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# Spectral Efficiency Enhancement Based on Sparsely Indexed Modulation for Green Radio Communication

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**ABSTRACT** Jointly enhancing both energy efficiency (EE) and spectrum efficiency (SE) of modulation schemes becomes one of the main issues for 5G mobile communications. Recently, an indexed modulation (IM) technique provides an interesting tradeoff between EE and SE. Data can be conveyed through the combination of subcarriers pattern that can be divided between activated/non-activated subcarriers in the frequency domain. Maximum SE can be attained at half subcarrier activation, hence producing symbols with half energy of the conventional orthogonal frequency-division multiplexing (OFDM) system. In this paper, alternatively, the new concept of sparsely indexing modulation (SIM) on overall subcarrier space is clarified. Sparse (few) subcarrier activations provide much higher EE, while the combinatorial indexing of the sparse subcarriers on the overall subcarriers as a single group spans huge combinatorial space that provides approximately the same SE of the plain OFDM system. The fallacy of indexing difficulty on overall subcarrier space without grouping is resolved. Moreover, a further SE improvement is suggested by introducing permutation-based indexing and combinatorial indexing on over-complete dictionaries. Sparsely indexing represents the cornerstone, which enables compressive sensing tools to enforce IM gains. Based on the conducted simulations, the proposed SIM scheme outperforms the conventional OFDM system in terms of the error performance, the peak-to-average power ratio, and the EE with the same spectral efficiency without channel coding complexity. The proposed SIM scheme is considered one of the energy saving-oriented modulations.

**INDEX TERMS** Index modulation, sparse index modulation, OFDM, OFDM-IM, double data/channel sparsity, critical sparsity, combinatorial/permutational indexing, overcomplete/non-orthogonal dictionary indexing, green modulation.

## I. INTRODUCTION

In this paper, sparse multicarrier indexing approach is introduced as a sub-class from the OFDM-IM. The proposed scheme is concerned in satisfying green radio requirements through extending frequency indexing to sparse orthogonal/non-orthogonal multicarrier indexing. Sparse multicarrier mapping besides natural channel multi-path sparsity add another advantage of the so-called ''double sparsity''. Recently, the prior-knowledge of the signal sparsity prompts better system processing under compressive sensing (CS) based signal processing approaches.

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### *A. GREEN MODULATION*

Green cellular network relays on the integration of many strategies for minimizing energy at both the base station (BS) and the user equipment (UE) [1], [2]. The growing tendency for employing an energy efficient communication network is accompanied with encountering the unlimited growth in data demands/network capacity [3]. Saving in signal transmission (green radio) represents an essential aspect affecting the overall energy saving. Modulation schemes aims at maximizing both spectral efficiency (SE) and the energy efficiency (EE) independently fall at conflicting goals; however, certain joint optimization should be attained [4].

Although immigration towards millimeter wave (mm-wave) band 30 $\sim$ 300 GHz provides huge spectral resources enough for satisfying data rate needs, it has a very limited coverage range due to extremely high propagation loss. Moreover, due to some technology constrains, by increasing carrier frequency the capability of providing high output power decreases. Hence, the power efficiency at mm-wave band is much worse than micro-wave band [5]. Therefore, power consideration besides other factors; govern the choice between the lower power single carrier and the higher power multi-carrier modulation schemes in mm-wave band. Therefore, enhancing EE of the employed modulation scheme (or reducing energy per transmitted bit) becomes more critical issue for the operation in mm-wave band. On the other hand, multi-carrier transmission is not recommended for uplink transmission from the battery-based mobile systems as it has a high peak-to-average power ratio (PAPR).

### B. INDEXED MODULATION OVERVIEW

Green radio or green modulation can be addressed through the advance of index modulation (IM) where the data can be conveyed through on/off combinatorial subcarrier modulation. OFDM-MFSK [6] can be regarded as the primary form of the index (combinatorial) modulation where the frequency domain is divided into groups of subcarriers and the data is conveyed by activating only one subcarrier out of $m$ subcarriers per group.

Currently, an increasing research attention is given for what the so-called OFDM-IM [7]–[9], [12] that is the combination of conventional OFDM with indexed modulation (IM). The main motivation for that resides in providing a trade-off between SE and EE. Another advantage of IM appears in the enhanced robustness of the loaded data on subcarrier indices compared to the data conveyed on conventional amplitude-phase constellation [7].

In the conventional OFDM-IM, the half numbers of subcarriers are activated per group for maximizing the SE of index modulation. For instance, regarding the OFDM-IM scheme, consider $k$ active subcarriers out from $m$ subcarriers per group, then the corresponding combinatorial space includes number of different states equals to $C(m,k) \equiv \binom{m}{k} = \frac{\mathrm{m!}}{\mathrm{(m-k)!k!}}$, where, (:) is the binomial coefficient and ! stands for the factorial multiplication. Hence, the equivalent encoded bits are $\lfloor log_2 C(m,k) \rfloor$ bits per subcarrier group where, $\lfloor . \rfloor$ denotes the floor to the nearest integer. SE can be increased using modulating the activated signal by quadrature amplitude-phase modulation. So, it conveys $\lfloor log_2 C(m,k) \rfloor + kLog_2(M_{QAM})$ bits per subcarrier group, where $M_{QAM}$ is the number of QAM constellation states. However, loading additional data on symbol constellation leads to some degradation in the bit error rate (BER) performance. This scheme relays on group (block) indexing for mitigating indexing complexity increases. Maximum spectral efficiency of IM can be attained under the half number of subcarrier activation. Hence, energy saving resulting from the OFDM-IM symbol is limited to the half of conventional OFDM symbol. Another SE improvement in OFDM-IM system is introduced as the generalization of IM (OFDM-GIM) [9] by, 1) increasing the combinatorial space through allowing a variable number of activated subcarriers from one subcarrier to the half number of subcarriers per group, 2) the independent indexing on in-phase and quadrature subcarrier spaces where the combinatorial indexing is performed twice in the real and imaginary spaces, consequently, the constellation of activated subcarrier will be limited on BPSK constellation.

In [13] and [14], there is an interesting SE enhancement approach through QAM modulating all subcarriers while the additional IM is attained through dividing subcarriers into two different constellation groups (dual-mode). However, transmitted symbols have high power levels without turning-off any subcarriers as in the plain OFDM system. Generalization of the dual mode indexing is introduced in [15] and [16] through the so-called multi-mode-OFDM-IM (MM-OFDM-IM). In the MM-OFDM-IM system, all subcarriers are activated while the corresponding QAM symbol constellation is drawn from many distinct groups. Moreover, multi-mode constellation provides an enlarged indexing domain via permutational indexing where ordering of the subcarrier group is carried out using the mode order. However, the effective QAM order becomes higher than the individual subcarrier QAM order. It is providing much higher spectral efficiencies through permutational indexing over the dense QAM plane rather than the essential ON/OFF subcarrier indexing. For instance, to create permutational 8 modes, 16-QAM constellation is employed where each mode is assigned to 2 different QAM states, that provides an effective BPSK subcarrier modulation while the subcarrier group introduces a permutaional indexing.

Really, IM is not limited to the frequency indexing, but extends to multidimensional indexing (space antenna [17]–[19], [21], time, code [22]–[24], radio frequency mirrors [25]–[28] or any communication resources) [29]–[31]. Jointly indexing in multidimensional communication resources exhibits some sparsity degree in the transmitted signal. Consequently, compressive sensing (CS) can be leveraged effectively for improving the overall performance.

For enhancing the spectral efficiency, combinatorial domain is enlarged through assuming indexing in a virtual digital domain [32] of higher dimension than the subcarrier domain. This assumes sparsity in the supposed virtual digital domain of higher dimension. Then CS mapping is performed to the frequency domain with lower dimension. In this case, there is no sparsity in the true frequency domain; all subcarriers are activated in each group.

An interesting practical real-time examination of OFDM-IM is introduced in [33], through software defined radio

(SDR) implementation. FPGA-based implementation of space shift keying (SSK) is introduced in [34].

Recently, permutational (rather than combinatorial) index modulation over multiple consecutive time slots is introduced in [35] and [36]. There is only one activated subcarrier per subcarrier group. The ordering is performed through the time slot order.

At this end, it is worth to emphasize on the energy saving as the most significant prospected attributes of the IM. Hence, IM has been emerged as the best modulation scheme satisfying energy restrictions in wireless sensor networks (WSN) and internet-of-things (IOT) [37]–[39].

In general, IM offer many performance enhancements through occupying less communication resources [12], but, what is the degree of the less activation?. Usually, in OFDM-IM, activating the half number of subcarriers is suggested for maximum spectral efficiency (SE) [7]. So, the claimed maximum SE does not exhibit any sparsity.

Recently, extreme IM starvation is introduced in [40]–[42] as sparsely index modulation that will be discussed/enhanced deeply in this paper.

### C. CURRENT TRENDS FOR NON-ORTHOGONAL MODULATION

OFDM plays a major role in the current standardization of the wireless communication, as in the long-term evolution (LTE) cellular system along 3GPP standardization and wireless local area network (WLAN) along IEEE802.11 standardization. However, for the next generation wireless communication, it is recommended to replace OFDM with non-orthogonality-based communication schemes. Non-orthogonality may be generated through decreasing the frequency spacing between subcarriers or smoothing the waveform shaping rather than rectangular waveform. Non-orthogonal waveform shaping such as filter bank multicarrier (FBMC) provides better spectrum usage on the cost of increasing the recovery complexity. On the other hand, OFDM may loss the orthogonality advantage through Doppler frequency shift, or carrier frequency offset (CFO). Getting rid of orthogonality limitations of the OFDM, and relaying on new non-orthogonal waveform designs are addressed in [43]–[48]. Moreover, as reported in [47], the employment of non-orthogonal pulses is optimum for minimizing ISI and ICI in double dispersive channels.

In [48], a scheme of non-orthogonal multi-tone MFSK is regarded as non-orthogonal index modulation on a single subcarrier group. The SE of MFSK is enhanced by relaxing the orthogonality constrains in the tone space. The same bandwidth can be covered by higher number of non-uniformly spaced non-orthogonal tones (symbol constellation). Under equal SE, the target outperforms the corresponding orthogonal MFSK in terms of error performance. The optimum choice of these non-orthogonal tones is performed by non-exhaustive searching algorithm. The searching objective is to minimize the worst-case correlation between any two selected tones [48]. It may be regarded as a type of dictionary training. This scheme has succeeded in outperforming the corresponding orthogonal MFSK with the small number of subcarriers. On the other hand, it doesn't improve the error performance over indexing of large number of subcarriers.

### D. LEVERAGING OF COMPRESSIVE SENSING (CS) IN COMMUNICATION SYSTEMS

Recently, CS has emerged as a powerful signal processing tool on the condition of signal sparsity in certain domain. It exhibits a superior signal recovery performance even with under sampled signals. Many applications of CS in wireless communication system are addressed in [49]–[56]. For instance, CS employment in the context of Wireless sensor networks (WSNs) [51] requires inherent signal sparsity for providing reliable communication link under low power transmission/lossy channel without channel coding overhead. Also, many practical wireless channel behaviors can be modeled by impulse response with few and distributed number of paths (taps) with different Doppler spread for each path (channel's delay-Doppler sparsity). This channel sparsity phenomenon allows CS-based sparse channel estimation [52]–[56] that provides much better accurate channel estimation through less training pilots.

### E. DATA/CHANNEL DOUBLE SPARSITY: ADVANTAGES AND MOTIVATIONS

Normally, double sparsity, the data sparsity besides channel sparsity can't be attained under the conventional multicarrier systems neither in the time-domain nor in the frequency domain. On the other hand, in the ultra-wide band (UWB) communication [56], there is an explicit double sparsity represented in the transmission of sparse data pulses over sparse channel impulse response. Hence, the same CS-based algorithm (and consequently the same hardware) can be exploited for joint data detection and channel estimation under low speed (sub-Nyquist sampling rate) of the analog-to-digital converter (ADC) which provide power saving at the receiver side. This represents the main motivation for us to gain similar performance for the multicarrier index modulation. Therefore, IM is adapted for exhibiting similar double sparsity such as the UWB communication. To do that, artificial sparsity in multicarrier (MC) data is presented through combinatorial based sparsely mapping in the frequency domain.

### F. CONTRIBUTIONS

In this paper, the main contributions can be summarized as follows:

- The new concept of the sparse index modulation [40], [41], is clarified. The main design point resides in pursuing the upper bound of energy efficiency without losing the spectral efficiency.
- Based on complexity validation, sparsely indexing modulation (SIM) enables frequency indexing on the whole subcarrier domain without grouping.

- Due to the created sparsity encoding in the frequency domain, compressive sensing (CS) concept is enabled for efficient sparse signal detection and sparse channel estimation under low signal-to-noise ratio (SNR) levels without channel coding/decoding.
- Explicit signal sparsity offers an increased noise-immunity that provides better BER performance at much low SNR levels without channel coding. Bypassing channel coding relaxes the related computational complexities (time relaxation) and energy consumption in both encoding/decoding processing and radio transmission of the redundant bits.
- However, instead of the traditional adaptation of the channel coding rate to the varying channel state conditions, an alternative CS-based strategy is introduced.
- The concept of critical sparsity is clarified from a communication point of view. The proposed sparsity adaptation strategy relays on maintaining a minimum sparsity level for achieving approximate error-free detection.
- Many capabilities can be extracted from CS to provide remarkable performance enhancement in the multicarrier communication. Many of results will be highlighted.
- Similar to the work introduced in [48], the combinatorial space can be expanded through indexing on non-orthogonal tones, along with sparsely indexing on large number of subcarriers and CS-based signal processing tools. The non-orthogonal tones are distributed uniformly without learning efforts.
- Further, SE enhancement through combinatorial/ permutational indexing on complete (orthogonal)/ over-complete (non-orthogonal) Fourier dictionaries. The work is introduced based on SIM concept and super-resolution features based on the CS sparsity estimation.
- Permutation indexing is performed for enlarging the indexing space in different manner than that introduced in [13]–[16] and [36].

The rest of the paper is organized as follows: Section II reviews the spare indexing modulation concept including the main features and the generation/detection process. Section III introduces the proposed combinatorial/ permutational indexing on complete/over-complete indexing and the main design parameters. Section IV provides a sparsity-based problem formulation and the critical sparsity concept. Computational complexity is discussed in section V. Section VI presents the simulation results. Finally, conclusion and further work are introduced in Section VII.

## II. SPARSE INDEX MODULATION OVERVIEW

In this section, the main concept of SIM [40], [41], is reviewed. Consider activation of $N_s$ subcarriers out from $N_T$ available equally spaced (orthogonal) subcarriers whose indices are $\{0, 1, 2, \ldots\ldots\ldots\ldots, N_T - 1\}$ irrespective of the order of selection. So, any combinatorial pattern C(m,k) can be represented with a set of indices as follows:

$$C\left(m, k\right) \equiv C\left(N_T, N_S\right) \equiv \binom{N_T}{N_S} = \{c_k, c_{k-1}, \ldots, c_2, c_1\}, \tag{1}$$

where, $N_T - 1 \geq c_k > c_{k-1} > \cdots > c_1 \geq 0$. According to combinatory, any combination can be indexed by unique number (such as lexicographic order) that can be found rapidly as

$$I = \binom{c_k}{k} + \ldots\ldots + \binom{c_2}{2} + \binom{c_1}{1}. \tag{2}$$

In the sparse index modulation, the bit stream is regarded as an index of a certain combination of subcarriers in frequency domain. So, the combinatorial mapping/de-mapping is performed in transmitter/receiver side. The complexity of mapping/de-mapping will be discussed later in details.

### A. MAIN SIM FEATURES

SIM can be regarded as a sub-class of the well-known IM [7], however, there are some strength points that characterize SIM as follows:

- While the superior energy performance promotes the research in the IM direction, the proposed SIM [40], [41] was introduced for exploring the limiting edge of the EE maximization without the SE sacrifice.
- Unlike the IM, the proposed SIM scheme is based on creating equivalent combinatorial states through the combinatorial mapping/un-mapping on the whole number of subcarriers without grouping.
- The number of activate subcarriers conserves the frequency domain sparsity, $N_S << N_T$, for satisfying the essential requirement of energy saving that represents the main design criteria, while obeying the CS constraint.
- On the other hand, conventional IM activates the half number of subcarriers to maximize the SE of the IM along group-based indexing (rather than single group indexing) to mitigate the exhaustive complexities of the index mapping/de-mapping and the maximum likelyhood (ML) detection.
- In the proposed SIM, complexity of indexing mapping/ de-mapping is relaxed by employing better indexing algorithms [57], [58] with lower complexity cost.
- Fortunately, the bit stream/combinatorial subcarrier mapping draws more attention. For instance, in [59], the mapping is based on designing a codebook adapted to the instantaneous channel state information (CSI).
- By relaying on CS superiority, SIM does not need channel coding/decoding. Hence, for a fair comparison with the conventional OFDM/OFDM-IM schemes, the comparison should be carried out based on the data without the channel redundancy. Moreover, simple energy

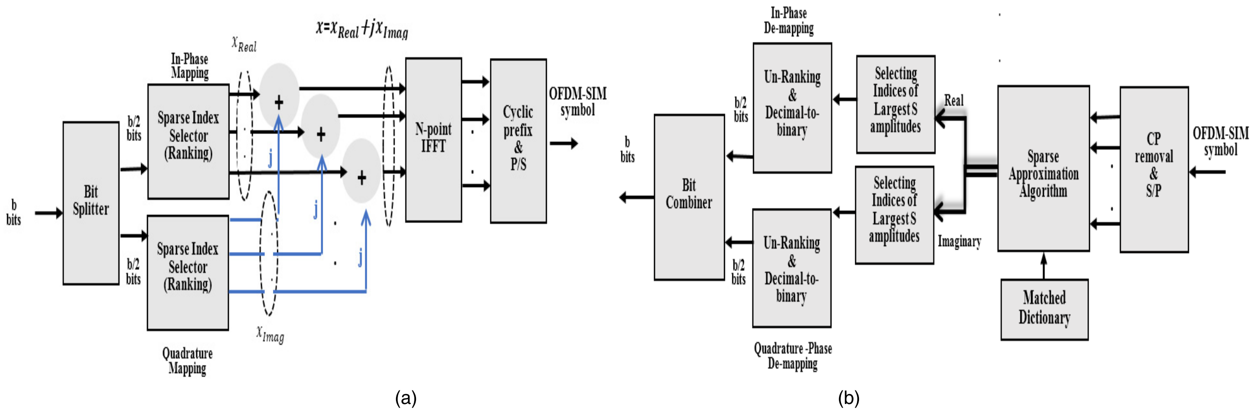


**FIGURE 1. Block diagrams for (a) SIM transmitter and (b) SIM receiver.**

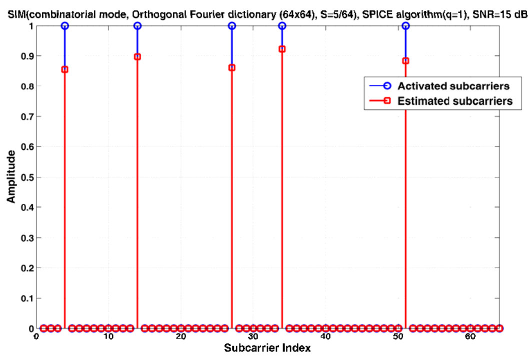


**FIGURE 2. Sparsely activating (indexing) in OFDM-SIM.**

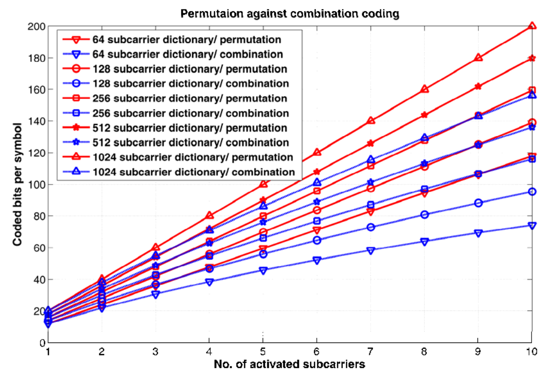


**FIGURE 3. Encoded bits per symbol under various dictionay size, combinatorial/permutational indexing and sparsity order.**

detection is employed after sparsity approximation algorithm.

### *B. SIM GENERATION/DETECTION*

Independent indexing on in-phase and quadrature subcarrier spaces is introduced as in the OFDM-GIM system. Therefore, combinatorial indexing (Eq. 1) is carried out twice to provide two groups of sparsely activated subcarriers in real space ($C_{Real}$) and in imaginary space ($C_{Imag}$). Transmitter/ receiver block diagram is shown in Fig.1. An example of sparsely activated subcarriers is given Fig.2, where the bit stream mapping selects only 5 sparcse-subcarrier from 64 allocated subcarriers.

In the transmitter side, data stream is divided into two blocks for real/imaginary subcarrier indexing. Each bit block represents the combinatorial index (address) for certain combination of $N_S$ active subcarriers per the real/imaginary space. Then, activated subcarriers from the real/imaginary spaces are combined in the frequency domain to be converted to the time domain signal through IFFT operation. At the end, CP is added.

On the receiver side, CP is removed, and the channel effect will be equalized before applying the sparse detection approach. Real/imaginary indices will be extracted by applying simple energy detection technique. The activated subcarrier group is regarded as the $N_S$ subcarriers with higher power. Then combinatorial de-mapping is applied to provide the index corresponding to each subcarrier combination. The detected indices are converted to the corresponding binary representations and are combined.

## III. PROPOSED SPARSELY INDEXING SCHEME

By inspecting the resulting combinatorial coded bits $b_{SIM} = 2Log_2\left\{\binom{N_T}{N_s}\right\}$ *bits*, which can be further improved by increasing either $N_T$, $N_S$ or both. However, the increase of $N_S$ is limited by the sparsity constraint while the increase in $N_T$ is limited by allocated spectral constraint.

The main target is to expand the combinatorial space spanned without increasing the allocated bandwidth (BW). The proposed work in this paper introduces three mapping techniques to enhance the SE of the proposed SIM without increasing allocated spectral BW. Total number of indexed subcarriers can be increased by employing more dense the non-orthogonal subcarriers. Hence, it can be considered indexing on over-complete dictionary. Also, resulting combinatorial space can be increased by providing a way for ordering selected (activated) subcarriers. Hence, combinatorial

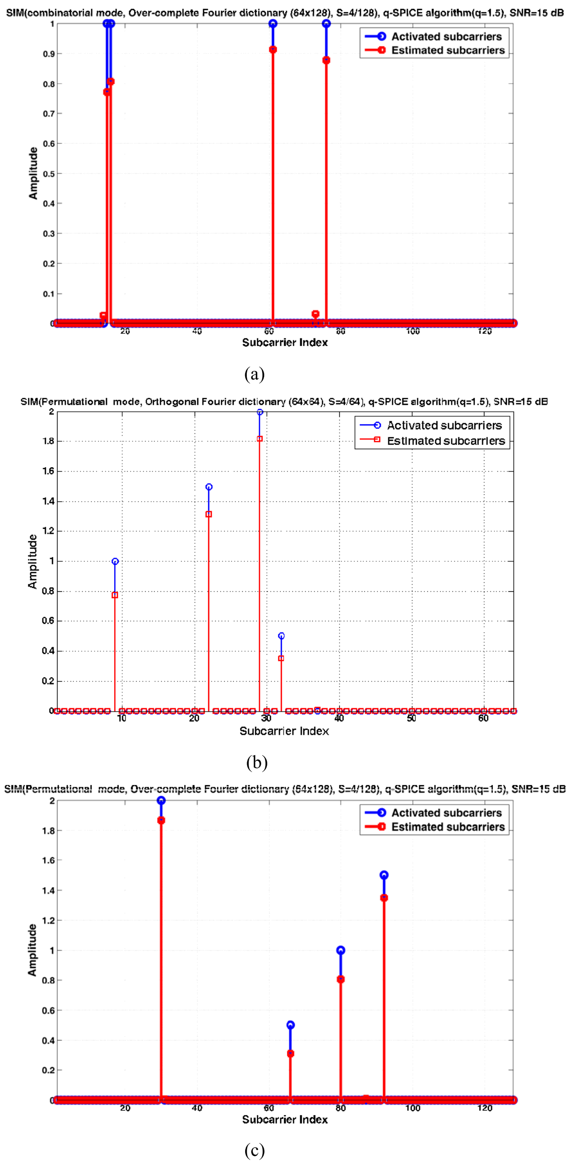


**FIGURE 4. Sparsity recover from Fourier dictionary. (a) SIM with combinatorial mode, Over-complete Fourier dictionary (64 × 128), S = 4/128 and q-SPICE algorithm (q = 1.5), SNR = 15 dB. (b) SIM with Permutational mode, Orthogonal Fourier dictionary (64 × 64), S = 4/64) and q-SPICE algorithm (q = 1.5), SNR = 15 dB. (c) SIM with Permutational mode, Over-complete Fourier dictionary (64 × 128), S = 4/128) and q-SPICE algorithm (q = 1.5), SNR = 15 dB.**

indexing is replaced by permutational indexing. Permutational indexing can be performed on over-complete dictionary that means generating corresponding indexed states with lower number of activated subcarriers. Figure 3 compares the encoded number of bits per symbol with the orthogonal dictionary (64 atoms) and the over-complete Fourier dictionaries (128, 256, 512, 1024 atoms), with different sparsity order. It is clear that the length of the encoded bits per OFDM-SIM block increases by increasing the number of combinatorial activated subcarriers ($N_S$), the subcarrier space ($N_T$) or through the permutational indexing. Figure 4 demonstrates the three proposed solutions for indexing over Fourier dictionary.

### A. COMBINATORY ON OVER-COMPLETE DICTIONARY

Number of available subcarriers $N_T$ can be increased by decreasing the frequency spacing (fine frequency grid) in Fourier dictionary that becomes non-orthogonal dictionary. In this case, the number of columns in the matrix becomes larger than the number of rows ($N_T > M$) where the columns should be normalized to ensure equal energy for non-orthogonal subcarriers (atoms). Reduced frequency spacing may be regarded as a way for increasing the spectral efficiency by increasing the size of the combinatorial space. In another word, the same data rate can be attained through increasing the number of the available subcarriers (non-orthogonal) along with reducing the number of the selected (activated) subcarriers as in Fig.4.a. In this case, classical Fourier analysis suffers from spectral leakage, while spectral compressive sensing provides a promising performance. CS algorithms can be simply extended to sparse spectrum detection for non-orthogonal subcarriers by considering the matched dictionary. Super-resolution abilities of CS can be exploited to decompose the signal into its sparsest components from proper over-complete/non-orthogonal dictionary. Some attention should be paid to mutual coherence between dictionary vectors and matched operating SNR for proper recovery. In other words, the corresponding critical sparsity should not be exceeded to avoid losing the CS advantages. From the SE perspective, critical sparsity confines SE upper bound of the sparsely indexing scheme.

### B. PERMUTATIONAL INDEXING

Permutational indexing provides larger space than combinatorial space; however, activated subcarriers should by order. In this paper, ordering is performed based on allocating different (unique) amplitudes for activated subcarriers. In this case, the resulting permutational space is

$$P\left(N_T, N_S\right) = \frac{N_T!}{(N_T - N_S)!} = N_T(N_T-1)(N_T-2)\cdots(N_T-N_S+1)$$

which is larger than the resulting combinatorial space.

Sparsely coded subcarriers are assigned different amplitudes, such as $\{0.5, 1, 1.5, 2\}$ for providing ascending order of the four activated subcarriers as shown in Fig.4.b. It is performed in the same time slot. Also; it is worth to mention that the proposed ordering does not rely on multi-QAM symbol constellation as in [13]–[16].

### C. PERMUTATION INDEXING ON OVER-COMPLETE FOURIER DICTIONARY

Both former solutions can be combined by applying the permutation indexing on over-complete, as shown in Fig.4.c. In this case, the same indexed space can be created by activating a smaller number of subcarriers but with the cost of increased error rate. In general, permutational indexing has

**TABLE 1.** **Basic design metrics (where $M_{QAM}$ denotes symbol constellation).**

| | Plain OFDM | Proposed OFDM-SIM |
|---|---|---|
| $\boldsymbol{N_{Active}}$ Active subcarriers | $N_T$ | $2N_S\ (<< N_T)$ |
| $\boldsymbol{b_{net}}$, bits | $R_{cc}\ N_T Log_2\{M_{QAM}\}$ | $2\ Log_2\left\{\binom{N_T}{N_S}\right\}$ |
| SE ratio ($\boldsymbol{\eta_{SE}}$) | 1 (OFDM as baseline) | $\frac{2\ Log_2\left\{\binom{N_T}{N_S}\right\}}{R_{cc}\ N_T Log_2\{M_{QAM}\}}$ |
| EE ratio ($\boldsymbol{\eta_{EE}}$) | 1 (OFDM as baseline) | $\frac{\eta_{SE}}{S} = \frac{\mathcal{R}_{SIM}}{S\,\mathcal{R}_{OFDM}}$. |
| Maximum theoretical PAPR | $10\ Log_{10}\{N_T\}$ (for $M_{QAM} = 4$) | $10\ Log_{10}\{N_S\}$ |

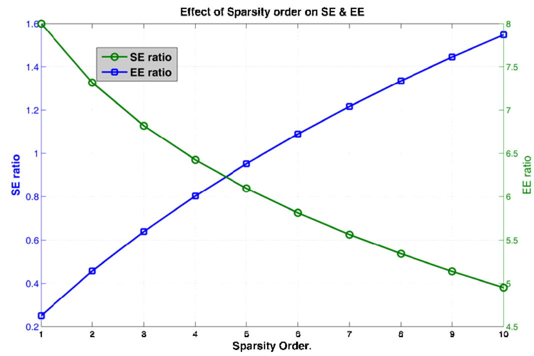


**FIGURE 5.** **Effect of sparsity order on SE and EE ratios w.r.t conventional OFDM (IEEE802.11a).**

less noise-immunity than combinatorial indexing. This is due to the simplicity of combinatorial that requires only identifying activated subcarriers irrespective of relatively estimated amplitudes which affects ordering in permutational indexed case.

### *D. MAIN SIM DESIGN PARAMETERS*

Table 1 summarizes the main design metrics relative to plain OFDM system as a baseline. The number of active subcarriers ($\mathbf{N_{Active}}$) is the main factor affecting the overall performance. Under the proposed SIM, there are $2N_S(<< N_T)$ active subcarriers at most, while the OFDM scheme activates the total number of subcarriers ($N_T$). Hence, under the same transmitted power, activated subcarriers in SIM scheme gain higher power than the individual subcarriers of the OFDM system. The receiver is relaxed to only discriminate between that activated group along higher power and null subcarrier group irrespective of the exact amplitude/phase of each subcarrier. The exact number of bits per transmitted symbol $b_{net}$ is found for the OFDM system by regarding the added redundancy bits represented by the channel coding rate ($0 < R_{cc} < 1$).

Nearly, most subcarriers $N_T$, half number of subcarriers $\frac{N_T}{2}$ and $2N_S(<< \ N_T)$ subcarriers are activated in OFDM, OFDM-IM and OFDM-SIM schemes, respectively. So, the OFDM-SIM has an energy saving factor of $(1 - S)$ w.r.t OFDM where$S = 2N_S/N_T$ denotes the sparsity order (or the energy ratio).

By regarding the plain OFDM system as a reference scheme, normalizing to the OFDM [9], SE ratio ($\eta_{SE}$) and EE ratio ($\eta_{EE}$) can be given as follows,

$$\eta_{SE} = \frac{\mathrm{R}_{SIM}}{\mathrm{R}_{OFDM}} = \frac{2Log_2\left\{\binom{N_T}{N_s}\right\}}{R_{cc}N_T Log_2\{M_{QAM}\}}, \tag{3}$$

$$\eta_{EE} = \frac{\eta_{SE}}{S} = \frac{\mathrm{R}_{SIM}}{S\mathrm{R}_{OFDM}}. \tag{4}$$

For a given (allocated) number of subcarriers, $N_T$, changing the sparsity order, $S$, (by changing the number of activated subcarriers, $N_S$,) has a different impact on both SE and EE. For maximizing SE, the combinatorial space should be increased by increasing $N_s$, but, this reduces the sparsity order and consequently reduces EE. However, a huge combinatorial space can be attained by following the sparse indexing (very low $N_s$) over un-grouped subcarrier space. Hence, the resulting combinatorial space, $\binom{N_T}{N_s} = \frac{N_T!}{(N_T-N_S)!N_S!}$, compensates the sparseness of selected subcarriers ($N_S$) by selecting them from a large number of subcarriers ($N_T$) without grouping.

To achieve a comparable SE while maintaining sparsity constrains, the proposed scheme should set against the conventional coded OFDM operating at low *QAM* order. Usually, the proposed sparse index modulation provides comparable performance to that of OFDM-QPSK modulated signal. In another words, proposed scheme provide high performance at lower SNR levels (without channel coding) where the conventional OFDM must work at low QAM orders (BPSK & QPSK) along low channel coding rate to provide reliable communication. Figure 5 demonstrates the effect of increasing $N_s$ on both SE and the EE compared to corresponding standard IEEE802.11a; using 64 allocated subcarriers, QPSK modulated along 1/2 channel coding rate. A higher EE can be attained under any sparsely indexing while a just comparable or higher SE may be attained through satisfying the following

$$2Log_2\left\{\binom{N_T}{N_s}\right\} \geq R_{cc}N_T Log_2\{QAM\}\,(5) \tag{5}$$

i.e.

$$\binom{N_T}{N_s} \geq QAM^{\left(\frac{R_{cc}N_T}{2}\right)}. \tag{6}$$

## IV. SPARSITY-BASED PROBLEM FORMULATION

The proposed SIM exhibits an explicit sparsity in frequency domain that inspires replacing the conventional signal processing tools by more robust CS-based signal processing tools. So, a short overview is introduced about the sparsity-based solutions. Then, the concept of critical sparsity is highlighted from a communication point-of-view. Moreover, many gains of the enabled CS algorithms are emphasized.

### A. CRITICAL SPARSITY CONCEPT

By increasing the size of the employed dictionary (redundant over-complete), it is most likely to have sparser representation or more indexing constellation space. However, increasing the number of candidate atoms increases the mutual coherence (correlation) between dictionary atoms that degrades the overall performance. This is resolved through the so-called continuous CS (grid-less CS) where continuous parameter estimation is allowed without discretization limit [60]–[66]. However, there is a maximum or critical sparsity [64] level that should not be exceeded in order to provide free-error recovery (100% correct sparsity recovery). This interesting concept of the critical sparsity can be regarded from a communication point-of-view to attain zero bit error rate (BER). Under the proposed sparsity encoding, maintaining subcarrier activation ratio (sparsity level ($S = N_S/N_T$)) under critical point guarantees free error performance. Moreover, the critical point may be varied with the operating SNR value and depends on the applied algorithm. SNR level corresponding to critical sparsity depends on the employed dictionary for indexing. Over-complete dictionary exhibits the same critical sparsity level for the orthogonal dictionary but at higher SNR levels.

### B. SPARSITY APPROXIMATION ALGORITHM

The SIM can be regarded as a spectral line estimation problem where the receiver role is to discriminate the sparsely activated subcarriers out from the total number of allocated subcarriers.

More specifically, consider Fourier matrix (dictionary) for spectral indexing with each column represents a time domain signal of certain subcarrier.

$$F = \begin{pmatrix} 1 & 1 & 1 & \cdots\cdots\cdots & 1 \\ 1 & e^{j\omega_1} & e^{j\omega_2} & \cdots\cdots\cdots & e^{j\omega_{N-1}} \\ 1 & e^{j2\omega_1} & e^{j2\omega_2} & \cdots\cdots\cdots & e^{j2\omega_{N-1}} \\ 1 & e^{j3\omega_1} & e^{j3\omega_2} & \cdots\cdots\cdots & e^{j3\omega_{N-1}} \\ 1 & e^{j4\omega_1} & e^{j4\omega_2} & \cdots\cdots\cdots & e^{j4\omega_{N-1}} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & e^{jM\omega_1} & e^{jM\omega_2} & \cdots\cdots\cdots & e^{jM\omega_{N-1}} \end{pmatrix}$$

where $N \equiv N_T$ denotes the number of equally spaced subcarriers and M represents number of the samples. Orthogonality constraint requires $N = M$ for complete orthogonal Fourier dictionary.

The generated OFDM-SIM signal may be formed by summing the sparsely activated subcarriers in the real and imaginary spaces as follows:

$$\mathrm{y} = \mathrm{Re}\,\{\mathrm{F}\}\, X_{Real} + J\,\mathrm{Imag}\,\{\mathrm{F}\}\, X_{Imag}, (7) \tag{7}$$

where $X_{Real}$ and $X_{Imag}$ denote sparsely coded vectors for combinatorial in-phase/quadrature mapping that are consisting of zeros for all indices except combinatorial mapped indices indicated by $C_{Real}$ and $C_{Imag}$, respectively. Elements of activated indices can be taken as $\pm 1$.

Alternatively, y can be regarded as the inverse Fourier transform of $\boldsymbol{X} = X_{\boldsymbol{Real}} + JX_{\boldsymbol{Imag}}$.

From CS perspective, this problem can be regarded as a parameter approximation **X**, of the traditional linear model along a sparsity,

$$\boldsymbol{y} = \boldsymbol{F}\boldsymbol{X} + \boldsymbol{e}, \tag{8}$$

where, $\mathbf{y} \in^{\mathrm{M}}$ is the observation vector (received signal), $\mathbf{F} \triangleq (\mathbf{f_1 f_2} \ldots\ldots \mathbf{f_N}) \in^{\mathrm{M\times N}}$ is the indexed dictionary, $\mathbf{X} \in^{\mathrm{N}}$ is the unknown sparse parameter vector and $\mathbf{e}$ is the unknown additive noise. CS allows spectral estimation of signals even under a smaller number of time samples M, than the number of regression vectors, N $\equiv N_T$. The introduced solution represents the sparsest linear representation of the observation signal **y** over the Fourier dictionary. Orthogonal dictionary requires M $=$ N for sparsely indexed OFDM, while, non-orthogonal dictionary has M $< N$, which become an over-complete dictionary. Sparsity estimation problem can be thought as a spectral line estimation of the activated subcarrier group that approximates the received signal.

For instance, the well-known LASSO (least absolute shrinkage and selection operator) optimization problem imposes sparsity prior-knowledge on the cost function by $l_1$-norm as follows:

$$\arg\min_{\mathbf{x}} \frac{1}{2} \left\|\mathbf{y} - \boldsymbol{F}\boldsymbol{X}\right\|_2 + \mu \left\|\mathbf{X}\right\|_1, \tag{9}$$

where $\|.\|_1$ stands for $\ell_1$-norm, and $\mu$ is a regularization parameter.

Many iterative solutions may be addressed for approximating the solution, for instance, sparse iterative covariance-based estimator (SPICE) [67], [68]. SPICE represents an iterative hyper-parameter free algorithm for solving the equivalent square-root LASSO problem.

Moreover, $\ell_1$-norm constrains employed to SPICE can be replaced by $q$-norm that matches the signal sparsity order through a generalized SPICE [69] or the so-called q-SPICE. It is proofed that q-SPICE ($q > 1$) outperforms the original SPICE ($q = 1$) especially under over-complete dictionary. Complete derivation and explanation can be found in [67]–[69]. Moreover, its MATLAB implementations of SPICE[1] and q-SPICE[2] are published on the author's page.

Any sparsity approximation algorithm may be employed for validating the proposed concept of sparsely indexing modulation. However, without loss of generality, we recommended to follow SPICE and q-SPICE algorithms for sparsity-based spectral line estimation. Really, the selected approximation algorithm impacts the overall performance. So, it is regarded as open point for further research to select

[1]https://www.it.uu.se/katalog/davza513.

[2]http://www.maths.lu.se/fileadmin/maths/personal_staff/Andreas_Jakobsson/code_for_q_SPICE.zip

proper detecting algorithms even under highly redundant (over-complete) dictionaries.

### C. GAINS OF ENABLED COMPRESSIVE SENSING (CS)

As reported, CS-based signal processing algorithms introduce a super-resolution spectral estimation even for over-complete dictionary [60]–[62], and higher noise immunity [63]. In the proposed scheme, the combinatorial/per-mutational indexing (on orthogonal/over-complete dictionary) is based on sparsely activating subcarriers out of all subcarrier space (without grouping). Created sparsity in data encoding is interesting from many perspectives:

1- Providing equivalent (to conventional OFDM/ OFDM-IM) data rate/SE with sparse active subcarriers that implies large energy saving/EE.
2- Lower ranking/un-ranking complexity (as proved in former section).
3- CS enabled in data detection implies enhanced noise-immunity compared to traditional signal processing tools. Hence, it allows communication under lower SNR levels.
4- CS superiority allows the operation without channel coding/de-coding without performance degradation.
5- Providing sparsity in encoded data in addition to the already existing channel sparsity. Hence, joint channel/data detection may be performed through the same algorithm that implies hardware saving.
6- Lower ADC sampling rate for both data detection/channel estimation.
7- Super-resolution capabilities of CS can be exploited to increase the combinatorial/permutational space, and consequently to further increase the SE, by indexing on over-complete (non-orthogonal) Fourier dictionary.
8- Higher EE along lower PAPR arises from activating small number of subcarriers instead of activating all subcarriers simultaneously.

## V. COMPUTATIONAL COMPLEXITY

### A. INDEXING COMPLEXITY

The problem of un-grouped indexing is reported in [7], where the complexity of index mapping/un-mapping on the whole number of subcarriers as a single group will be too cumbersome. For mitigating the combinatorial mapping complexity under indexing on the whole subcarriers space, combinatorial indexing is performed on groups having smaller number of subcarriers. Fortunately, by combinatorics investigation, lower complexity for both ranking/unranking is introduced in [57] and [58] of order $O\,(klogm)$ which provides good performance for selecting small $k$ elements out from a large $m$ element group (i.e., unranking of small combinations from large sets). Table 2 compares the main parameters affecting the indexing cost.

For instance, Fig.6 introduces a simple complexity comparison of indexing based on proposed SIM (S = 5/64) against conventional indexing on 64 subcarriers with varying the number of subcarrier groups (from 2, to 16).

**TABLE 2.** Indexing complexity cost.

| | OFDM_IM | Proposed OFDM-SIM |
|---|---|---|
| Allocated subcarriers | $N_T$ | $N_T$ |
| Subcarrier groups | $g$ | $1$ |
| subcarriers per group | $N_T/g$ | $N_T$ |
| Active subcarriers per group | $N_T/(2g)$ | $2N_S\ (<< N_T)$ |
| Indexing complexity cost | $O([N_T/2]\,log(N_T/g)\,)$ | $O(N_S\,logN_T)$. |

**TABLE 3.** Performance comparison.

| Mode | Orthogonal / Non-orthogonal | $N_T$ | $N_S$ | Coded bits | Free error SNR (dB) | PAPR improvement over OFDM (dB) | $\eta_{SE}$ | $\eta_{EE}$ |
|---|---|---|---|---|---|---|---|---|
| Combinatorial | Orthogonal | 64 | 5 | 45 | 4 | 2 | 0.93 | 5.99 |
| | Non-orthogonal | 128 | 4 | 46 | 10 | 3 | 0.95 | 7.66 |
| | | 128 | 5 | 55 | 10 | 2 | 1.14 | 7.33 |
| Permutational | Orthogonal | 64 | 4 | 47 | 10 | 4 | 0.97 | 7.83 |
| | Non-orthogonal | 128 | 4 | 55 | 22 | 4 | 1.14 | 9.16 |

### B. OVERALL COMPLEXITY

Fair complexity assessment should regard the following points for the proposed SIM compared with the plain OFDM:

- Relaxed indexing complexity,
- Relaxed channel coding/de-coding complexity,
- Relaxed detection complexity through applying simple energy detection compared to ML detector employed in the plain OFDM,
- On the other hand, the increased complexity arising from replacing simple FFT algorithm by the sparsity-based algorithms. However, there are many recent CS-algorithms that promises lower complexities even under redundant over-complete dictionaries such as in [66].
- Moreover, the proposed SIM platform can be extended for relaxing channel estimation/ equalization in future work.

## VI. SIMULATION RESULTS

### A. SIMULATION SETUP

Similar to [8], the simulation is running on $N_T = 64$ modulated subcarriers for data with a slowly varying Rayleigh

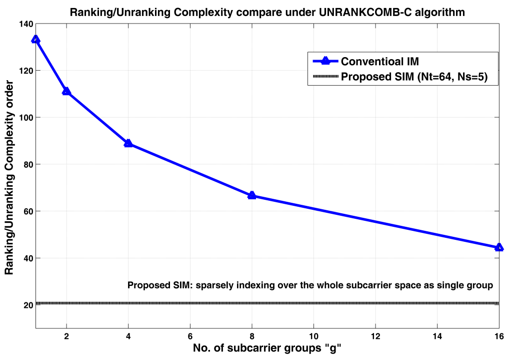


**FIGURE 6.** **Ranking/Un-ranking complexity under various number of groups(*g*).**

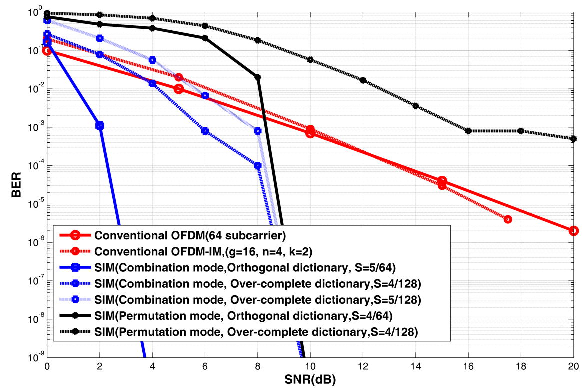


**FIGURE 7.** **Bit-error-rate performance.**

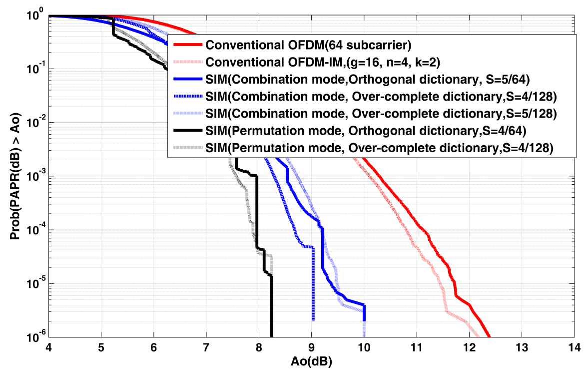


**FIGURE 8.** **PAPR performance.**

fading channel conditions. The performance of standard coded OFDM and coded OFDM-IM systems are compared to the proposed sparsely indexing including orthogonal/ non-orthogonal indexing system and combinatorial/permutational indexing system. Cyclic prefix (CP) length will be selected longer than the effective channel impulse response. Both plain OFDM and OFDM-IM systems are modulated by Quadrature phase shift keying (QPSK) and channel coded by conventional coding (CC) algorithm with 1/2 coding rate. OFDM-IM employs 32 subcarrier groups with 4 subcarriers per group. As usually, OFDM-IM activates half number of subcarriers per each group for maximum spectral efficiency. On the other hand, the proposed scheme does not employ neither data loading on the constellation of active subcarriers nor the channel coding. For both combinatorial and permutational indexing, the total number of subcarriers ($N_T$) is assigned as 64 and 128 for orthogonal and non-orthogonal case, respectively. The number of sparsely activated subcarriers ($N_S$) is adapted between 4 and 5 subcarriers per the whole subcarrier space. The indexing is carried out twice on the real/imaginary space independently. The sparsity order is selected to provide nearly the same spectral efficiency of standardized IEEE802.11a system; i.e. using the OFDM system with 64 subcarriers, channel coding with rate equals 1/2, and providing 48 data bits per frame. In permutational indexing, there are 4 activated subcarriers ordered through assigning different amplitudes. Based on the featured noise-immunity of the followed CS-based detection algorithm, the proposed scheme doesn't need channel coding redundancy. So, to compare data rates of coded systems with un-coded system fairly, the comparison is carried out based on the net user data ($b_{net}$).

The proposed scheme relays on SPICE/q-SPICE for recovery process in orthogonal (q = 1)/ non-orthogonal (q>1) sparsity recovery. It is found that q-SPICE provides optimal performance under q = 1.5 for over-complete Fourier dictionary (64 × 128). To simplify EE comparison, net energy of the signal composed of non-orthogonal subcarriers is adapted to equal the corresponding energy of the signal constructed from orthogonal subcarriers system.

### B. SIMULATION RESULTS

Figure 7 compares the BER performance of the coded OFDM, the coded OFDM-IM system and the proposed SIM system. Recalling critical sparsity concept can provide justification for corresponding free-error SNR as indicated in Table 3. Critical sparsity is regarded in the following cases:

- For combinatorial mode: 4dB for the proposed OFDM-SIM (S = 5/64) and at 10dB for the proposed SIM-Over-complete dictionary (SIM-OCD) (S = 4/128 & 5/128).
- For permutational mode: 10 dBs for the proposed OFDM-SIM (S = 4/64) and at 22 dBs for the over-complete dictionary.

However, corresponding OFDM/OFDM-IM exhibits $10^{-4}$ BER at SNR more than 12 dBs. Hence, under the same propagation conditions, the same coverage area can be attained under the proposed OFDM-SIM and SIM-OCD schemes through transmitting only 15 % and 63% respectively, from the transmitted power in the OFDM/OFDM-IM case.

Except the permutational mode on the over-complete dictionary, the proposed sparsely indexing exhibits low BER under low SNR values compared to both the OFDM system and the OFDM-IM systems due to superiority of employed CS compared to the classical signal processing tools. It is clear that, non-orthogonal/permutational indexing provides better spectral efficiency under the same number of activated subcarriers but with lower BER performance than the corresponding orthogonal/combinatorial indexing. Permutational indexing encounters lower BER performance due to a lot of challenging requirements of the accurately estimated while combinatorial indexing requires only the consideration of the most $N_S$ strongest energy subcarriers as activated subcarriers irrespective of relatively estimated amplitudes.

PAPR performance is shown in Fig. 8, it is clear that the combinatorial indexing provides about 2-3 dB improvement over the conventional OFDM/OFDM-IM. However, the lower PAPR level is introduced from permutational indexing where the sparsely activated subcarriers are added with different amplitudes. There is about 4 dB improvement over the conventional OFDM/OFDM-IM. Table 3 summaries the most important parameters of the proposed SIM with IEEE802.11a (QPSK, 1/2 CC). It introduces an interesting tradeoff between SE, EE, PAPR and BER performance.

## VII. CONCLUSION AND FURTHER WORK

This paper extends the idea of sparsely indexed modulation to enhance the SE of the communication systems. Many outcomes of sparsely indexing are highlighted. The CS-tools provide free BER performance under critical sparsity adaptation. Indexing on non-orthogonal Fourier dictionary is performed based on super-resolution ability of employed compressive spectral estimation. Combinatorial/permutational indexing on over-complete (non-orthogonal) dictionary is demonstrated on (64 × 128) Fourier dictionary. However, it is interesting to explore wider over-complete dictionary for achieving higher SE. Especial care should be given to increased mutual coherence encountered in the fine frequency grid dictionary. Mainly, the proposed sparsely indexed modulation provides great EE improvement. Therefore, it considers an important for green modulation technology. Moreover, a promising BER performance and lower PAPR levels can be achieved with comparable SE enhancement. The simplicity of the proposed framework should be extended for relaxing the need of the channel estimation and equalization besides the relaxing of the channel coding/decoding. This corresponds to a non-coherent version of the SIM approach.

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## REFERENCES

[1] W. Guo, S. Wang, C. Turyagyenda, and T. O'Farrell, "Integrated cross-layer energy savings in a smart and flexible cellular network," in *Proc. 1st IEEE Int. Conf. Commun. China Workshops (ICCC)*, Aug. 2012, pp. 79–84.

[2] M. H. Alsharif, R. Nordin, and M. Ismail, "Survey of green radio communications networks: Techniques and recent advances," *J. Comput. Netw. Commun.*, vol. 2013, pp. 1–13, Aug. 2013.

[3] Y. Wu *et al.*, "Green transmission technologies for balancing the energy efficiency and spectrum efficiency trade-off," *IEEE Commun. Mag.*, vol. 52, no. 11, pp. 112–120, Nov. 2014.

[4] M. Wen, X. Cheng, and L. Yang, "Optimizing the energy efficiency of OFDM with index modulation," in *Proc. IEEE Int. Conf. Commun. Syst. (ICCS)*, Nov. 2014, pp. 31–35.

[5] Y. Zou *et al.*, "Impact of major RF impairments on mm-Wave communications using OFDM waveforms," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2016, pp. 1–7.

[6] M. Wetz, I. Periša, W. G. Teich, and J. Lindner, "Robust transmission over fast fading channels on the basis of OFDM-MFSK," *Wireless Pers. Commun.*, vol. 47, no. 1, pp. 113–123, Oct. 2008.

[7] E. Başar, U. Aygölü, E. Panayırcı, and H. V. Poor, "Orthogonal frequency division multiplexing with index modulation," *IEEE Trans. Signal Process.*, vol. 61, no. 22, pp. 5536–5549, Nov. 2013.

[8] M. Wen, X. Cheng, M. Ma, B. Jiao, and H. V. Poor, "On the achievable rate of OFDM with index modulation," *IEEE Trans. Signal Process.*, vol. 64, no. 8, pp. 1919–1932, Apr. 2016.

[9] R. Fan, Y. J. Yu, and Y. L. Guan, "Improved orthogonal frequency division multiplexing with generalised index modulation," *IET Commun.*, vol. 10, no. 8, pp. 969–974, May 2016.

[10] N. Ishikawa, S. Sugiura, and L. Hanzo, "Subcarrier-index modulation aided OFDM—Will it work?" *IEEE Access*, vol. 4, pp. 2580–2593, 2016.

[11] E. Basar, M. Wen, R. Mesleh, M. Di Renzo, and Y. Xia, "Index modulation techniques for next-generation wireless networks," *IEEE Access*, vol. 5, pp. 16693–16746, 2017.

[12] X. Cheng, M. Zhang, M. Wen, and L. Yang, "Index modulation for 5G: Striving to do more with less," *IEEE Wireless Commun.*, vol. 25, no. 2, pp. 126–132, Apr. 2018.

[13] T. Mao, Z. Wang, Q. Wang, S. Chen, and L. Hanzo, "Dual-mode index modulation aided OFDM," *IEEE Access*, vol. 5, pp. 50–60, 2016.

[14] S. A. Çolak, Y. Acar, and E. Basar, "Adaptive dual-mode OFDM with index modulation," *Phys. Commun.*, vol. 30, pp. 15–25, Oct. 2018.

[15] M. Wen, E. Basar, Q. Li, B. Zheng, and M. Zhang, "Multiple-mode orthogonal frequency division multiplexing with index modulation," *IEEE Trans. Commun.*, vol. 65, no. 9, pp. 3892–3906, Sep. 2017.

[16] Q. Li, M. Wen, E. Basar, H. V. Poor, B. Zheng, and F. Chen, "Diversity enhancing multiple-mode OFDM with index modulation," *IEEE Trans. Commun.*, vol. 66, no. 8, pp. 3653–3666, Aug. 2018.

[17] P. Yang, M. Di Renzo, Y. Xiao, S. Li, and L. Hanzo, "Design guidelines for spatial modulation," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 6–26, 1st Quart., 2015.

[18] E. Basar, "On multiple-input multiple-output OFDM with index modulation for next generation wireless networks," *IEEE Trans. Signal Process.*, vol. 64, no. 15, pp. 3868–3878, Aug. 2016.

[19] S. AbuTayeh, M. Alsalahat, I. Kaddumi, Y. Alqannas, S. Althunibat, and R. Mesleh, "A half-full transmit-diversity spatial modulation scheme," in *Broadband Communications, Networks, and Systems. BROADNETS* (Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering), vol. 263, V. Sucasas, G. Mantas, and S. Althunibat, Eds. Cham, Switzerland: Springer, 2018, pp. 257–266.

[20] M. Elsayed, H. S. Hussein, and U. S. Mohamed, "Fully generalised spatial modulation," in *Proc. 35th Nat. Radio Sci. Conf. (NRSC)*, Mar. 2018, pp. 274–282.

[21] H. S. Hussein, M. Elsayed, U. S. Mohamed, H. Esmaiel, and E. M. Mohamed, "Spectral efficient spatial modulation techniques," *IEEE Access*, vol. 7, pp. 1454–1469, 2018. doi: 10.1109/ACCESS.2018.2885826.

[22] G. Kaddoum, Y. Nijsure, and H. Tran, "Generalized code index modulation technique for high-data-rate communication systems," *IEEE Trans. Veh. Technol.*, vol. 65, no. 9, pp. 7000–7009, Sep. 2016.

[23] Q. Li, M. Wen, E. Basar, and F. Chen, "OFDM spread spectrum with index modulation," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2017, pp. 1–6.

[24] J. Li, Y. Peng, X. Jiang, Y. Yan, and P. Ranjan, "Enhanced index modulated OFDM spread spectrum," *IEEE Access*, vol. 6, pp. 71028–71037, 2018.

[25] E. Basar. (Nov. 2018). "Media-based modulation for future wireless systems: A tutorial." [Online]. Available: https://arxiv.org/abs/1811.08730

[26] I. Yildirim, E. Basar, and I. Altunbas, "Quadrature channel modulation," *IEEE Wireless Commun. Lett.*, vol. 6, no. 6, pp. 790–793, Dec. 2017.

[27] E. Basar and I. Altunbas, "Space-time channel modulation," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 7609–7614, Aug. 2017.

[28] I. Yildirim, E. Basar, and G. K. Kurt, "Media-based modulation for secrecy communications," *Electron. Lett.*, vol. 54, no. 12, pp. 789–791, Jun. 2018.

[29] E. Başar, U. Aygolu, E. Panayirci, and H. V. Poor, "Space-time block coded spatial modulation," *IEEE Trans. Commun.*, vol. 59, no. 3, pp. 823–832, Mar. 2011.

[30] B. Shamasundar, S. Bhat, S. Jacob, and A. Chockalingam, "Multidimensional index modulation in wireless communications," *IEEE Access*, vol. 6, pp. 589–604, 2017. doi: 10.1109/ACCESS.2017.2772018.
[31] S. Lu, I. A. Hemadeh, M. El-Hajjar, and L. Hanzo, "Compressed-sensing-aided space-time frequency index modulation," *IEEE Trans. Veh. Technol.*, vol. 67, no. 7, pp. 6259–6271, Jul. 2018.
[32] H. Zhang, L.-L. Yang, and L. Hanzo, "Compressed sensing improves the performance of subcarrier index-modulation-assisted OFDM," *IEEE Access*, vol. 4, pp. 7859–7873, 2016.
[33] S. Gokceli, E. Basar, M. Wen, and G. K. Kurt, "Practical implementation of index modulation-based waveforms," *IEEE Access*, vol. 5, pp. 25463–25473, 2017.
[34] O. Hiari, F. Shahin, S. Alshaer, and R. Mesleh, "Hardware implementation of space shift keying on a Xilinx Zynq platform," *Broadband Communications, Networks, and Systems* (Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering). 2018, pp. 267–275.
[35] R. Mesleh, S. Althunibat, and A. Younis, "Differential quadrature spatial modulation," *IEEE Trans. Commun.*, vol. 65, no. 9, pp. 3810–3817, Sep. 2017.
[36] R. Mesleh and S. Althunibat, "Coherent versus non-coherent subcarrier index modulation systems," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2018, pp. 1–6.
[37] E. Soujeri, G. Kaddoum, M. Au, and M. Herceg, "Frequency index modulation for low complexity low energy communication networks," *IEEE Access*, vol. 5, pp. 23276–23287, 2017.
[38] S. Althunibat and R. Mesleh, "Index modulation for cluster-based wireless sensor networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 6943–6950, Aug. 2018.
[39] M. Chafii, F. Bader, and J. Palicot, "SC-FDMA with index modulation for M2M and IoT uplink applications," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2018, pp. 1–5.
[40] M. Salah, O. A. Omer, and U. S. Mohamed, "Joint compressive sensing framework for sparse data/channel estimation in non-orthogonal multicarrier scheme," *J. Eng. Sci.*, vol. 44, no. 5, pp. 537–554, Sep. 2016.
[41] M. Salah, O. A. Omer, and U. S. Mohamed, "Compressive sensing approach in multicarrier sparsely indexing modulation systems," *China Commun.*, vol. 14, no. 11, pp. 151–166, Nov. 2017.
[42] M. Salah, O. A. Omer, and U. S. Mohammed, "Enhanced MFSK spectral efficiency based on super-resolution spectral estimation," in *Proc. Int. Conf. Innov. Trends Comput. Eng. (ITCE)*, Feb. 2018, pp. 209–213.
[43] G. Wunder *et al.*, "5GNOW: Non-orthogonal, asynchronous waveforms for future mobile applications," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 97–105, Feb. 2014. doi: 10.1109/MCOM.2014.6736749.
[44] P. Banelli, S. Buzzi, G. Colavolpe, A. Modenini, F. Rusek, and A. Ugolini, "Modulation formats and waveforms for 5G networks: Who will be the heir of OFDM?: An overview of alternative modulation schemes for improved spectral efficiency," *IEEE Signal Process. Mag.*, vol. 31, no. 6, pp. 80–93, Nov. 2014.
[45] A. Farhan, N. Marchetti, F. Figueiredo, and J. P. Miranda, "Massive MIMO and waveform design for 5th generation wireless communication systems," in *Proc. 1st Int. Conf. 5G Ubiquitous Connectivity*, Nov. 2014, pp. 70–75.
[46] F. Schaich, T. Wild, and Y. Chen, "Waveform contenders for 5G—Suitability for short packet and low latency transmissions," in *Proc. IEEE 79th Veh. Technol. Conf. (VTC Spring)*, May 2014, pp. 1–5.
[47] W. Kozek and A. F. Molisch, "Nonorthogonal pulseshapes for multicarrier communications in doubly dispersive channels," *IEEE J. Sel. Areas Commun.*, vol. 16, no. 8, pp. 1579–1589, Oct. 1998.
[48] A. Das and B. D. Rao, "Adaptive non orthogonal MFSK," *IEEE Trans. Signal Process.*, vol. 62, no. 23, pp. 6077–6088, Dec. 2014.
[49] G. Wunder, H. Boche, T. Strohmer, and P. Jung, "Sparse signal processing concepts for efficient 5G system design," *IEEE Access*, vol. 3, pp. 195–208, 2015.
[50] J. W. Choi, B. Shim, Y. Ding, B. Rao, and D. I. Kim, "Compressed sensing for wireless communications: Useful tips and tricks," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 3, pp. 1527–1550, 3rd Quart., 2017.
[51] L. Wu, K. Yu, D. Cao, Y. Hu, and Z. Wang, "Efficient sparse signal transmission over a lossy link using compressive sensing," *Sensors*, vol. 15, no. 8, pp. 19880–19911, 2015.
[52] G. Tauböck, F. Hlawatsch, and H. Rauhut, "Compressive estimation of doubly selective channels: Exploiting channel sparsity to improve spectral efficiency in multicarrier transmissions," *IEEE J. Sel. Topics Signal Process.*, vol. 4, no. 2, pp. 255–271, Apr. 2010.
[53] J. Meng, Y. Li, N. Nguyen, W. Yin, and Z. Han, "High resolution OFDM channel estimation with low speed ADC using compressive sensing," in *Proc. IEEE Int. Conf. Commun.*, Kyoto, Japan, Jun. 2011, pp. 1–6.
[54] C. R. Berger, Z. Wang, J. Huang, and S. Zhou, "Application of compressive sensing to sparse channel estimation," *IEEE Commun. Mag.*, vol. 48, no. 11, pp. 164–174, Nov. 2010.
[55] Y. Zhang, R. Venkatesan, O. A. Dobre, and C. Li, "Novel compressed sensing-based channel estimation algorithm and near-optimal pilot placement scheme," *IEEE Trans. Wireless Commun.*, vol. 15, no. 4, pp. 2590–2603, Apr. 2016.
[56] O. U. Khan, S.-Y. Chen, D. D. Wentzloff, and W. E. Stark, "Impact of compressed sensing with quantization on UWB receivers with multipath channel estimation," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 2, no. 3, pp. 460–469, Sep. 2012.
[57] Z. Kokosinkiński, "Algorithms for unranking combinations and other related choice functions," Dept. Comput. Softw., Univ. Aizu, Aizuwakamatsu, Japan, Tech. Rep. 95-1-06, 1995.
[58] T. Shimizu, T. Fukunaga, and H. Nagamochi, "Unranking of small combinations from large sets," *J. Discrete Algorithms*, vol. 29, pp. 8–20, Nov. 2014.
[59] S. Dang, G. Chen, and J. P. Coon, "Lexicographic codebook design for OFDM with index modulation," *IEEE Trans. Wireless Commun.*, vol. 17, no. 12, pp. 8373–8387, Dec. 2018.
[60] E. J. Candès and C. Fernandez-Granda, "Towards a mathematical theory of super-resolution," *Commun. Pure Appl. Math.*, vol. 67, no. 6, pp. 906–956, 2013.
[61] E. J. Candès, Y. C. Eldar, D. Needell, and P. Randall, "Compressed sensing with coherent and redundant dictionaries," *Appl. Comput. Harmon. Anal.*, vol. 31, no. 1, pp. 59–73, Jul. 2011.
[62] D. L. Donoho, Y. Tsaig, I. Drori, and J.-L. Starck, "Sparse solution of underdetermined systems of linear equations by stagewise orthogonal matching pursuit," *IEEE Trans. Inf. Theory*, vol. 58, no. 2, pp. 1094–1121, Feb. 2012.
[63] V. Vivekanand, L. Vidya, U. S. Kumar, and D. Mishra, "Noise immunity analysis of compressed sensing recovery algorithms," in *Proc. Int. Conf. Signal Process. Integr. Netw. (SPIN)*, vol. 34, Feb. 2014, pp. 30–34.
[64] W. Dai and O. Milenkovic, "Subspace pursuit for compressive sensing: Closing the gap between performance and complexity," Univ. Illinois Urbana-Champaign, Springfield, IL, USA, Tech. Rep. 0803.0811, 2008.
[65] S. Sahnoun, P. Comon, and A. P. Da Silva, "A greedy sparse method suitable for spectral-line estimation," Dept. Images Signal, GIPSA, Saint-Martin-d'Hères, France, Res. Rep. GIPSA-Lab, Hal-01315258, 2016.
[66] M. Butsenko, J. Swärd, and A. Jakobsson, "Estimating sparse signals using integrated wide-band dictionaries," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, Mar. 2017, pp. 4426–4430.
[67] P. Stoica, D. Zachariah, and J. Li, "Weighted SPICE: A unifying approach for hyperparameter-free sparse estimation," *Digit. Signal Process.*, vol. 33, pp. 1–12, Oct. 2014.
[68] P. Stoica and P. Babu, "SPICE and LIKES: Two hyperparameter-free methods for sparse-parameter estimation," *Signal Process.*, vol. 92, pp. 1580–1590, Jul. 2012.
[69] J. Swärd, S. I. Adalbjörnsson, and A. Jakobsson, "Generalized sparse covariance-based estimation," *Signal Process.*, vol. 143, pp. 311–319, Feb. 2018.

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