Single-Carrier Frequency-Domain Equalization With Index Modulation

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***Abstract*—Motivated by the recent index modulation (IM) concept in the spatial, frequency, and space-time domains, we propose a novel broadband single-carrier (SC)-based IM (SC-IM) scheme as well as its low-complexity frequency-domain equalization (FDE) algorithm. The proposed FDE-aided SC-IM scheme outperforms the conventional FDE-aided SC scheme, while achieving a comparable low level of detection complexity. In addition, in order to reduce the inter-channel correlation arising from the activated symbol indices, we propose a symbol mapping algorithm, which further improves the achievable error-rate performance of the SC-IM scheme. Our simulation results demonstrate the performance advantage of the proposed FDE-aided SC-IM scheme over the conventional FDE-aided SC scheme.**

***Index Terms*—Broadband, cyclic prefix, fast Fourier transform, frequency-domain equalization, index modulation, single carrier.**

I. Introduction

INDEX modulation (IM) is the recent popular modulation concept, which is able to convey information by activating a subset of indices, in addition to the classic amplitude and phase shift keying (APSK), such as phase-shift keying (PSK) and quadrature amplitude modulation (QAM). More specifically, the IM concept has been introduced in communication systems, where additional information is modulated in the spatial [1], [2], the frequency [3], [4], the space-time [5], [6], and the beam-space [7], [8] domains. The spatial modulation (SM) scheme is an IM scheme that operates in the spatial (antenna) dimension [1], [2], where one out of multiple transmit antenna elements is activated during each symbol interval, thus increasing the amount of information that the activated antenna index can convey. Hence, the SM scheme is capable of increasing the transmission rate, by increasing the number of transmit antenna elements, while maintaining a low-cost single radio frequency (RF) transmitter.

Orthogonal frequency-domain modulation (OFDM) with IM (OFDM-IM) [3], [4] is an IM scheme that is used in the frequency dimension, where a subset of the subcarriers is activated in each OFDM frame, in order to transmit additional information. The OFDM-IM scheme tends to exhibit an improvement in performance compared to the conventional OFDM scheme, especially in a low-rate scenario. However, the OFDM-IM scheme typically exhibits a high peak-to-average power ratio (PAPR) and a high power-backing off, which are comparable to those for the conventional OFDM scheme, as mentioned in [4]. Additionally, in [9] Chung proposed the generalized OFDM framework, referred to as orthogonally multiplexed orthogonal amplitude modulation (OMOAM), where the orthogonal multiplexing and grouping methods were used in the frequency domain with pulse amplitude signaling, and hence it is capable of striking a tradeoff between the transmission rate, the error rate, and the PAPR.

In addition to multicarrier communications systems, such as the above-mentioned OFDM and OFDM-IM schemes, single-carrier (SC) symbol transmission with frequency-domain equalization (FDE) [10]–[12] is a promising broadband wireless technique. More specifically, the FDE allows us to attain a low detection complexity, even when experiencing the long-tap channel impulse responses (CIRs) which are encountered in the practical broadband dispersive channels. Since the FDE-aided SC scheme is capable of attaining a significantly lower PAPR than the OFDM family, the FDE-aided SC scheme is typically employed in the uplink scenario of the current standards, where the use of a low-cost amplifier at mobile terminals is desirable. As for the receiver of broadband SC scheme exploiting the IM concept, the time-domain equalization was developed for the SM scheme in [13], while its FDE counterpart was proposed in [14]. To the best of our knowledge, the IM concept has not been used for the FDE-aided SC scheme before.

Against this background, the contributions of this letter are as follows. We propose a novel broadband SC scheme, combined with the IM concept, which is referred to as the SC-IM scheme in this letter. In the SC-IM scheme, activated indices of time-domain symbols in subframes convey additional information, hence increasing the transmission rate. Then, a low-complexity FDE algorithm is introduced for the SC-IM scheme. In order to further improve the performance of the FDE-aided SC-IM scheme, we also propose a symbol mapping scheme, which is capable of reducing the inter-channel correlation between the symbols in the SC-IM subframe. Our simulation results demonstrate an improvement in the performance of the proposed FDE-aided SC-IM scheme over the conventional FDE-aided SC scheme.

II. System Model

A. SC-IM Signaling

The signaling model for our SC-IM scheme is shown in the upper part of Fig. 1. Similar to the conventional FDE-aided SC scheme, N-length data symbols $\mathbf{s} = [s_1, \cdots, s_N]^T \in \mathbb{C}^N$ and the J-length cyclic prefix (CP) are included in each frame of the SC-IM scheme. The data symbols $\mathbf{s}$ consist of L subframes as follows: $\mathbf{s} = [\mathbf{s}^{(1)T}, \cdots, \mathbf{s}^{(L)T}]^T$, where we have $\mathbf{s}^{(l)} =$

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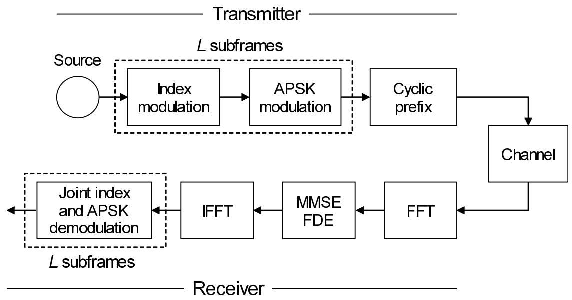


Fig. 1. Transceiver structure of proposed FDE-aided SC-IM scheme.

$[s_1^{(l)}, \cdots, s_M^{(l)}] \in \mathbb{C}^M$ $(l = 1, \cdots, L)$. Each subframe spans M symbol durations. This implies that $N = L \cdot M$. The $(N+\nu)$ SC-IM frame is transmitted over the J-tap frequency-selective fading channel, with coefficients $\mathbf{h} = [h_0, \cdots, h_{J-1}]^T \in \mathbb{C}^J$.

In each SC-IM subframe $\mathbf{s}^{(l)}$, K out of M symbols are selected for the P-point APSK modulation, while the remaining $(M-K)$ symbols are set to zero. More specifically, a B_1 information bit sequence, $\mathbf{b}_1 \in \mathbb{Z}^{B_1}$, is used to modulate the activated symbol indices, and the B_2 bit sequence $\mathbf{b}_2 \in \mathbb{Z}^{B_2}$ is used to modulate the K APSK symbols Note that the K non-zero APSK-modulated symbols are scaled by $\sqrt{M/K}$, so that the average transmission power per subframe is unity, i.e., $\sum_{m=1}^{M} |s_m^{(l)}|^2/M = 1$. Hence, $B = B_1 + B_2$ information bits are used to modulate the non-zero indices as well as the classic APSK symbols in each SC-IM subframe.

For example, let us consider the SC-IM parameters $(M, K, P) = (4, 1, 2)$, where one out of four symbols is activated in each SC-IM subframe, while employing binary PSK (BPSK) modulation. Then, the legitimate symbol sequences for the SC-IM subframe are represented by

$$\mathbf{s}^{(l)} \in \left\{ \begin{bmatrix} \pm 2 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ \pm 2 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ \pm 2 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ \pm 2 \end{bmatrix} \right\}, \tag{1}$$

noting that $B = 3$ bits are used to modulate each SC-IM subframe in this specific scenario.

The normalized throughput of our FDE-aided SC-IM scheme is given by

$$R = \frac{N}{N+\nu} \cdot \frac{K \log_2 P + \left\lfloor \log_2 \binom{M}{K} \right\rfloor}{M} \text{ [bits/symbol]}, \tag{2}$$

where the coefficient $N/(N+\nu)$ represents the rate loss from CP insertion. Furthermore, the power penalty imposed by the CP is $10 \log_{10}[(N+\nu)/N]$ dB. This power loss becomes marginal for long block-size scenarios, which is similar to the loss for the OFDM and the conventional FDE-aided SC schemes.

B. FDE for SC-IM

At the receiver, the SC-IM symbols are detected according to the minimum mean-square error (MMSE)-FDE, which corresponds to the lower half of Fig. 1. Firstly, by removing the ν-length signals associated with the CP from the total $(N+\nu)$ received signals in each SC-IM frame, we arrive at the N-length received signal block, which is represented by

$$\begin{aligned} \mathbf{y} &= [y_1, \cdots, y_N]^T \in \mathbb{C}^N \\ &= \mathbf{Hs} + \mathbf{n}, \end{aligned} \tag{3}$$

where $\mathbf{n} = [\eta_1, \cdots, \eta_N]^T \in \mathbb{C}^N$ represent the corresponding additive white Gaussian noise (AWGN) components, which are given by complex-valued Gaussian random variables with zero-mean $\mathcal{CN}(0, N_0)$, and variance N_0. Furthermore, the channel matrix $\mathbf{H}$ has a circulant structure, consisting of the J-length channel coefficients $\mathbf{h}$.

In this letter, we focus our attention on the use of the MMSE-FDE for detecting the transmitted SC-IM symbols $\mathbf{s}$. Since the channel matrix $\mathbf{H}$ has a circulant structure, we obtain the eigenvalue decomposition of $\mathbf{H} = \mathbf{Q}^T \Lambda \mathbf{Q}^*$, where $\mathbf{Q} \in \mathbb{C}^{N \times N}$ are the eigenvectors. At our FDE-aided SC-IM receiver, the received signals, represented in the time domain, are transformed to their frequency-domain counterparts as follows:

$$\mathbf{y}_f = \mathbf{Q}^* \mathbf{y} \tag{4}$$
$$= \Lambda \mathbf{Q}^* \mathbf{s} + \mathbf{Q}^* \mathbf{n} \tag{5}$$
$$= \Lambda \mathbf{s}_f + \mathbf{n}_f, \tag{6}$$

where $\mathbf{s}_f$ and $\mathbf{n}_f$ correspond to the frequency-domain signal and noise vectors, respectively. Then, the diagonal MMSE weights $\mathbf{W} \in \mathbb{C}^{N \times N}$ can be readily obtained according to

$$w_{(i,i)} = \lambda^*_{(i,i)} / (|\lambda_{(i,i)}|^2 + N_0). \tag{7}$$

Here, $w_{(i,i)}$ and $\lambda_{(i,i)}$ represent the ith-row and ith-column elements of $\mathbf{W}$ and Λ, respectively. Finally, we arrive at the time-domain symbol estimates:

$$\hat{\mathbf{s}} = [\hat{\mathbf{s}}^{(1)T}, \cdots, \hat{\mathbf{s}}^{(L)T}]^T = \mathbf{Q}^T \mathbf{W} \mathbf{y}_f \tag{8}$$

In order to elaborate a little further, the MMSE weight calculation of (7) as well as the channel inversion operation of (8) are implemented efficiently by exploiting the diagonal structure of $\mathbf{W}$.

Finally, $(\mathbf{b}_1, \mathbf{b}_2)$, which are used to modulate the lth SC-IM subframe, are estimated by the exhaustive search as follows:

$$(\hat{\mathbf{b}}_1, \hat{\mathbf{b}}_2) = \arg \min_{(\mathbf{b}_1, \mathbf{b}_2)} \left\| \hat{\mathbf{s}}^{(l)} - \mathbf{s}^{(l)} \Big|_{(\mathbf{b}_1, \mathbf{b}_2)} \right\|. \tag{9}$$

The computational complexity of the exhaustive search of (9) is imposed on the SC-IM scheme, but not on the conventional SC scheme. However, the resulting complexity is not significantly high for moderate sizes of (M, K), since (9) does not contain the channel coefficients. Furthermore, it may be reduced with the aid of log-likelihood ratio detection [15] and successive detection [16], which were developed for the OFDM-IM and the SM schemes.

C. Error-Rate Analysis of SC-IM Scheme

In this section, we analytically derive the error-rate bound of the proposed SC-IM scheme under the assumption of employing optimal maximum-likelihood detection, which typically achieves the better error-rate performance than MMSE detection. By defining $\boldsymbol{\lambda} = [\lambda_{(1,1)}, \cdots, \lambda_{(N,N)}]^T$ and $\mathbf{S}_f =$

diag[$\mathbf{s}_f$], (6) is rewritten by $\mathbf{y}_f = \mathbf{S}_f\boldsymbol{\lambda} + \mathbf{n}_f$. Then, from this frequency-domain system model, the conditional pairwise error probability (PEP), where $\mathbf{S}_f$ is erroneously detected as $\mathbf{S}'_f$ is given by [17]

$$P(\mathbf{S}_f \rightarrow \mathbf{S}'_f|\boldsymbol{\lambda}) = Q\left(\sqrt{\left\|(\mathbf{S}_f - \mathbf{S}'_f)\boldsymbol{\lambda}\right\|^2/2N_0}\right), \quad (10)$$

where $Q(\cdot)$ is the Q-function [17]. Unlike in the conventional index-modulation schemes assuming the frequency-flat channels [18], [19], in general it is quite a challenging task to derive the closed-form unconditional PEP bound $P(\mathbf{S}_f \rightarrow \mathbf{S}'_f) = \mathbb{E}[P(\mathbf{S}_f \rightarrow \mathbf{S}'_f|\boldsymbol{\lambda})]$ for the FDE-aided SC scheme experiencing the frequency-selective channels [20]. Hence, the Monte Carlo simulations are typically needed for averaging the unconditional PEP. The analytical BER bound is calculated from the PEP $P(\mathbf{S}_f \rightarrow \mathbf{S}'_f)$ as [18]

$$P_{\rm ber} \leq \frac{1}{B2^B}\sum_{\mathbf{S}_f}\sum_{\mathbf{S}_f \neq \mathbf{S}'_f} d(\mathbf{S}_f, \mathbf{S}'_f)P(\mathbf{S}_f \rightarrow \mathbf{S}'_f), \quad (11)$$

where $d(\mathbf{S}_f, \mathbf{S}'_f)$ represents the Hamming distance between $\mathbf{S}_f$ and $\mathbf{S}'_f$.

III. Symbol Arrangement for Reduced-Correlation SC-IM Scheme

In general, the IM-based system typically suffers from performance degradation when there is a high correlation between the channels, which corresponds to indexed symbols. In order to combat this limitation, symbol mapping schemes to reduce the channel correlation were developed for the SM scheme [21] and the OFDM-IM scheme [19], [22], [23].

In this section, we propose a symbol arrangement algorithm which is capable of reducing the effects of inter-channel correlation for our SC-IM scheme. More specifically, in our SC-IM scheme, any two symbols which are transmitted within a J-length window typically suffer from the effects of inter-channel correlation, since the CIR length is J. This deteriorates the detection performance of information bits $\mathbf{b}_1$, which are associated with the activated symbol indices.

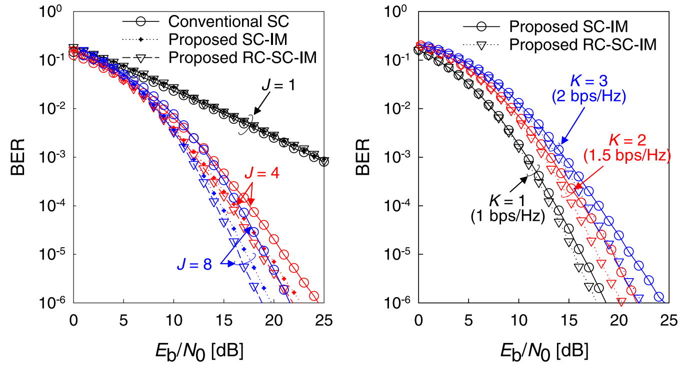
In the original SC-IM signaling of Section II-A, M symbols $\mathbf{s}^{(l)}$ in each SC-IM subframe are transmitted over the successive M symbol intervals. Hence, the corresponding transmitted symbol sequence in the time-domain is represented by

$$\{s_1^{(1)}, \cdots, s_M^{(1)}\}, \{s_1^{(2)}, \cdots, s_M^{(2)}\}, \cdots, \{s_1^{(L)}, \cdots, s_M^{(L)}\}. \quad (12)$$

By contrast, we propose a reduced-correlation (RC)-SC-IM symbol mapping scheme, where M symbols $\mathbf{s}^{(l)}$ in each SC-IM subframe are distributed over the entire L-length SC-IM frame, which is formatted as follows:

$$\{s_1^{(1)}, \cdots, s_1^{(L)}\}, \{s_2^{(1)}, \cdots, s_2^{(L)}\}, \cdots, \{s_M^{(1)}, \cdots, s_M^{(L)}\}.$$

When the delay spread J is lower than the number of subframes L, there is no additional channel correlation imposed by tap coefficients in the proposed symbol allocation scheme.



(a) $(M, K, P) = (4, 1, 4)$ (b) $(M, P) = (4, 4)$

Fig. 2. Achievable BER performance of proposed SC-IM scheme, proposed RC-SC-IM scheme, and conventional SC scheme, where MMSE-FDE was employed for each scheme. (a) The CIR length was given by $J = 1$, 4, and 8, while the normalized transmission rate was $R = 1$ bps/Hz. (b) The CIR length was given by $J = 8$, while varying the number of activated symbols per subframe from $K = 1$ to 3.

IV. Simulation Results

In this section we present the results of our simulations, in order to assess the performance of the SC-IM and RC-SC-IM transceivers. We assumed a frequency-selective Rayleigh fading channel, having a CIR length of J, where each fading coefficient was randomly generated according to the zero-mean complex-valued Gaussian distribution, having the variance of $1/J$. The block length and the CP length were set to $N = 256$ and $\nu = 32$, respectively, where the power penalty imposed by the CP insertion was as low as 0.51 dB. The conventional FDE-aided SC scheme was selected as the benchmark.

Fig. 2(a) shows the achievable BER performance for the SC-IM, RC-SC-IM, and SC schemes, where the FDE was employed for all three schemes. The IM parameters were set to $(M, K, P) = (4, 1, 4)$ for the SC-IM and RC-SC-IM schemes, while BPSK modulation was used for the SC scheme. Hence, the transmission rate for all three schemes was $R = 1$ bps/Hz. Furthermore, the delay spread was given by $J = 1$, 4, and 8. Let us observe in Fig. 2(a) that in the scenario of $J = 1$, corresponding to a narrowband frequency-flat fading channel, neither the SC-IM nor the RC-SC-IM scheme exhibited any performance advantage over the SC scheme. However, upon increasing the delay spread to $J = 4$ and 8, the RC-SC-IM scheme outperformed the SC scheme, where a performance gap of more than 2 dB was recorded for BER= 10^{-6}. Furthermore, in Fig. 2(b) we investigated the effects of number of activated symbols per subframe K, which was varied from $K = 1$ to 3, while maintaining $M = 4$. The CIR length was set to $J = 8$, and the QPSK modulation was employed. As shown in Fig. 2(b), upon decreasing K, the error-rate performance of the proposed schemes improved, which was achieved at the cost of the reduction in the transmission rate.

Next, Fig. 3 compares the effective SNR, which achieves a BER of 10^{-5}, between the SC-IM scheme, RC-SC-IM scheme, and SC scheme. The system parameters of Fig. 3 is the same as those used in Fig. 2(a). The CIR length was varied from $J = 1$ to 20 with steps of size 1. As seen in Fig. 3, while there

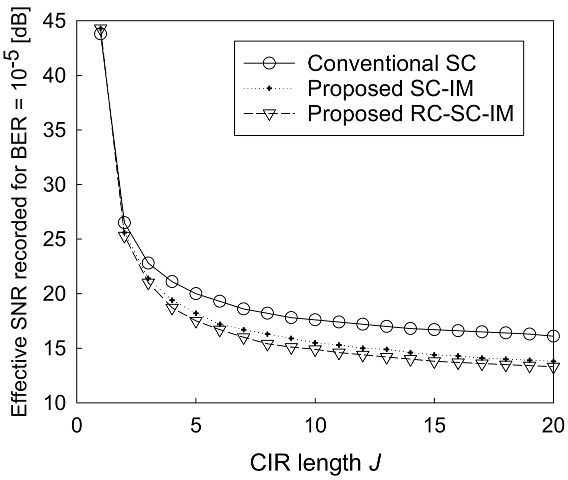


Fig. 3. Effective SNR comparisons of SC-IM scheme, RC-SC-IM scheme, and SC scheme, which were recorded for a BER of 10^{-5}. The CIR length was varied from $J = 1$ to 20 with steps of size 1.

were not any substantial performance differences between the three schemes for the low CIR length of $J \leq 2$, a distinct performance advantage for the RC-SC-IM scheme over the SC scheme was found for $J > 3$, and the performance gain of the RC-SC-IM scheme over the conventional SC benchmark was 1.6 dB for $J = 20$. Note that the broadband SC scenario typically exhibits tens of CIR length [11].[1] Additionally, the performance advantage of the SC-IM scheme over the SC scheme increased, with increasing CIR length, while the performance gap between the two proposed schemes decreased. Considering that the SC transmissions induce a substantial CIR length, this performance improvement of the RC-SC-IM scheme is beneficial for the uplink scenario in next-generation cellular systems.[2]

V. Conclusions

In this letter, we have introduced the concept of index modulation in the context of broadband SC systems, in order to increase the transmission rate of the conventional SC scheme. We also proposed a symbol allocation referred to as RC-SC-IM scheme, which is capable of reducing the effects of inter-channel correlation.[3] A low-complexity FDE algorithm was derived for the SC-IM scheme.

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[1] As shown in [4], the performance advantage of the OFDM-IM scheme over the classic OFDM counterpart is typically in the range of several dB. Since the SC-IM scheme is motivated by the OFDM-IM scheme, there is naturally the similar relationship between the SC-IM scheme and the conventional SC scheme.

[2] Similar to the conventional FDE-aided SC scheme [24], the proposed FDE-aided SC-IM scheme operates for the scenario of the SC frequency-division multiple access (FDMA) uplink.

[3] In order to exploit an explicit performance advantage over the conventional SC scheme in the entire CIR-length range, the use of RC-SC-IM scheme, rather than the SC-IM scheme, is typically needed.

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