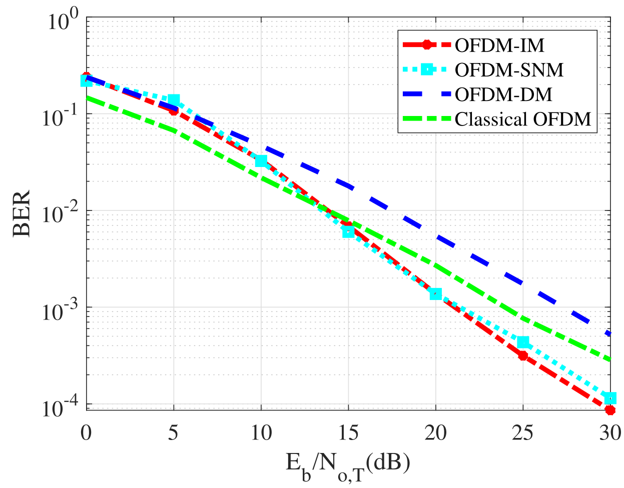

FIGURE 11. BER of the featured modulation options of OFDM.

C. PAPR AND POWER EFFICIENCY

Peak-to-average power ratio (PAPR) is defined as the ratio of maximum power to average power of the waveform. The OFDM waveform has a high PAPR, due to the possible constructive combination of subcarriers with independent phases, causing non-linearity issues when the OFDM signal is passed through a high power amplifier (HPA) at the transmitter. This also reduces the efficiency of the HPA. The power efficiency analysis of OFDM modulation options is significantly important aspect to account for in the system design. PAPR of OFDM waveform is heavily influenced by the pulse shape of each subcarrier and the number of available subcarriers (N_F). The average power per subcarrier is the same among all subcarriers, which equals to the total transmitted power (P_{tx}) divided by N_F.

Assuming that OFDM symbols are uncorrelated to each other within each OFDM block, the PAPR performances of OFDM-IM [50], OFDM-SNM, OFDM-DM, and conventional OFDM are high and almost the same as shown

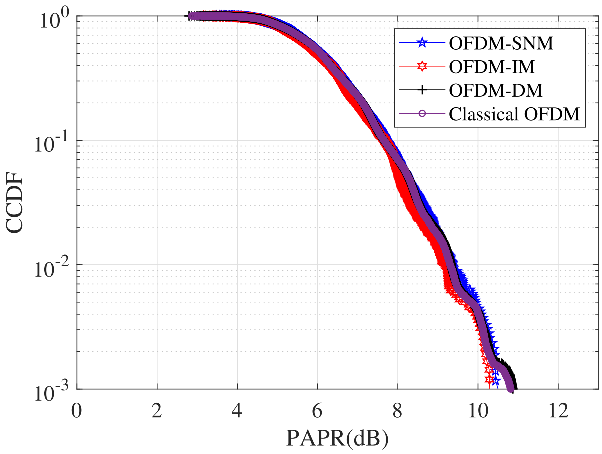

FIGURE 12. **PAPR of the featured modulation options of OFDM.**

in Fig. 12. It should also be emphasized that although the number of active subcarriers in some modulation options such as OFDM-IM and OFDM-SNM is less than that used in conventional OFDM, their PAPR still remain high and comparable to that of the traditional OFDM. This is due to the fact that the active subcarriers in case of OFDM-IM or OFDM-SNM are sparse in nature (i.e., scatteredly distributed and not localized). It should be noted that PAPR of OFDM-PSM is high and almost matches to the PAPR of the classical OFDM due to having superimposed pulses together within the same time-frequency region which significantly increases the peak power of the transmitted OFDM-PSM signal. It is worthy to mention that SM-OFDM achieves practically, for a large number of subcarriers, the same PAPR performance as that in the V-BLAST OFDM system [51].

Besides the power efficiency related to the PAPR of the OFDM waveform with different modulation options, there is another type of power efficiency that can be achieved due to not activating all the subcarriers (i.e., not sending power over these subcarriers). Particularly, an improvement in power efficiency is expected as a result of the reduction in the power consumption of OFDM-IM and OFDM-SNM schemes (only active subcarriers carry data symbols, while inactive subcarriers have zero power) compared to the basic OFDM. In OFDM-IM, the average power per active subcarrier is $(\frac{P_{tx}}{KN_F})$.

In OFDM-SNM scheme, the probability of observing K active subcarriers in each subblock of length N is assumed to follow binomial distribution with a random variable N_{ac} as

$$\Pr(N_{ac} = K) = \binom{N}{K} p_r^K (1 - p_r)^{N-K}. \quad (6)$$

For a fair comparsion with other featured OFDM modulation options, the total transmitted power for an OFDM-SNM symbol is P_{tx}, and the power is equally distributed to all subblocks. Then, the power consumed by OFDM-SNM scheme is formulated as [13]:

$$P_c = \frac{P_{tx}}{G\,N} \sum_{g=1}^{G} K(g)\ \Pr(N_{ac} = K(g)), \quad (7)$$

where $K(g)$ represents the number of active subcarriers in the subblock g. Thus, the average power allocated per subcarrier is P_c/N_F. With respect to SM-OFDM, although information data can be sent through the transmit antennas in SM-OFDM, the number of transmit antennas does not affect the power consumed at SM-OFDM transmitter. As a result, SM-OFDM can be considered as an energy efficient system [52].

D. OUT-OF-BAND EMISSION

Side-lobes are caused by the multiple Sinc-shaped subcarriers of OFDM. In particular, larger side-lobes result in high out-of-band emission (OOBE), which is one of the main drawbacks of OFDM-based systems [53]. The good modulation option for OFDM is the option in which side-lobes are minimized. Assuming that the same transmit power is allocated to the OFDM symbol, Fig. 13 shows that the OOBE leakage of OFDM-IM [54] and OFDM-SNM has almost similar performance to that of OFDM-DM and conventional OFDM, due to the sparsity nature of the active subcarriers in the transmission blocks of OFDM-IM and OFDM-SNM. Moreover, the OOBE of SM-OFDM has a minimal level due to the activation of single transmit antenna at each time instant which significantly reduces the interference between the transmit antennas. It should be emphasized that OFDM-PSM has less side lobes compared to that of conventional OFDM due to using localized Hermite-Gaussian pulses instead of the non-localized Sinc pulses.

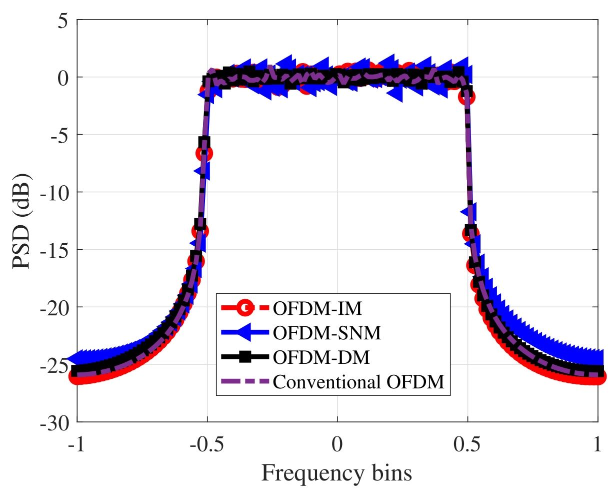

FIGURE 13. **PSD of the featured modulation options of OFDM.**

E. COMPLEXITY ANALYSIS

The receiver detection algorithms should consider the cost (computational complexity) of the scheme so that an optimized design could be achieved. The total number of complex

TABLE 3. Assessment of modulation options of OFDM.

OFDM modulation options	Reliability	Spectral Efficiency	PE in terms of PAPR	PE in terms of transmission power	OOBE	Computational complexity
Conventional OFDM [24]	High at low SNR and low at high SNR	$\frac{N_F \log_2(M)}{N_F + N_{CP}}$	High due to the constructive combination of subcarriers with independent phases	High due to sending power on all subcarriers	High due to the rectangular transmit pulse	$\mathcal{O}(M)$
OFDM-DM [25]	Low at low and high SNR	Relative loss in throughput is higher compared to conventional OFDM	High	High due to sending power on all subcarriers	High	$\mathcal{O}(M)$
SM-OFDM [11]	High at low SE, depends on a trade-off between $Nt \times Nr$ and M at high SE	$\frac{N_F \log_2(N_t) + \log_2(M)}{N_F + N_{CP}}$	High for a large number of subcarriers	Low due to sending power only to single transmit antenna at a time	Low due to significantly reduction in the interference between the transmit antennas	$\mathcal{O}(N_t, N_r, M)$
OFDM-IM [12]	Low at low SNR and high at high SNR	$\frac{N_F \left(\log_2(M^k) + \lfloor \log_2(\binom{l}{k}) \rfloor\right)}{(N_F + N_{CP})l}$	High due to sparse distribution of active subcarriers	Low due to sending power to fixed number of activated subcarriers in each subblock	High due to the sparsity nature of the active subcarriers	$\mathcal{O}(M)$
OFDM-SNM [13]	Low at low SNR and high at high SNR	$\frac{\sum_{g=1}^{G} (\log_2(N) + K(g)\log_2(M))}{N_F + N_{CP}}$	High due to sparse distribution of active subcarriers	Medium and depends on the varied number of activated subcarriers in each subblock	High due to the sparsity nature of the active subcarriers	$\mathcal{O}(N, K, M)$
OFDM-PSM [14]	High at low SNR and low at high SNR	High and depends on the number of superimposed Hermite-Gaussian pulses	High due to having superimposed pulses together within the same time-frequency region	High and depends on the number of superimposed Hermite-Gaussian pulses	Low due to using localized Hermite-Gaussian pulses	$\mathcal{O}((D+1), K, L, M)$

operations per subcarrier is used as an assessment tool for complexity analysis. In our analysis, we do not consider the channel estimation or equalization processes. Moreover, we assume perfect synchronization in all modulation options for OFDM-based waveforms. Conventional OFDM is computationally efficient since it only uses IFFT and FFT at the transmitter and receiver sides, respectively. The computational complexity of conventional and differential OFDM increases with modulation order (M). Near optimal log likelihood ratio (LLR) detector has been adopted with OFDM-IM, which provides comparable decoding complexity. The computational complexity of OFDM-SNM scheme increases with N, K, and M.

For OFDM-PSM, there are KM multiplications with K polyphase components of the filter with length L for each D order of Hermite-Gaussian function [16]. The complexity of SM-OFDM increases with the rise of the number of transmit antennas (N_t), receive antennas (N_r), and modulation order (M) [55]. In SM-OFDM, single transmit antenna is activated at a time which eliminates the need for multiple bulky and expensive RF chains. Specifically, a single RF chain and a switch can handle the SM-OFDM transmission. It should be noted that the physical size of the wireless device, in which a small number of antennas can be used, would limit the number of mapped bits in SM-OFDM. In the last column of Table 3, we provide a brief comparison between different modulation options in terms of their complexity level.

IV. THE POSSIBLE INTERACTIONS OF MODULATION OPTIONS WITH THE REQUIREMENTS OF 5G NETWORKS

The 5G and beyond wireless systems are featured by a number of new, unprecedented use cases, scenarios, and services whose requirements are very diverse and challenging to meet. Particularly, the enormous diversity of future devices, applications and services including ultra-reliable low-latency communications (URLLC), massive machine type communications (mMTC), enhanced mobile broadband (eMBB) makes it almost impossible for a single radio technology to meet all the requirements of different services simultaneously. Due to this shortcoming and deficiency, the concept of multi-numerology OFDM-based frame structure with different, flexible parameterization is proposed as a promising solution [3], [56]. Among the many different parameters that are expected to have significant impact on the capability of the OFDM waveform to meet the different requirements of 5G services is the type of modulation that can be used with the adopted waveform.

There are a lot of potential modulation techniques that can be used and integrated with OFDM waveform in 5G networks as explained in the previous section. Since different modulation options have varied performances in terms of different metrics and criteria as shown above in the figures where different BER and throughput performances are obtained,[4] a specific modulation option with certain parameters can be used to meet the requirements of each service.

To help predict the possible interactions with the requirements of 5G networks, in Table 3, we qualitatively summarize and compare the performance of different possible modulation options for OFDM. The main criteria to evaluate the efficiency of a modulation type are its reliability, spectral efficiency, power efficiency, OOBE and their complexity performances.

The OFDM-SNM scheme can be used in applications that requires relatively high throughput with lower modulation orders from one hand (i.e., BPSK) to provide lower BER values; and with short subblock sizes from another hand (i.e., 4 subcarriers) to achieve less detection complexity. Besides, OFDM-SNM has an inherent ability to reduce adjacent channel interference (i.e., inter-band-service interference) in 5G multi-numerology design as the activated subcarriers can be situated at any location within the OFDM subblock. For IoT applications, where low energy consumption at the devices is required and handling asynchronous impairments is preferable, OFDM-IM along with energy-based detector seems to be a good option due to its flexible, low complexity and adaptive structure. Moreover, OFDM-IM with low activation ratios alongside compressed sensing-based receiver structure is deemed to be suitable for URLLC applications due to their high reliability and low latency resulting from reducing the transceiver complexity. In the next generation 5G systems, robust receiver against unknown interference is needed. The low-complexity, threshold-based detector used in index and number-based OFDM modulation options is considered as a robust receiver against unknown interference. Exploiting empty subcarriers in index and number-based OFDM modulation options, such as OFDM-IM and OFDM-SNM schemes, could be helpful in the 5G applications where low PAPR and easier inter-carrier-interference (ICI) mitigation are critical. Also, SM-OFDM fits more to mMTC due to its improved power efficiency, enhanced reliability alongside flexibility. The OFDM-PSM scheme is a good modulation candidate for the applications where robustness towards multi-user interference is favorable due to its low OOBE.

V. FUTURE RESEARCH DIRECTIONS

A. SCHEDULING AND RESOURCE ALLOCATION

In a multi-user environment, scheduling the available time and frequency resources among users in an efficient and fair manner is one of the indispensable tasks in most of centralized communication networks in order to ensure maximal and fair performance in terms of throughput and reliability while minimizing interference. One of the most effective scheduling techniques used in the literature is channel-dependent scheduler [57]. In this scheduler, the subcarriers corresponding to good subchannel gains with respect to a certain user are selected and assigned for data transmission to that specific user, whereas the other subcarriers are assigned to other different users whose subchannels corresponding to these remaining subcarriers are in good quality.

This channel-based resource allocation scheduler has been studied extensively for OFDM with conventional constellation modulation, for example as presented in [58]; however, to the best of authors' knowledge, there are no works reported in the literature that investigate the possibility of using such scheduler when index modulation is used with OFDM waveform. It is anticipated that OFDM-IM with its current design may deem incompatible and unsuitable to be used directly with channel-dependent scheduler. The reason for this is that, in OFDM-IM, the subcarriers selected for data transmission are dependent solely on the incoming data bits, whereas in channel-dependent scheduling, the subcarriers chosen for data transmission are dependent solely on the channel characteristics.

So, the research question that poses itself here is that "Is it practically possible to make the selected subcarriers in OFDM to be both data and channel dependent simultaneously?" if no, then "What alternatives can be used" and if yes, then "What changes should be introduced to the transceiver structure to make the design work properly?". These questions and others need thorough thinking and deep investigation to answer them confidently and then try to come up with novel, compatible or alternative designs to coexist and integrate subcarrier index selection modulation with subcarrier channel-based selection scheduling if possible in a seamless manner.

[4]It should be mentioned that the simulation setup example presented in this paper is given to demonstrate a simple, basic comparison between modulation options. However, it should be emphasized that the differences in the BER and throughput performances can be far greater as they are heavily dependent on many other parameters such as the subblock size, activation ratio and modulation order. For example, a comprehensive, detailed study on the huge range of different throughput and reliability values that OFDM-IM is capable of achieving can be found in [33], where the performance comparisons of both low and high SE scenarios are presented.

B. PHYSICAL LAYER SECURITY

In wireless communication medium, it is necessary to secure our transmission against eavesdroppers who can capture the data-carrying signals and then try to decode them [59], [60]. Naturally, using fixed modulation does not result in any secrecy gain as the transmission in this case is independent of the channel. However, channel-based adaptive constellation modulation can result in a significant secrecy performance due to the fact that the selected modulation orders in this case would be close to optimal with respect to only the legitimate receiver, resulting in a better performance; whereas the selection would be random with respect to the eavesdropper's channel, resulting in no favorable gain to the eavesdropper.

Most of the works in the literature have focused on securing the transmission of OFDM with conventional constellation modulation, whereas very little amount of works have appeared on securing the other new types of modulation such as index modulation [46], [61]. Many of the existing physical layer security may not be directly applicable due to the differences between index and conventional data symbol modulation. Therefore, new index modulation-tailored security techniques need to be developed for securing the data sent by the indices of the transmit entities. Accordingly, more research attention should be focused on the joint security of both the information sent by indices and that sent by signal constellations.

C. ROBUSTNESS TO MULTI-ACCESS AND NARROW BAND INTERFERENCE

1) MULTI-ACCESS INTERFERENCE (INTER-USER INTERFERENCE)

Due to the enormous increase in the amount of machine and IoT devices that are expected to be served (often simultaneously and sporadically) by communication networks; there is an apparent, formidable need to reduce the amount of control and signaling overhead required to coordinate among users as it causes severe spectral efficiency loss and intolerant delay in the network [62]. Recently, there is a shift from coordinated, orthogonal systems such as legacy LTE networks to uncoordinated, asynchronous, and non-orthogonal systems. However, these uncoordinated, asynchronous networks would result in interference between users, degrading reliability as a consequence of reduced SINR.

To address this problem, techniques based on the usage of filtering, windowing, and guard bands are investigated in [63] as natural, classical solutions to deal with this multi-user interference issue; however, these traditional solutions have drawbacks such as increasing computational complexity and reducing spectral efficiency. To address the interference between adjacent users in a more efficient manner, it has recently been shown in [64] that OFDM-IM with some modification on the subcarrier selection process has the potential to effectively alleviate adjacent user interference in asynchronous transmission systems. This has been achieved by using a data to subcarriers mapping method that gives higher activation probability to the subcarriers located in the center of each subblock. Another alternative solution to adjacent interference problem can be realized and well handled with an even better performance by OFDM-SNM scheme as the activated subcarriers in this type of modulation can be easily localized in the center of the subblocks (away from the edges of the subblocks).

2) NARROW-BAND INTERFERENCE

The OFDM-IM and OFDM-SNM schemes are more robust and immune to narrow-band interference than OFDM with conventional constellation modulation. The reason for that lies in the fact that in IM and SNM, OFDM symbols have a sparse nature, which results in less interference effect. One of the main reason for narrow-band interference in 5G and beyond communication systems is the emergence of new services such as URLLC ones that are basically placed and installed in a small resource portion within the data packet. Such an integration for URLLC packet causes a narrowband interference to the hosting original data packet [65], resulting in a severe performance degradation at the receiver. Due to the sparse characteristics of this type of interference, it is possible to mitigate it using special modulation schemes that do not utilize all subcarriers of the OFDM structure for transmission.

Consequently, the investigation and analysis of the capability of sparse modulation schemes such as OFDM-SNM and OFDM-IM in mitigating narrowband interference (especially for URLLC services) can be a subject of future research studies.

D. PAPR REDUCTION

The OFDM-based waveforms suffer from a high PAPR, the survey in [66] includes several methods proposed to solve the PAPR problem in OFDM. To address the high PAPR problem, inherited from OFDM, in the other featured modulation options for OFDM-based waveforms, one may suggest to directly borrow the algorithms that proposed for classical OFDM. However, those techniques may not be very efficient because they do not consider the unique characteristic and features of the aforementioned modulation options for OFDM. Just recently, a few approaches for reducing the PAPR of index-based modulation schemes have appeared in the literature for OFDM-IM and SM-OFDM, respectively, as explained below.

1) PAPR reduction techniques in OFDM-IM system: OFDM-IM suffers from a high PAPR problem inherited from conventional OFDM [67]. The method in [68] has been proposed to solve this PAPR issue in OFDM-IM by exploiting the inactive subcarriers in OFDM-IM. It was shown that this method outperforms the selective mapping (SLM) and active constellation extension (ACE) presented in [66]. However, this method requires high computational cost for the PAPR reduction. A low computational complexity PAPR reduction method has been proposed in [50] for OFDM-IM system, and it considerably outperforms ACE in PAPR reduction with a slight degradation in BER. Moreover, Kim [69] proposed a

scheme where the dither signals could be given more freedom (a larger radius of dithering) in average, where much better PAPR reduction performance than the scheme in [68] has been obtained at the expense of a slight BER performance degradation compared to the original OFDM-IM signal case.

2) PAPR reduction techniques in SM-OFDM system: The major disadvantage of MIMO-OFDM system is having high levels of PAPR [70]. In the literature, several algorithms proposed to reduce PAPR in SM-OFDM systems. Examples of techniques which are used for PAPR reduction of SM-OFDM systems are directed selected mapping (d-SLM) [71] and spatial shifting (SS) [72]. However, there is a need for finding much better PAPR reduction techniques for SM-OFDM transmission scheme, since such a system exhibits greater sensitivity to the signal in the HPA clipping than V-BLAST OFDM technique for the same spectral efficiency and number of antennas [51].

As seen from the literature, only a few number of studies are available on the PAPR reduction for specific OFDM modulation options. Therefore, there is a need for exploring more suitable PAPR reduction techniques for different modulation options of OFDM-based waveforms.

VI. CONCLUSION

In this paper, various modulation options for the OFDM waveform are reviewed, investigated, classified and compared in terms of their reliability, SE, PAPR, PE, OOBE and their complexities performances. Signal plane dimensional-based classification is used to categorize the possible modulation options as: OFDM-DM and conventional and adaptive OFDM modulations exploit 2-D signal plane. SM-OFDM, OFDM-IM, OFDM-SNM, OFDM-PSM, and other additional OFDM-PPM exploit 3-D signal plane. As a conclusion, SM-OFDM can be preferred for its improved reliability, OFDM-IM for its high power efficiency, conventional OFDM and OFDM-DM for their simple transceiver structure, OFDM-PSM for its low OOBE, OFDM-SNM for its higher throughput when channel conditions allow BPSK modulation, and OFDM with adaptive hybrid modulation for its QoS based adaption. In addition, the connection between these different modulation candidates and the requirements of future 5G networks is illustrated. The paper is then concluded with some insightful recommendations and future research challenges.

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