Entropy Coding Aided Adaptive Subcarrier-Index Modulated OFDM

Mohammad Ismat Kadir, Hongming Zhan, Sheng Chen and Lajos Hanzo

***Abstract*—We propose entropy coding aided adaptive subcarrier index modulated orthogonal frequency division multiplexing (SIM-OFDM). In conventional SIM-OFDM, the indices of the subcarriers activated are capable of conveying extra information. We propose the novel concept of compressing the index information bits by employing Huffman coding. The probabilities of the different subcarrier activation patterns are obtained from an optimization procedure, which improves the performance of the scheme. Both the maximum-likelihood (ML) as well as the logarithmic-likelihood ratio (LLR-) based soft detector may be employed for detecting the subcarriers activated as well as the information mapped to the classic constellation symbols. As an additional advantage of employing the variable-length Huffman codebook, all the legitimate subcarrier activation patterns may be employed, whereas the conventional SIM-OFDM is capable of using only a subset of the patterns. Our simulation results show that an improved performance is attainable by the proposed system.**

***Index Terms*—Orthogonal frequency division multiplexing (OFDM), subcarrier index modulation-orthogonal frequency division multiplexing (SIM-OFDM), Entropy coding, capacity, energy-efficiency (EE).**

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) was conceived in the 1960s [1], [2], and it was included in numerous standards conceived for diverse applications [3]–[5]. The rudimentary idea behind OFDM transmission is to partition the transmit bitstream into many low-rate bitstreams, which are transmitted in parallel over different frequency subchannels. As a result, the transmission rate of each subchannel is considerably reduced and the subchannel bandwidth becomes much lower than the overall system's bandwidth. As a benefit, each of the individual subchannel signals experiences frequency-flat fading. Additionally, the inter-symbol interference (ISI) imposed by dispersive channels can be mitigated by introducing a sufficiently long cyclic prefix (CP). The most important aspect which made OFDM attractive is that the digital implementation of OFDM employing the discrete Fourier transform (DFT) is convenient [2]. On the other hand, a new research idea namely subcarrier-index modulated (SIM-) OFDM [6]–[9] has emerged, which activates only a specified limited number of OFDM subcarriers, rather than activating all the OFDM subcarriers during any of the OFDM symbol durations. Some of the source bits are mapped to the indices of the activated subcarriers in addition to the bits mapped to the classic constellation symbols. The first SIM-aided OFDM study was carried out in [6], where the concept was termed as the 'parallel combinatory OFDM' (PC-OFDM) and it was subsequently followed by [10]–[15]. The bits mapped to the subcarrier indices of the PC-OFDM system were referred to as the PC bits. The PC-OFDM was also employed for optical wireless systems in [10]. Later SIM-OFDM was also proposed [13], which was capable of exploiting the subcarrier index to carry information bits similarly to spatial modulation (SM) [16]–[18], where additional information is carried by the AE index or the spatial index. The detailed transceiver architecture of the SIM-OFDM system was provided in [7]–[9] and was extended to the SIM-aided MIMO-OFDM scenario in [15]. A detailed analysis of the achievable rate of the SIM-OFDM employing both the localized and the interleaved subcarrier grouping method was carried out in [14]. Compressed sensing was also invoked both at the encoder and the decoder of the SIM-OFDM system [19] in order to improve its performance.

The SIM-OFDM schemes referred to above deal with the mapping of the subcarrier index bits to the set of subcarriers activated with equal probabilities, regardless of the instantaneous channel quality. However, for reliable, energy-efficient and spectrally efficient wireless transmissions, the adaptation of the access technology to the time-variant channel state is of vital importance [20], [21]. To achieve high system capacity even in time-variant channel conditions, adaptive antenna selection was studied in [22], [23] in the context of multiple-input multiple-output (MIMO) systems. Energy-aware space-shift-keying (SSK) MIMO utilizing optimized power allocation for the activated antenna elements (AEs) was proposed in [24], [25]. Furthermore, the activation of the appropriate AE for providing both capacity-optimal as well as error-performance-optimal transmissions in SM-based MIMO systems was investigated in [26]–[28]. An adaptive channel-aware modulation scheme was conceived for different OFDM subcarriers [29]–[31] and a capacity-maximizing adaptive subcarrier selection was proposed in [32]. A plethora of algorithms is available in the literature for the subcarrier and power allocation of multiuser OFDM or for orthogonal frequency division multiple access (OFDMA) systems, for example [33]–[35]. It is thus imperative to conceive new OFDM-based systems which will be adaptive to the time-variant channel conditions.

A subcarrier allocation scheme or subcarrier grouping

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method based on the subcarrier index bits has been proposed in [36] for improving the performance of SIM-OFDM systems. On the other hand, an energy-efficient SSK transmission scheme employing the Huffman coding [37] principle was proposed in [25], where the source bits are mapped to the transmit AEs of a MIMO system based on the probabilities obtained by an energy-efficiency (EE) optimization procedure. As a further advance, an adaptive SM scheme relying on Huffman coding was also proposed [38], where the activated transmit AEs carry source information mapped to the $\mathcal{L}-$PSK/QAM symbols in addition to the bits mapped to the transmit AE indices in accordance with probabilities gleaned from an optimization procedure. To be more specific, in contrast to the conventional SM-MIMO [16], [17] where the source bits are mapped to the classic $\mathcal{L}-$PSK/QAM symbols as well as to the AE indices with equal probability, the adaptive SM scheme of [38] attaches different probabilties of being mapped to different AEs and these probabilities are obtained from an optimization procedure formulated either for maximizing the capacity or for minimizing the symbol error rate (SER), depending on the near-instantaneous channel conditions. The AE index bits are mapped to the activated AEs by Huffman coding using the above-mentioned probabilities. Since the SIM-OFDM system [7], [9] is in principle similar to the SM scheme, where additional implicit bits are mapped to the subcarrier indices rather than to the transmit AEs of the SM [16] or the generalized SM (GSM) [39], an adaptive SIM-OFDM may also be conceived. Specifically, in contrast to the classic SIM-OFDM system, where equal-length subcarrier index bit-segments are mapped to the subcarriers activated, the subcarrier activation pattern may be adaptively selected by using the variable-length coding strategy of Huffman codes [37]. In this paper, we propose an adaptive SIM-OFDM scheme relying on the variable-length entropy coding technique of Huffman codes [37], which is usually used for the lossless compression of source information. The proposed conceptual framework is shown in Fig. 1. The index bits of the classic SIM-OFDM system are mapped equi-probably to the subcarriers activated. By contrast, channel-aware and energy-aware probabilities of the different subcarrier activation patterns may be obtained by optimizing either the channel-capacity or the error-rate and/or the energy-efficiency (EE) of the system. Using these probabilities, the Huffman mapper of Fig. 1 is capable of generating variable-length codebooks. The subcarrier index bits may be mapped to the corresponding subcarrier activation patterns of the SIM-OFDM system.

It is noteworthy at this point that since the codewords generated by the Huffman mapper are of variable length, the mapped SIM-OFDM frames will be constituted of variable number of source bits. Some of the subcarrier activation patterns of the classic SIM-OFDM system were unutilized. The reason for this inefficiency is that if the number of combinations of activating N_p subcarriers from a total number of N_c subcarriers is not a power of 2, then at best $\left\lfloor \log_2 \binom{N_c}{N_p} \right\rfloor$ bits can be mapped to the subcarriers activated. This is equally true for the generalized SM scheme of [39] and for the generalized space-time shift keying (GSTSK) scheme of [40]. By contrast, our proposed Huffman coding based adaptive SIM-OFDM scheme has the potential of exploiting all the legitimate $\binom{N_c}{N_p}$ subcarrier activation patterns, which is an explicit benefit of the variable-length codebook utilized. This has the additional advantage that the decoding of the proposed system does not get trapped in the 'catastrophic set of active indices', as eloquently mentioned in [7].

The contributions of this paper may thus be summarized as follows:

1) We conceive a Huffman coding based adaptive SIM-OFDM technique for dispersive channels and characterize the capacity vs. the EE of the system. Furthermore, we device the procedure of adaptively selecting the subcarriers activated relying on the Huffman coding principle.
2) While the conventional SIM-OFDM system of [7], [9], [13] can only activate $2^{\left\lfloor \log_2 \binom{N_c}{N_p} \right\rfloor}$ subcarrier activation patterns, the proposed system is capable of activating all the $\binom{N_c}{N_p}$ legitimate patterns of subcarriers.
3) The system relies on the ML detector proposed or on the reduced-complexity log-likelihood (LLR)-based detector using the philosophy of [7]. However, since the system exploits all the legitimate subcarrier activation patterns, our new system has the additional advantage that in contrast to [7], it does not mistakenly detect any of the unutilized set of subcarriers.
4) Furthermore, since the subcarrier activation strategy is dependent on a number of probabilities gleaned from an optimization procedure, the proposed system is capable of adaptively striking a beneficial compromise amongst the capacity, the error performance as well as EE of the system.

A. Outline

The organization of the paper is as follows. In Section II, we provide an overview of our adaptive SIM-OFDM system and detail its transceiver architecture. The subcarrier mapping of the scheme relying on variable-length Huffman coding is described in Section III. Striking a tradeoff amongst the attainable capacity, the error performance and EE of our entropy-coded SIM-OFDM system is elaborated on in Section IV. Section V provides our numerical results demonstrating the efficacy of the proposed scheme. Finally, we conclude in Section VI.

B. Notations

The following notations are employed in this paper. We use capital boldface letter for example $\boldsymbol{A}$, boldface lowercase letter $\boldsymbol{a}$ and the notation $\boldsymbol{A}$**:** to represent a matrix, a vector and a block matrix respectively. The notations $\boldsymbol{A}^T$, $\boldsymbol{A}^H$, tr$(\boldsymbol{A})$, vec$(\boldsymbol{A})$, $|\boldsymbol{A}|$ and $\|\boldsymbol{A}\|$ represent the matrix transpose, the Hermitian transpose, the trace, the vectorial stacking operator, the determinant and the Frobenius norm of $\boldsymbol{A}$, respectively. The operator $\otimes$ represents the Kronecker product, $\mathcal{E}\{\bullet\}$ the expected value of '$\bullet$', $\boldsymbol{I}_T$ the $(T \times T)$-element identity matrix and $\mathbf{0}_{M\times T}$ the $(M \times T)-$element zero matrix. The notation

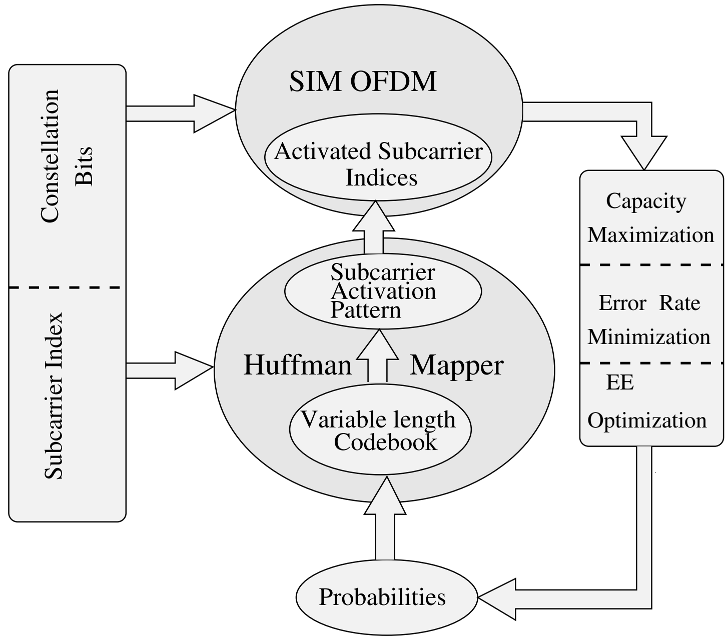


Fig. 1. The conceptual framework illustrating the employment of Huffman mapping based variable-length codebook for the selection of the subcarrier indices of the SIM-OFDM scheme. The probabilities associated with the Huffman coding are gleaned from the optimization of the capacity, the error performance as well as the energy-efficiency of the system.

$\mathtt{diag}\{x_1,\ldots,x_N\}$ denotes a diagonal matrix with $x_1,\ldots,x_N$ on its main diagonal, $\Pr(\cdot)$ the probability of '$\cdot$', while the N_c-point discrete Fourier transform (DFT) of the symbol stream '$\bullet$' and the N_c-point inverse discrete Fourier transform (IDFT) of '$\bullet$' are denoted by $\mathrm{DFT}_{N_c}\{\bullet\}$ and $\mathrm{IDFT}_{N_c}\{\bullet\}$, respectively. The corresponding DFT and the IDFT matrices are represented by $\boldsymbol{\mathcal{F}}_{N_c}$ and $\boldsymbol{\mathcal{F}}_{N_c}^H$, respectively. Furthermore, $\mathcal{CN}(\mu,\sigma^2)$ refers to the circularly symmetric complex Gaussian distribution with a mean of μ and a variance of σ^2.

II. System Overview of the Adaptive SIM-OFDM

Fig. 2 shows the schematic of our proposed adaptive SIM-OFDM system communicating over frequency-selective Rayleigh fading channels. Furthermore, N_c subcarriers are employed by our OFDM modem, out of the which N_p subcarriers are utilized by the SIM-OFDM for the transmission of the codeword symbols and the remaining subcarriers are *not activated,* i.e. they do not carry classic modulated symbols.

A. The Transmitter Model

Let us consider b source bits, which are to be transmitted in parallel during an OFDM symbol interval employing a total of N_c parallel subcarriers, as shown in Fig. 2. The b bits are partitioned into b_1 and b_2 bits. The b_1 bits are mapped to the classic $\mathcal{L}$-PSK/QAM symbols. By contrast, the b_2 bits are used for selecting the indices of the subcarriers of the SIM-OFDM scheme, respectively and may be termed as the 'index bits'. Each of these bits are further partitioned into K parallel blocks. We use a single $\mathcal{L}$-PSK/QAM constellation, hence each of the K parallel blocks and each of the N_a symbols in a particular parallel block contains an equal number of bits. By contrast, the number of index bits varies owing to using Huffman coding. Furthermore, the total number N_c of the available subcarriers is divided into N_b subcarriers for each of the K parallel blocks, where $N_c = KN_b$. Similarly, the total of N_p subcarriers to be selected by the SIM scheme is also partitioned into K blocks of N_a subcarriers each, where we have $N_p = KN_a$. The N_a number of symbols generated may be expressed by,

$$\boldsymbol{S}^k = \left(S^k[1], S^k[2], \ldots, S^k[N_a]\right)^T. \quad (1)$$

The b_2 bits of Fig. 2 are mapped to the appropriate variable-length codewords of the Huffman codebook in order to select the index to the N_a subcarriers activated from the N_b subcarriers for each block. As shown in Fig. 2, the b_2 bits are separated into K subblocks depending on the lengths of the codewords output by the Huffman codebook, so that each of the K subblocks activates a $(N_a\times 1)-$element subcarrier activation vector $\boldsymbol{a}^k$:

$$\boldsymbol{a}^k = \left(\boldsymbol{a}^k[1], \boldsymbol{a}^k[2], \ldots, \boldsymbol{a}^k[N_a]\right)^T, \quad (2)$$

where $\boldsymbol{a}^k[n_a] \in \mathbb{Z}^{N_a} \quad (n_a = 1,2,\ldots,N_a)$ are the indices of the subcarriers activated in a particular OFDM symbol duration.

Following the bit mapping to classic constellation symbols and the activation of the subcarriers represented by the set of indices $\boldsymbol{a}^k \quad (k=1,2\ldots,K)$, the symbols of all the K subblocks are concatenated to form OFDM frames and are transmitted after appropriate OFDM processing. To be more specific, the N_a symbols defined by $S^k[1], S^k[2], \ldots, S^k[N_a]$ along with the subcarrier activation pattern $\boldsymbol{a}^k$ for each of the parallel subblocks $k = 1,2\ldots K$ are passed through the 'OFDM Frame Constructor' block of Fig. 2, which generates a total of N_c frequency-domain (FD) symbols $X[1], X[2], \ldots, X[N_c]$. In contrast to the classic OFDM,

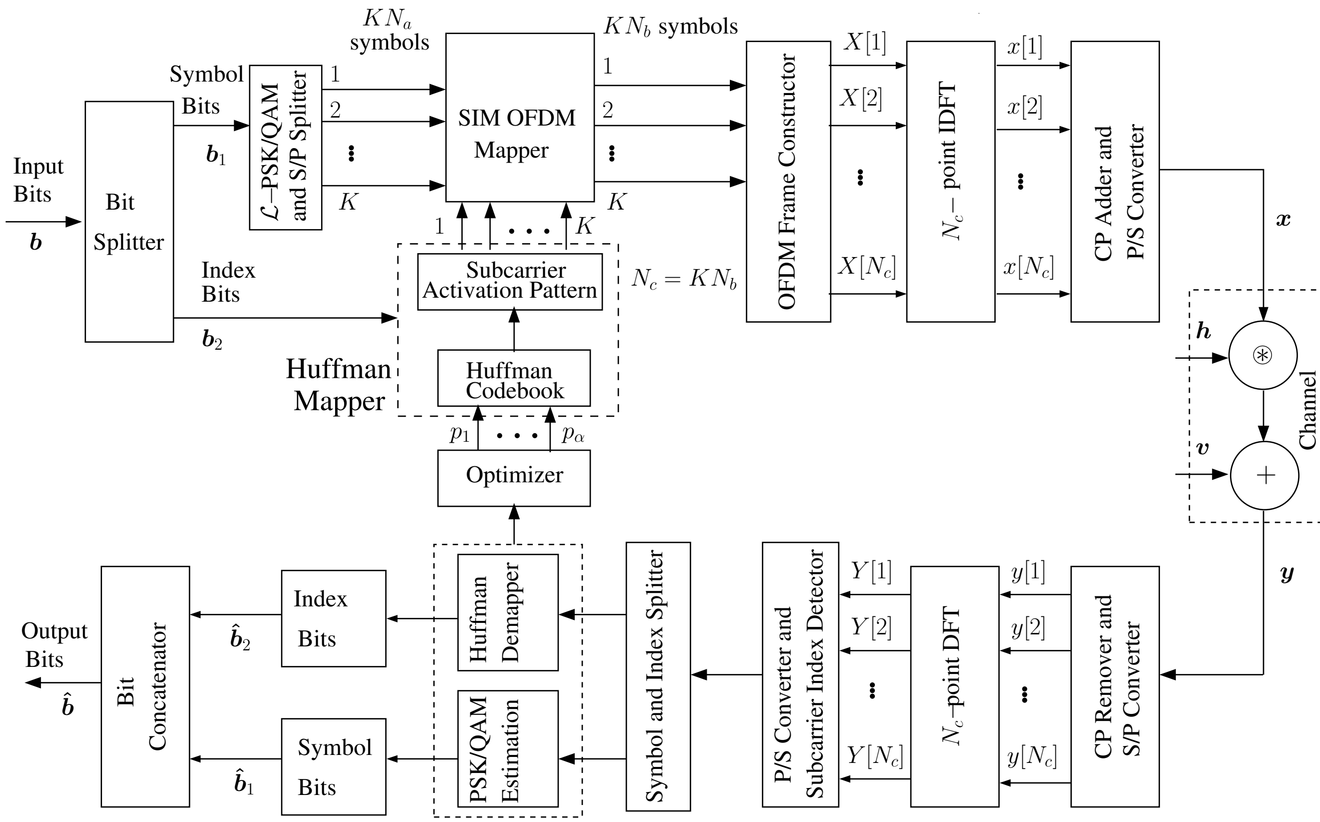


Fig. 2. Schematic diagram of the proposed adaptive SIM-OFDM transceiver relying on Huffman coding principle. A total of $N_c = KN_a$ symbols along with the subcarrier indices mapped by Huffman coding are passed through the SIM-OFDM mapper and the symbols are appropriately mapped to N_c subcarriers for transmission over dispersive channel.

however, not all the N_c terms of the resultant OFDM symbol denoted by the vector $\boldsymbol{X}$ contain constellation symbols. Rather, a total of $N_p = KN_a$ symbols are assigned to N_p subcarriers in each OFDM frame, whereas the remaining $(N_c - N_p) = k(N_b - N_a)$ subcarriers are 'inactive', i.e. blank.

To be more specific, assuming the relationship $N_c = KN_b$, a number of N_b subcarriers are utilized per parallel block. Due to the basic philosophy of the SIM scheme, N_a subcarriers out of the N_b subcarriers per block are activated and are modulated by the FD codeword symbols $S^k[1], S^k[2], \ldots, S^k[N_a] \quad k = 1, 2 \ldots K$ employing the subcarrier selection pattern $\boldsymbol{a}^k$. The 'OFDM Frame Constructor' generates N_b FD symbols represented by $X^k[1], X^k[2], \ldots, X^k[N_b] \quad k = 1, 2, \ldots, K$ for each block and the K parallel blocks thus generate a total of N_c FD symbols $\boldsymbol{X} = (X[1], X[2], \ldots, X[N_c])^T$, which constitute an OFDM symbol. Upon denoting the N_c-point discrete Fourier transform (DFT) matrix and the inverse DFT (IDFT) matrix by $\boldsymbol{\mathcal{F}}_{N_c}$ and $\boldsymbol{\mathcal{F}}_{N_c}^H$ respectively, we have the time-domain (TD) samples given by [9], [41], [42]:

$$\boldsymbol{x} = \sqrt{\frac{N_c}{N_p}} \mathrm{IDFT}_{N_c}\{\boldsymbol{X}\} = \sqrt{\frac{N_c}{N_p}} \boldsymbol{\mathcal{F}}_{N_c}^H \boldsymbol{X}. \tag{3}$$

The corresponding SIM-OFDM scheme may be unambiguously described by the (N_c, N_p, K) parameters.

B. The Subcarrier Mapping

Consider the formation of the OFDM frame, as discussed in Section II-A above. The FD symbols $\boldsymbol{X}^k = X^k[1], X^k[2], \ldots, X^k[N_b]$ for a particular block k may be viewed as:

$$\boldsymbol{X}^k = \underbrace{\left(S^k[1], 0, 0, S^k[2], \ldots, 0, S^k[N_a]\right)^T}_{N_a \text{ out of } N_b \text{ elements are nonzero}}, \tag{4}$$

where $\boldsymbol{S}^k = \left\{S^k[1], S^k[2], \ldots, S^k[N_a]\right\}$ represents the N_a constellation symbols given by (1). Eq. (4) may be further expressed as [38]:

$$\boldsymbol{X}^k = \boldsymbol{a}^k \cdot \boldsymbol{S}^k, \tag{5}$$

where $\boldsymbol{a}^k$ belongs to a finite set of $\alpha = \binom{N_b}{N_a}$ subcarrier activation patterns given by

$$\mathcal{A}^k = \left\{\boldsymbol{a}_1^k, \boldsymbol{a}_2^k, \ldots, \boldsymbol{a}_\alpha^k\right\}, \tag{6}$$

while $\boldsymbol{a}_i^k$ is the i-th $(N_a \times 1)-$element subcarrier activation vector as given by (2). When $\boldsymbol{a}_i^k$ is selected, the N_a subcarriers corresponding to it are activated and the remaining $(N_b - N_a)$ are inactive.

We denote the probability of selecting the i-th subcarrier activation pattern by $p_i = \Pr\left(\boldsymbol{a}^k = \boldsymbol{a}_i^k\right)$, so that we have $\sum_{i=1}^{\alpha} p_i = 1$.

Note that in the conventional SIM-OFDM of [7], [9], [13], the index bits are mapped equi-probably to the subcarrier activation patterns, i.e. the probabilities of selecting the different subcarrier activation patterns are equal, which is given by:

$$\begin{aligned} \mathfrak{p} &= \{p_1, p_2, \ldots, p_\alpha\} \\ &= \left\{\frac{1}{\alpha}, \frac{1}{\alpha}, \ldots, \frac{1}{\alpha}\right\}. \end{aligned} \tag{7}$$

By contrast, the probabilities in our proposed adaptive SIM-OFDM system are not equal. They are dependent on the channel quality and are obtained by employing an optimization procedure in order to maximize the channel capacity and/or EE under the requirement of a specific bit/symbol error ratio performance. Depending on the values of the probabilities, the Huffman mapper constructs a variable-length codebook. The Huffman codebook is used for mapping the incoming index bits to the subset of subcarriers activated.

C. The Receiver Model

Let us assume the channel to be frequency-selective, whose discrete-time channel impulse respone (CIR) is given by $\boldsymbol{h}$. Assuming perfect synchronization, the discrete-time signal at the receiver can be expressed by [30]

$$\boldsymbol{y} = \boldsymbol{h} \circledast \boldsymbol{x} + \mathbf{v}, \tag{8}$$

where $\circledast$ denotes the N_c-point circular convolution operator and $\mathbf{v}$ represents the corresponding time-domain (TD) additive white Gaussian noise (AWGN). After removing the CP, the received signal is first demodulated by applying the N_c-point discrete Fourier transform (DFT). The resultant FD output $\boldsymbol{Y} = \left(Y[1], Y[2], \ldots, Y[N_c]\right)^T \in \mathbb{C}^{N_c \times 1}$ may be written as [30]:

$$\begin{aligned} \boldsymbol{Y} &= \boldsymbol{\mathcal{F}}_{N_c} \boldsymbol{y} \\ &= \boldsymbol{\mathcal{F}}_{N_c} \left(\boldsymbol{h} \circledast \boldsymbol{x} + \mathbf{v}\right) \\ &= \tilde{\boldsymbol{H}} \boldsymbol{X} + \boldsymbol{V}, \end{aligned} \tag{9}$$

where $\tilde{\boldsymbol{H}} = \mathrm{diag}\{\tilde{H}[1], \tilde{H}[2], ..., \tilde{H}[N_c]\} \in \mathbb{C}^{N_c \times N_c}$ is a diagonal matrix whose diagonal elements are obtained by $\boldsymbol{\mathcal{F}}_{N_c} \boldsymbol{h} \in \mathbb{C}^{N_c \times 1}$ representing the FD channel transfer functions. Still referring to ((9)), we have the FD signal $\boldsymbol{X} = \left(X[1], X[2], \ldots, X[N_c]\right)^T \in \mathbb{C}^{N_c \times 1}$ and the FD AWGN $\boldsymbol{V} = \boldsymbol{\mathcal{F}}_{N_c} \boldsymbol{v} \in \mathbb{C}^{N_c \times 1}$ having a zero mean and a variance of N_0.

After the N_c-point DFT processing, the receiver detects the bits mapped to the constellation symbols as well as those mapped to the subcarrier indices. Due to the variable-length nature of the Huffman coding based index bits, conceiving a joint detector for simultaneously detecting both types of bits is not feasible. As shown in Fig. 2, the activated subcarriers are detected first. From the subcarrier activation pattern, the index bits may be detected using Huffman demapping and the constellation symbols may then be readily detected by a maximmum-likelihood (ML) detector.

1) ML Detector: As mentioned above, an ML detector may only be used in conjunction with our scheme after detecting the subcarriers activated. This may be performed by another ML search over all the OFDM subcarriers. In this search, a zero symbol is considered along with the $\mathcal{L}$ legitimate PSK/QAM symbols. If the detector detects zero rather than any of the $\mathcal{L}$ PSK/QAM symbols, then that subcarrier is considered to be inactive.

To be specific, the ML detector may be formulated as follows:

$$\hat{s_l} = \arg\min_{s_l \in \mathbb{S}} \left\| Y[n_c] - \tilde{H}[n_c] X[n_c] \right\|^2, \quad n_c = 1, 2, \ldots, N_c \tag{10}$$

where the set $\mathbb{S}$ consists of all the $\mathcal{L}$ PSK/QAM symbols, $s_l, \quad l = 1, 2, \ldots, \mathcal{L}$ and a zero symbol. After detecting the subcarriers activated, the ML detector then detects the $\mathcal{L}-$PSK/QAM symbols, which does not include the search over the zero symbol. The detected subcarrier patterns are then utilized for detecting the index bits with the aid of the Huffman demapper of Fig. 2.

2) Reduced-Complexity Soft-decision Detector: To avoid the high computational complexity of the ML detector of (10), we further propose a soft-decision detector based on (9) by relying on the logarithmic likelihood ratio (LLR) of the FD symbol. Additionally, since all the potential combinations of selecting N_a subcarriers out of the N_b available subcarriers can be used in our proposed scheme with the aid of variable-length coding, this detector does not detect any of the unutilized subcarriers patterns in contrast to [7], [9], [13]. According to the SIM-OFDM signalling strategy, some of the FD symbols are either non-zeros or zeros depending on whether the corresponding subcarriers are activated or de-activated. We thus define the LLR [7], [43] $L(n_c)$ of the n_c-th symbol in terms of the ratio of the following *a posteriori* probablities,

$$L(n_c) \triangleq \ln \frac{\sum_{\mu=1}^{\mathcal{L}} \Pr\left(X[n_c] = s_l \mid Y[n_c]\right)}{\Pr\left(X[n_c] = 0 \mid Y[n_c]\right)}. \tag{11}$$

Note that $\sum_{\mu=1}^{\mathcal{L}} \Pr\left(X[n_c] = s_l\right) = \frac{N_p}{N_c}$ and $\Pr\left(X[n_c] = 0\right) = \frac{(N_c - N_p)}{N_c}$. Using Bayes theorem in (11), we obtain [7], [44]:

$$\begin{aligned} L(n_c) = \ln(N_p) - \ln(N_c - N_p) + \frac{\left\|Y[n_c]\right\|^2}{2N_0} \\ + \ln\left(\sum_{\mu=1}^{\mathcal{L}} \exp\left(-\frac{1}{2N_0}\left\|Y[n_c] - \tilde{H}[n_c] X[n_c]\right\|^2\right)\right). \end{aligned} \tag{12}$$

For the sake of reducing the computational burden of the maximum *a posteriori* (MAP) algorithm, the Jacobian logarithm-based approximate logarithmic MAP (approx-log-

MAP) algorithm [45] may be invoked in (12). Specifically, using $N_p = N_c/2$, we have from (12):

$$L(n_c) = \frac{\|Y[n_c]\|^2}{2N_0} + \text{jac}\left(\sum_{\mu=1}^{\mathcal{L}} \exp\left(-\frac{1}{2N_0}\left\|Y[n_c] - \tilde{H}[n_c]X[n_c]\right\|^2\right)\right), \tag{13}$$

where jac$(\bullet)$ represents the Jacobian logarithm of '$\bullet$', which is recursively computed [45] over the $\mathcal{L}$ terms using $\text{jac}\left(\sum_{i=1}^{2}\exp(\delta_i)\right) = \max(\delta_1, \delta_2) + \ln(1 + \exp(-|\delta_1 - \delta_2|))$.

After calculating the LLRs corresponding to all the N_c subcarrier symbols, the detector then detects the N_p subcarriers activated. The detector decides in favour of the highest N_p LLR values and the corresponding subcarriers are deemed to be activated and the subcarrier index bits are estimated by the Huffman demapper of Fig. 2. After estimating the subcarrier index bits, the estimation of the bits mapped to $\mathcal{L}-$ PSK/QAM symbols is straight-forward. This may performed using the ML detector

$$\hat{s}_l = \arg\min_{s_l}\left\|Y[n_c] - \tilde{H}[n_c]X[n_c]\right\|^2, \quad n_c = 1, 2, \ldots, N_c \tag{14}$$

where the ML search is carried out only over the constellation symbols.

III. Huffman Coding Technique for Adaptive SIM-OFDM

As already mentioned above, Huffman coding based variable-length codewords are employed in our SIM-OFDM scheme for selecting the appropriate subcarrier activation pattern. In this section, we illustrate the Huffman coding aided subcarrier activation procedure.

Huffman coding is an entropy coding scheme which has been predominantly employed for lossless data compression. It exploits the probability of occurrence of a source symbol for mapping the high-probability symbols to a low number of bits and vice versa. We design our codebook for mapping the subcarrier index bits depending on some probabilities obtained from the optimization of either the capacity or the EE of the system. Again, subcarrier patterns with higher probability are mapped to a smaller number of index bits, whereas those with lower probability are mapped to a higher number of index bits. In addition, no codeword in the codebook should be the prefix to any of the other codewords. Huffman codes are generated by creating a binary tree of nodes. The procedure begins by sorting the symbols in ascending order of their probabilities or frequencies [37]. While there are more than two nodes, the two nodes having the lowest probabilities are removed and a new node relying on these two nodes and with a probability equal to the sum of the two nodes' probabilities is created. The nodes are then sorted again and the process continues [37]. The codes for any of the symbols are assigned by traversing the tree from the root and assigning a 0 for a higher probabilty node and a 1 for a lower probabilty node. The process is illustrated by following the example of Fig. 3 for an $(N_b = 4, N_a = 2, K = 16)$ SIM-OFDM system with two sets probabilities for the legitimate subcarrier activation patterns. In Fig. 3, only the first and the last steps of the Huffman coding procedure are shown for space economy.

Example: Let us now exemplify the subcarrier-allocation strategy of our SIM-OFDM considering $N_c = 64,\ N_p = 32$ and $K = 16$, which gives us $N_b = 4,\ N_a = 2$.

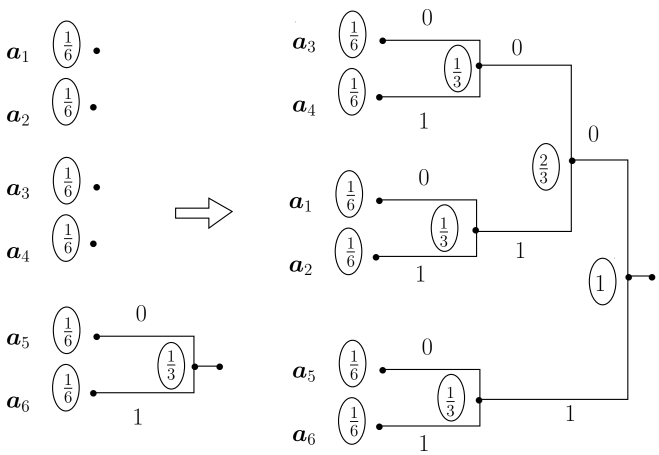
The conventional subcarrier mapping of [6], [7], [9] for these parameter values may be expressed by the (6×4) −element binary matrix

$$\boldsymbol{A}_{6,4}^{k} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix} \in \mathbb{Z}^{6\times 4}. \tag{15}$$

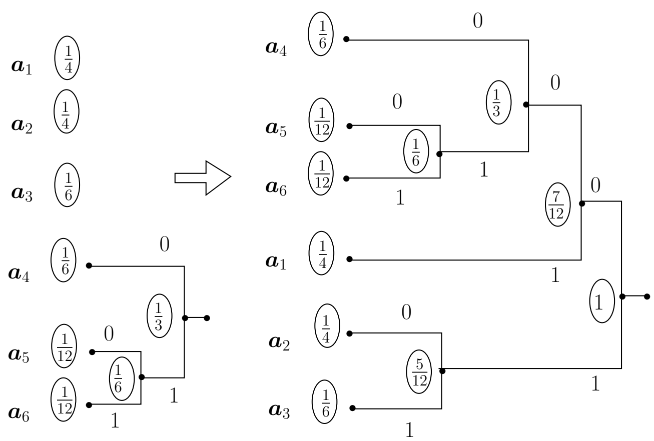
Specifically, the 6 rows of the matrix represent the 6 potential candidates of the subcarrier activation pattern and the location of the $1'$s in each row indicates the subcarriers activated. Thus the six legitimate subcarrier patterns of the conventional systems are: $\boldsymbol{a}_1^k = (1,2)^T, \boldsymbol{a}_2^k = (1,3)^T, \boldsymbol{a}_3^k = (1,4)^T, \boldsymbol{a}_4^k = (2,3)^T, \boldsymbol{a}_5^k = (2,4)^T$ and $\boldsymbol{a}_6^k = (3,4)^T$. The $b_2 = \left\lfloor \log_2\binom{4}{2}\right\rfloor = 2$ bits may, however, be mapped to $2^2 = 4$ rows of the binary matrix and the last 2 of the 6 rows are discarded. The conventional system thus uses the 4 activation patterns $\boldsymbol{a}_1^k = (1,2)^T, \boldsymbol{a}_2^k = (1,3)^T, \boldsymbol{a}_3^k = (1,4)^T$ and $\boldsymbol{a}_4^k = (2,3)^T$ only.

By contrast, our proposed SIM-OFDM scheme exploits all the 6 subcarrier activation patterns and employs a Huffman coding based approach rather than using the equi-probable binary matrix $\boldsymbol{A}_{6,4}^k$ of (15). We exploit the probabilities $p_i \quad i = 1, 2, \ldots, \alpha$ for all the legitimate $\alpha = \binom{N_b}{N_a} = 6$ subcarrier activation patterns. For the sake of exemplifying our mapping procedure, we consider two sets of probabilities $\mathfrak{p} = \left\{\frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}\right\}$ and $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{6}, \frac{1}{6}, \frac{1}{12}, \frac{1}{12}\right\}$ here. The corresponding Huffman coding tree is shown in Fig. 3(a) and Fig. 3(b), respectively. The encoding process is performed by assigning a 0 for the node with higher probability and a 1 for that with a lower probabilty. The mapping of the codewords to the corresponding subcarrier activation patterns are shown in Table I and Table II. Note that we have shown only the first and the last steps for the generation of the Huffman tree [37] in Fig. 3(a) and Fig. 3(b). The subscript k of $\boldsymbol{a}_i^k$ is not shown in Fig. 3 and either in Table I or in Table II for the sake of notational simplicity.

It is worth noting at this point that the probability values for the different subcarrier patterns are obtained by an optimization procedure. The Huffman mapper of Fig. 2 maps the random index bitstream of the source information to the appropriate subcarrier activation patterns. This mapping relies on the probability values depending on the channel conditions. The channel state information assists in optimizing either the capacity or the error performance and/or the EE of the system and this optimization provides the unequal probability values. Using the probability values, the Huffman mapper of Fig. 2 generates the variable-length Huffman codebook. The



(a) Huffman mapping for probabilities, $\mathfrak{p} = \left\{\frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}\right\}$.



(b) Huffman mapping for probabilities, $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{6}, \frac{1}{6}, \frac{1}{12}, \frac{1}{12}\right\}$.

Fig. 3. Huffman mapping example corresponding to the two typical sets of probabilities, $\mathfrak{p} = \left\{\frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}\right\}$ and $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{6}, \frac{1}{6}, \frac{1}{12}, \frac{1}{12}\right\}$. Only the first and the last steps of the Huffman mapping procedure [37] are shown.

Table I
HUFFMAN MAPPING OF CODEWORD BITS TO SUBCARRIER ACTIVATION PATTERNS FOR $\mathfrak{p} = \left\{\frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}\right\}$.

Codeword Bit Sequence	Probability, p_i	Subcarrier Activation Pattern, $\boldsymbol{a}_i$
010	$\frac{1}{6}$	$\boldsymbol{a}_1 = (1,2)^T$
011	$\frac{1}{6}$	$\boldsymbol{a}_2 = (1,3)^T$
000	$\frac{1}{6}$	$\boldsymbol{a}_3 = (1,4)^T$
001	$\frac{1}{6}$	$\boldsymbol{a}_4 = (2,3)^T$
10	$\frac{1}{6}$	$\boldsymbol{a}_5 = (2,4)^T$
11	$\frac{1}{6}$	$\boldsymbol{a}_6 = (3,4)^T$

incoming random index bitstream is mapped to the OFDM subcarriers activated using the Huffman codebook generated. Since the Huffman codebook is of variable length, the index bits mapped to different subcarrier activation patterns are not equal in number.

The Huffman codebook has the unique property that no

Table II
HUFFMAN MAPPING OF CODEWORD BITS TO SUBCARRIER ACTIVATION PATTERNS FOR $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{6}, \frac{1}{6}, \frac{1}{12}, \frac{1}{12}\right\}$.

Codeword Bit Sequence	Probability, p_i	Subcarrier Activation Pattern, $\boldsymbol{a}_i$
01	$\frac{1}{4}$	$\boldsymbol{a}_1 = (1,2)^T$
10	$\frac{1}{4}$	$\boldsymbol{a}_2 = (1,3)^T$
11	$\frac{1}{6}$	$\boldsymbol{a}_3 = (1,4)^T$
000	$\frac{1}{6}$	$\boldsymbol{a}_4 = (2,3)^T$
0010	$\frac{1}{12}$	$\boldsymbol{a}_5 = (2,4)^T$
0011	$\frac{1}{12}$	$\boldsymbol{a}_6 = (3,4)^T$

codeword is a prefix of any other codeword. As a result, the incoming subcarrier index bits can be uniquely mapped to the subcarrier activation patterns. Moreover, the bijective function of Table I between the codewords and the subcarrier patterns facilitates unambiguous decoding of the mapping patterns to the index bits transmitted. To be more specific, the incoming index bits b_2 of Fig. 2 are sequentially and uniquely mapped to the subcarrier activation patterns $\boldsymbol{a}_i^k$. As shown in Table I for the probabilities $\mathfrak{p} = \left\{\frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}\right\}$, if the incoming bit 1 is followed by another 1, then the subcarriers 3 and 4 (corresponding to pattern $\boldsymbol{a}_6^k = (3,4)^T$) are activated for the parallel block k. However, if the first 1 is followed by a 0, then the subcarriers 2 and 4 (corresponding to pattern $\boldsymbol{a}_5^k = (2,4)^T$) are activated for the $k-$th subblock. Similarly, for the first incoming bit of 0, there are 4 different patterns of activating the subcarriers. Bearing in mind the variable length of the bit-pattern to be mapped to the subcarriers, the average number of index bits per subcarrier activation pattern may be computed as $\frac{1}{6}\times 2+\frac{1}{6}\times 2+\frac{1}{6}\times 4+\frac{1}{6}\times 4+\frac{1}{6}\times 4+\frac{1}{6}\times 4 = 2.67$ bits.

On the other hand, when the probabilities are $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{6}, \frac{1}{6}, \frac{1}{12}, \frac{1}{12}\right\}$, the mapping of the incoming bits b_2 of Fig. 2 is shown in Table II. Due to the unique prefix property of Huffman coding, all the potential incoming bit combinations are included in Table II, where the bit sequences are unambiguously mapped to the subcarrier activation patterns $\boldsymbol{a}_1^k = (1,2)^T, \boldsymbol{a}_2^k = (1,3)^T, \boldsymbol{a}_3^k = (1,4)^T, \boldsymbol{a}_4^k = (2,3)^T, \boldsymbol{a}_5^k = (2,4)^T$ and $\boldsymbol{a}_6^k = (3,4)^T$ during the $k-$th subblock duration. Since there is a one-to-one correspondence between the codeword bit sequences and the subcarrier activation patterns, the subcarriers activated for subblock k can be uniquely decoded to the subcarrier index bits. Table II illustrates the variable-length codewords mapped to subcarriers activated for probabilities $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{6}, \frac{1}{6}, \frac{1}{12}, \frac{1}{12}\right\}$. Under these probability values, the average number of bits transmitted via the subcarrier indices are $\frac{1}{4}\times 2+\frac{1}{4}\times 2+\frac{1}{6}\times 2+\frac{1}{6}\times 3+\frac{1}{12}\times 4+\frac{1}{12}\times 4 = 2.50$ bits.

The proposed adaptive SIM-OFDM system finds the set of probabilities $\mathfrak{p}$ in order to optimize its performance. The optimization problem may be formulated as

$$\begin{aligned} \max_{\mathfrak{p}}/\min \quad & F(\mathfrak{p}) \\ \text{s.t.} \quad & \mathfrak{p} \in \mathbb{P} \end{aligned} \tag{16}$$

where $F(\mathfrak{p})$ is the objective function (OF) dependent on the probabilities $\mathfrak{p}$ and $\mathbb{P}$ is the legitimate domain of $\mathfrak{p}$. Considering the binary nature of the bit mapping as well as of the Huffman coding tree and the number of combinations available for activating N_a out of N_b subcarriers, we consider the following discrete set as the domain of $\mathfrak{p}$:

$$\mathbb{P} = \left\{ \begin{array}{ll} \mathfrak{p} \mid \sum_{i=1}^{\alpha} p_i = 1, & p_i = 0, 1, 2^{-1}, 2^{-2}, \cdots, 2^{-\beta}, \\ & \alpha^{-1}, (2\alpha)^{-1}, \cdots, (2\alpha)^{-\beta} \end{array} \right\}, \tag{17}$$

where β is the probability search depth and $1 \leq \beta \leq N_b$.

IV. Capacity-Optimal, Symbol Error Rate (SER-) Optimal and EE-Optimal Adaptive SIM-OFDM

In this secttion, we propose the capacity-optimal, the SER-optimal and the EE-optimal design of our adaptive SIM-OFDM system. Specifically, we optimize our system for maximizing the OF of capacity, SER as well as EE for finding the best set of probabilities, $\mathfrak{p}$.

A. Capacity-Optimal Design

In this approach, our objective is to find $\mathfrak{p}$, which maximizes the capacity of our adaptive SIM-OFDM system. The problem is formulated as:

$$\begin{aligned} \max_{\mathfrak{p}} \quad & C(\mathfrak{p}) \\ \text{s.t.} \quad & \mathfrak{p} \in \mathbb{P}. \end{aligned} \tag{18}$$

Consider the system model given by (9). When the subcarrier activation pattern $\boldsymbol{a}_i^k$ is encountered in the $k-$th subblock, the received signal corresponding to the $k-$th subblock may be expressed by

$$\boldsymbol{Y}_i^k = \tilde{\boldsymbol{H}}_i^k \boldsymbol{X}_i^k + \boldsymbol{V}_i^k, \tag{19}$$

where

$$\boldsymbol{Y}_i^k = \boldsymbol{Y}^k \mid \left(\boldsymbol{a}^k = \boldsymbol{a}_i^k\right) \in \mathbb{C}^{N_b \times 1}, \tag{20}$$

$$\begin{aligned} \tilde{\boldsymbol{H}}_i^k &= \operatorname{diag}\{\tilde{H}[1], \tilde{H}[2], ..., \tilde{H}[N_b]\} \\ &= \underbrace{\begin{bmatrix} \tilde{H}[1] & 0 & 0 & 0 \\ 0 & \tilde{H}[1] & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \tilde{H}[N_b] \end{bmatrix}}_{\substack{N_a \text{ out of } N_b \text{ diagonal} \\ \text{elements are nonzero}}} \in \mathbb{C}^{N_b \times N_b} \end{aligned} \tag{21}$$

and

$$\boldsymbol{X}_i^k = \underbrace{\begin{bmatrix} S^k[1] \\ 0 \\ S^k[2] \\ 0 \\ \vdots \\ S^k[N_a] \end{bmatrix}}_{\substack{N_a \text{ out of} \\ N_b \text{ elements} \\ \text{are nonzero}}} \mid \left(\boldsymbol{a}^k = \boldsymbol{a}_i^k\right) \in \mathbb{C}^{N_b \times 1}. \tag{22}$$

For the sake of notational simplicity, we denote the conditional probability density function (PDF) $f\left(\boldsymbol{Y}^k \mid \boldsymbol{a}^k = \boldsymbol{a}_i^k\right) \ , \forall k$ by $f_i(Y)$, and we have, $f(Y) = \sum_{i=1}^{\alpha} p_i f_i(Y)$.

The capacity of the scheme may be expressed in terms of the mutual information $I(X;Y)$ in a manner similar to [18]

$$C = (C_1 + C_2), \tag{23}$$

where $C_1 = I\left(\boldsymbol{X}^k; \boldsymbol{Y}^k \mid \boldsymbol{a}^k\right) \ , \forall k$ represents the amount of information transmitted using the $\mathcal{L}-$PSK/QAM symbols, whereas $C_2 = I\left(\boldsymbol{a}^k; \boldsymbol{Y}^k\right) \ , \forall k$ denotes the information mapped to the specific indices of the subcarries activated.

Furthermore, denoting the signal-to-noise ratio (SNR) by $\gamma = \sigma_X^2/N_0$, where σ_X^2 is the transmit signal power of each of the subcarriers, C_1 and C_2 may be expressed [18], [38], [46] by

$$C_1 = I\left(\boldsymbol{X}^k; \boldsymbol{Y}^k \mid \boldsymbol{a}^k\right) = \sum_{i=1}^{\alpha} p_i \log_2 \left(1 + \gamma \sum_{k=1}^{K} \|\tilde{\boldsymbol{H}}_i^k\|^2\right) \tag{24}$$

and

$$C_2 = I\left(\boldsymbol{a}^k; \boldsymbol{Y}^k\right) = \sum_{i=1}^{\alpha} p_i \int_Y f_i(Y) \log_2 \frac{f_i(Y)}{f(Y)} dY. \tag{25}$$

It is difficult to further simplify (25) to obtain a closed-form expression. However, both the upper and the lower bound of C_2 may be found similarly to [18], [38], [46]

$$C_2^{\text{upper}} = \underbrace{\sum_{i=1}^{\alpha} p_i \log_2 \left[\frac{1}{\sum_{j=1}^{\alpha} p_j e^{-B_{i,j}}}\right]}_{I^{\text{upper}}\left(\boldsymbol{a}^k; \boldsymbol{Y}^k\right)}, \tag{26}$$

and

$$C_2^{\text{lower}} = \underbrace{\sum_{i=1}^{\alpha} p_i \log_2 \left[\frac{1}{\sum_{j=1}^{\alpha} p_j D_{i,j}}\right]}_{I^{\text{lower}}\left(\boldsymbol{a}^k; \boldsymbol{Y}^k\right)}, \tag{27}$$

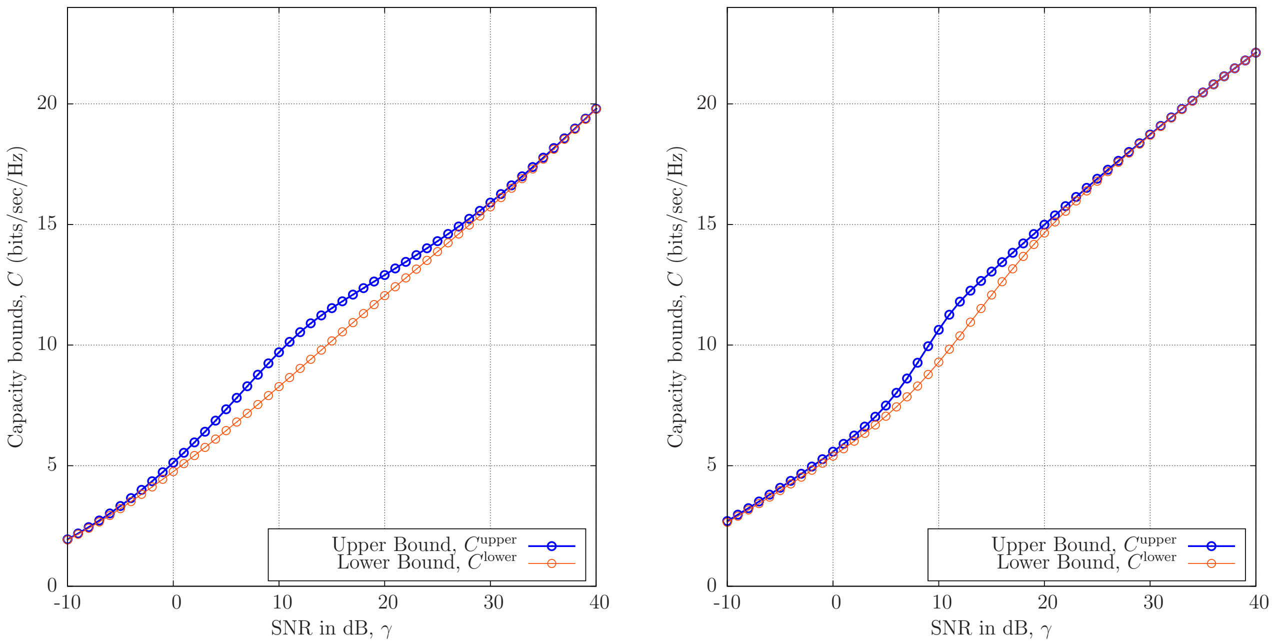


Fig. 4. (a) The upper as well as the lower bound on the capacity of the proposed adaptive SIM-OFDM system using $\mathfrak{p} = \left\{\frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}\right\}$. (b) The capacity upper and lower bounds employing $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}\right\}$.

respectively, where $B_{i,j}$ and $D_{i,j}$ are given by

$$B_{i,j} = \ln \frac{1+\gamma\sum_{k=1}^{K}\|\tilde{\boldsymbol{H}}_j^k\|^2}{1+\gamma\|\tilde{\boldsymbol{H}}_i\|^2} + \frac{\gamma\sum_{k=1}^{K}\left(\|\tilde{\boldsymbol{H}}_i^k\|^2-\|\tilde{\boldsymbol{H}}_j^k\|^2\right)}{1+\gamma\|\tilde{\boldsymbol{H}}_j\|^2} + \frac{\gamma^2\sum_{k=1}^{K}\left(\|\tilde{\boldsymbol{H}}_i^k\|^2\|\tilde{\boldsymbol{H}}_j^k\|^2-\|\left(\tilde{\boldsymbol{H}}_i^k\right)^H\tilde{\boldsymbol{H}}_j^k\|^2\right)}{1+\gamma\sum_{k=1}^{K}\|\tilde{\boldsymbol{H}}_j\|^2}, \tag{28}$$

and

$$D_{i,j} = \frac{\sqrt{\left(1+\gamma\sum_{k=1}^{K}\|\tilde{\boldsymbol{H}}_i^k\|^2\right)\left(1+\gamma\sum_{k=1}^{K}\|\tilde{\boldsymbol{H}}_j^k\|^2\right)}}{\left(1+\frac{\gamma\sum_{k=1}^{K}\left(\|\tilde{\boldsymbol{H}}_i\|^2+\|\tilde{\boldsymbol{H}}_j\|^2\right)}{2}+\frac{\gamma^2\sum_{k=1}^{K}\left(\|\tilde{\boldsymbol{H}}_i^k\|^2\|\tilde{\boldsymbol{H}}_j^k\|^2-\|\left(\tilde{\boldsymbol{H}}_i^k\right)^H\tilde{\boldsymbol{H}}_j^k\|^2\right)}{4}\right)}, \tag{29}$$

respectively.

Observe in (26) and (28) that $B_{i,i} = 0$ and $0 \leq B_{i,j} \leq 1 \quad (i \neq j)$. Thus, we have $0 \leq I^{\text{upper}}\left(\boldsymbol{a}^k; \boldsymbol{Y}^k\right) \quad \forall k \leq \sum_{i=1}^{\alpha} p_i \log_2\left[\frac{1}{p_i}\right]$, where $\sum_{i=1}^{\alpha} p_i \log_2\left[\frac{1}{p_i}\right]$ is exactly the information conveyed via the subcarrier activation pattern. Similarly, we obtain $0 \leq I^{\text{lower}}\left(\boldsymbol{a}^k; \boldsymbol{Y}^k\right) \leq \sum_{i=1}^{\alpha} p_i \log_2\left[\frac{1}{p_i}\right] \quad \forall k$ from (27) and (29).

Fig. 4 portrays the capacity bounds of $C^{\text{upper}} = \left(C_1 + C_2^{\text{upper}}\right)$ and $C^{\text{lower}} = \left(C_1 + C_2^{\text{lower}}\right)$ as given by (24), (26) and (27) using $N_b = 4$, $N_a = 2$ and the set of probabilities $\mathfrak{p} = \left\{\frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}\right\}$ and $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}\right\}$. As seen in Fig. 4, the upper and the lower bounds $C^{\text{upper}}$and C^{lower} on the capacity are tight for both the two sets of probabilities. Thus either C^{upper} or C^{lower} may be taken as a measure of $C(\mathfrak{p})$ for the optimization of the probabilities given by $\mathfrak{p}$.

B. Symbol Error Rate (SER-) Optimal Design

In this approach, the adaptive SIM-OFDM finds the specific set of probabilities $\mathfrak{p}$, which minimizes the SER.

Considering the system model of (9), the condititonal pairwise symbol error probability (PSEP) of misinterpreting the transmit vector $\boldsymbol{X}^k$ corresponding to a specific subcarrier activation pattern $\boldsymbol{a}^k$ for $\tilde{\boldsymbol{X}}^k$, which corresponds to another subcarrier pattern $\tilde{\boldsymbol{a}}^k$, may be expressed by [7]

$$\Pr\left(\boldsymbol{X}^k \rightarrow \tilde{\boldsymbol{X}}^k \mid \tilde{\boldsymbol{H}}^k\right) = Q\left(\sqrt{\frac{d^2}{2\sigma_V^2}}\right), \tag{30}$$

where

$$d^2 = \left\|\tilde{\boldsymbol{H}}^k\left(\boldsymbol{X}^k - \tilde{\boldsymbol{X}}^k\right)\right\| = \left(\tilde{\boldsymbol{H}}^k\right)^H \boldsymbol{\Lambda}\tilde{\boldsymbol{H}}^k \tag{31}$$

and

$$\boldsymbol{\Lambda} = \left(\boldsymbol{X}^k - \tilde{\boldsymbol{X}}^k\right)^H\left(\boldsymbol{X}^k - \tilde{\boldsymbol{X}}^k\right). \tag{32}$$

Furthermore, the unconditional PSEP of misinterpreting $\boldsymbol{X}^k$ for $\tilde{\boldsymbol{X}}^k$ depending on the set of probabilities $\mathfrak{p}$ may be expressed as [7]

$$\begin{aligned}\text{SER}(\mathfrak{p}) =& \Pr\left(\boldsymbol{X}^k \rightarrow \tilde{\boldsymbol{X}}^k\right)\\ =& \frac{1/12}{|\boldsymbol{I}_{N_b} + q_1 \boldsymbol{K}_{N_b}\boldsymbol{\Lambda}|} + \frac{1/4}{|\boldsymbol{I}_{N_b} + q_2 \boldsymbol{K}_{N_b}\boldsymbol{\Lambda}|},\end{aligned} \tag{33}$$

where $q_1 = 1/(4N_0)$, $q_2 = 1/(3N_0)$ and $\boldsymbol{K}_{N_b}$ is defined by

$$\boldsymbol{K}_{N_b} \triangleq \mathcal{E}\left\{\left(\tilde{\boldsymbol{H}}^k\right)^H \tilde{\boldsymbol{H}}^k\right\}. \tag{34}$$

The optimization problem for the SER-optimal design of our adaptive SIM-OFDM may thus be formulated as

$$\begin{aligned}\min_{\mathfrak{p}} \quad & \text{SER}(\mathfrak{p})\\ \text{s.t.} \quad & \mathfrak{p} \in \mathbb{P}.\end{aligned} \tag{35}$$

Specifically, we consider only the legitimate values of $\mathfrak{p}$ based on the discrete domain of (17). The sets of probabilities $\mathfrak{p} \in \mathbb{P}$ are then used for mapping the incoming index bits to the *candidate* transmit vector $\breve{\boldsymbol{X}}^k$. The unconditional PSEP for all these candidate $\breve{\boldsymbol{X}}^k$ are calculated using (33) and the value of $\mathfrak{p}$, which provides the minimum unconditional PSEP based on the optimization of (35), which is then used by the Huffman mapper to map the index bits to the subcarrier activation pattern.

C. EE-Optimal Design

In this section, we design Huffman mapping aided adaptive SIM-OFDM scheme by employing the probabilities $\mathfrak{p}$ gleaned from the EE optimization of the system. We adopt the 'bit-per-Joule' definition [47] of EE here, in the context of frequency-selective channels, as detailed in [48], [49]. To be specific, the EE of our scheme is defined by the transmission data rate R per unit energy usage. The total power consumed by the transmission of a single subblock of our SIM-OFDM system may be expressed as $P_T = P_c + \frac{1}{\zeta}\sum_{n_a=1}^{N_a} P_{n_a}$, where P_c denotes the circuit power representing the average energy consumption of device electronics such as filters, digital-to-analog converters etc. excluding that of the power amplifiers involved in the transmission. Furthermore, $\zeta \in [0,1]$ indicates the power amplifier efficiency and P_{n_a} refers to the per subcarrier signal power of $P_{n_a} = \sigma_X^2 \quad \forall n_a$, which may be expressed in terms of the SNR as $P_{n_a} = \gamma N_0$. The EE of the system may thus be expressed as [48]

$$\eta_{\text{EE}} = \frac{R}{P_c + \frac{1}{\zeta}\sum_{n_a=1}^{N_a} P_{n_a}}. \tag{36}$$

Since the achievable rate of the system may be expressed in terms of the mutual information given by (23) and as the upper and the lower bounds on the capacity given by $\left(C_1 + C_2^{\text{upper}}\right)$and $\left(C_1 + C_2^{\text{lower}}\right)$ are tight, we may consider the transmission rate to be equal to $\left(C_1 + C_2^{\text{lower}}\right)$. Thus, considering equal EE performance for each of the K parallel blocks, we have

$$\eta_{\text{EE}} = \frac{\sum_{i=1}^{\alpha} p_i \log_2\left(1 + \gamma\|\tilde{\boldsymbol{H}}_i^k\|^2\right) + \sum_{i=1}^{\alpha} p_i \log_2\left[\frac{1}{\sum_{j=1}^{\alpha} p_j D_{i,j}}\right]}{P_c + \frac{N_a \gamma N_0}{\zeta}}. \tag{37}$$

Having defined the EE in terms of the probabilities p_i in (37), the optimum set $\mathfrak{p}$ of probabilities may be obtained by solving

$$\begin{aligned}\min_{\mathfrak{p}} \quad & \eta_{\text{EE}}(\mathfrak{p})\\ \text{s.t.} \quad & \mathfrak{p} \in \mathbb{P}.\end{aligned} \tag{38}$$

The optimized set $\mathfrak{p}$ of probabilities may now be used for mapping the index bits to the subcarrier activation patterns of (6) by the Huffman coding aided principle.

V. Numerical Results

In this section, we numerically characterize our entropy-coding assisted adaptive SIM-OFDM system in terms of its capacity, bit-error-ratio (BER) and EE.

A. Capacity

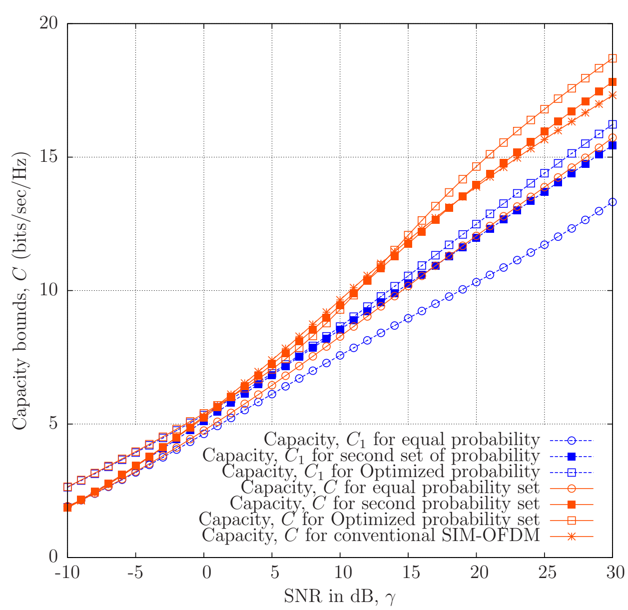


Fig. 5. Capacity of the proposed SIM-OFDM system in dispersive COST207-RA channels having a normalized Doppler frequency of $f_d = 0.01$. The capacity of the proposed scheme is computed under different scenario as listed in Table III and employing a set of equal probabilities of $\mathfrak{p} = \left\{\frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}\right\}$ as well as a second set of $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}\right\}$ and is compared with that of the classic SIM-OFDM benchmarker.

We investigate the information theoretic capacity of the proposed adaptive SIM-OFDM system in Fig. 5 employing a set of equal probabilities of $\mathfrak{p} = \left\{\frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}\right\}$ as well as a second set of $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}\right\}$ and using the

Table III
MAIN SIMULATION PARAMETERS

Channel model	COST207-RA
Fast fading envelope	Rayleigh
Normalized Doppler frequency	0.01
No. of subcarriers, N_c	64
CP length	32
Modulation order, $\mathcal{L}$	2/ 4
Number of parallel subblocks, K	16
Circuit Power P_c	100 mW=0.1 J/sec
Power amplifier efficiency ζ	0.8

optimization of (18). The capacity C as given by (23) is shown for the above-mentioned probabilities and the capacity C_1 as given by (24) is also shown. This gives us an idea of how the total capacity C is divided between the capacity of the constellation symbols C_1 and the capacity C_2 of the subcarrier indices. The capacity of the classic SIM-OFDM system of [7], [9], [13] is also shown as a benchmarker. We observe that our adaptive SIM-OFDM scheme outperforms the classic SIM-OFDM scheme. This is because we are capable of adaptively selecting the best set of probabilities with the aid of the Huffman variable-length mapping, whereas the conventional SIM-OFDM scheme only employs the equal-probability scenario. In addition, the variable-length codebook facilitates the employment of all the legitimate $\binom{N_b}{N_a}$ subcarrier activation patterns, while the classic SIM-OFDM system can only cater for $2^{\left\lfloor \log_2 \binom{N_b}{N_a} \right\rfloor}$ number of patterns to be activated.

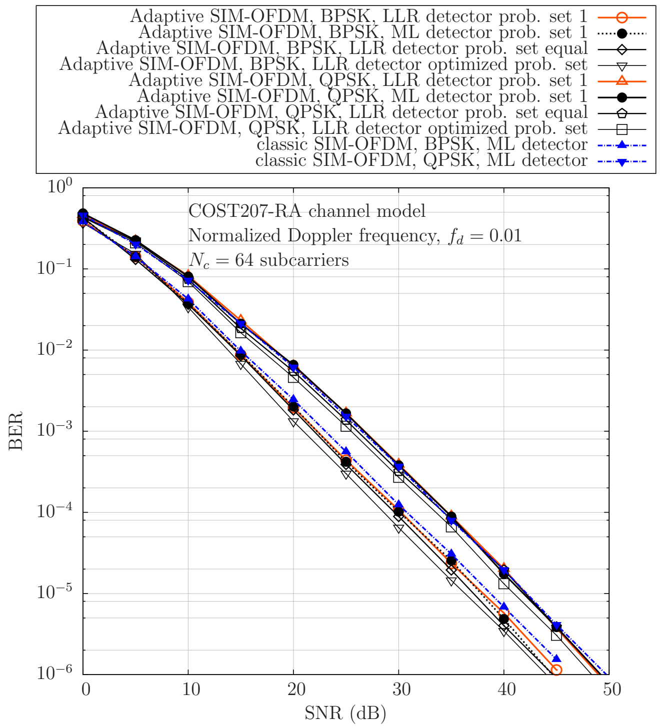


Fig. 6. Bit-error-performance of the proposed adaptive SIM-OFDM system in conjunction with the $\mathcal{L}-$ary modulation in dispersive COST207-RA channels having a normalized Doppler frequency of $f_d = 0.01$ employing both the ML detector and the reduced-complexity soft-decision detector of Section II-C1 and Section II-C2 respectively. The performance with different probability set as well as an optimized set of probabilities are shown and are compared with those of the correspondingclassic SIM-OFDM benchmarkers.

B. Bit Error Performance

Fig. 6 portrays the BER of the proposed adaptive SIM-OFDM system employing both the ML detector of Section II-C1 and the soft-decision LLR detector of Section II-C2. We have considered the dispersive COST207-RA channel model of [50] having a normalized Doppler frequency of $f_d = 0.01$. The main simulation parameters of this investigation are listed in Table III. We have considered both BPSK and QPSK modulation with the aid of $N_c = 64$ OFDM subcarriers and CPs of appropriate length were appended to each OFDM symbol in order to eliminate the intersysmbol interference (ISI). Observe that the LLR detector provides a performance similar to that attained by the ML detector. This is because the LLRs defined by (13) for the soft-decision detector are expressed in terms of the ML metric of minimizing the error probability, which depends on the Euclidean distance between any two symbols. We observe that our scheme provides a better BER performance than its classic SIM-OFDM counterpart, especially when appropriately optimized.

To compare the performance for different probability search depths as given by β of (17), we have investigated the BER performance of the proposed adaptive SIM-OFDM system in Fig. 7. To be specific, since we have considered $N_b = 4$, $N_a = 2$, we have $\alpha = \binom{4}{2} = 6$ and hence we can consider $p_i = 0, 1, 1/2, 1/4, 1/8, 1/6, 1/3$ from (17). Using these values, the legitimate set of probabilities can be considered, while ensuring that $\sum_{i=1}^{6} p_i = 1$. Using a lower β value will give us a lower number of probability set. However, reducing β and the associated number of probability sets may degrade the performance. Fig. 7 illustrates the BER performance of our proposed adaptive SIM-OFDM system for $\beta = 1, 2, 3$. We observe that reducing β from 3 to 2 does not significantly degrade the performance under this specific scenario, but an excessive reduction of β leading to having only a few sets pf probabilities is expected to degrade the performance.

C. Energy-Efficiency

In Fig. 8, we have investigated the EE of our proposed adaptive SIM-OFDM system as given by (37). We adopted the parameters listed in Table III and considered the set of probabilities $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}\right\}$in Fig. 8. We also show the EE of the optimized adaptive SIM-OFDM against that of the classic SIM-OFDM system. We observe that the adaptive SIM-OFDM scheme is capable of outperforming the classic SIM-OFDM of [7], [9], [13] in terms of its EE.

VI. CONCLUSIONS

In this paper, we proposed a novel adaptive subcarrier index modulated OFDM system with the aid of the Huffman entropy coding principle. The source information is mapped to the subcarriers of an OFDM system as well as to the indices

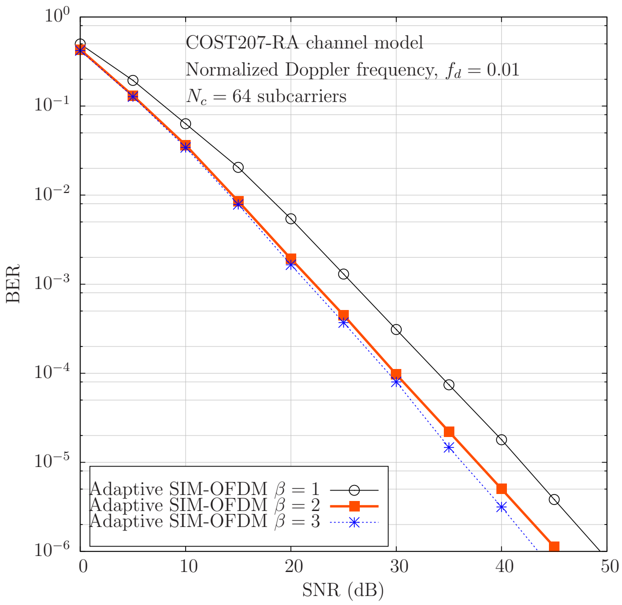


Fig. 7. The bit-error-ratio performance of the proposed adaptive SIM-OFDM system is investigated for different probability search depths as given by β of (17).

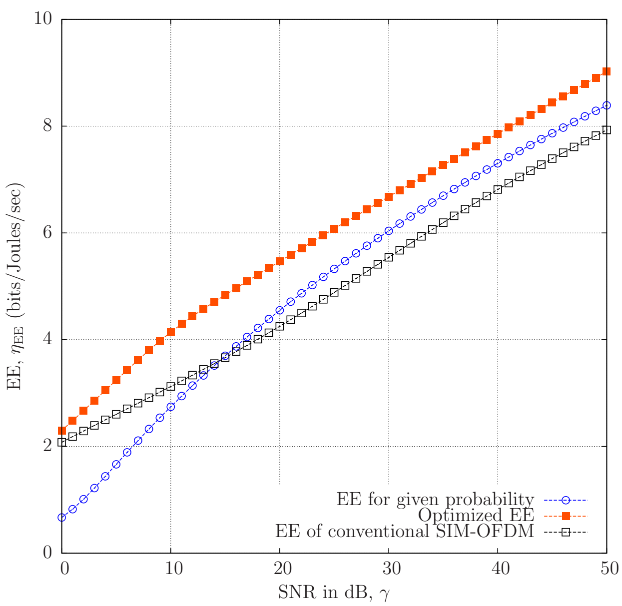


Fig. 8. The EE of the adaptive SIM-OFDM scheme employing the probability set of $\mathfrak{p} = \left\{\frac{1}{4}, \frac{1}{4}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}\right\}$ as well as with the optimized set of probabilities are shown against that of the conventional SIM-OFDM scheme. Our optimized adaptive SIM-OFDM scheme outperforms the classic SIM-OFDM scheme of [7], [9].

of the subcarriers activated like in the SIM-OFDM system. However, rather than mapping the index bits equiprobably to the subcarrier activation patterns, we map them using specific probabilities gleaned from an optimization procedure. These probabilties are then employed by Huffman coding for generating a codebook in order to map the index information bits to the subcarriers activated. The employment of the variable-length codebook has the advantage that we are capable of employing all the legitimate patterns of subcarriers to be activated, while the conventional SIM-OFDM schemes can only use a subset of these patterns. Additionally, the probability used in Huffman coding can be adaptively chosen in order to optimize either the channel capacity, or the error performance, or alternatively the EE of the system. A pareto-optimal design of the adaptive SIM-OFDM system constitutes a promising open problem for future study.

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