Orthogonal Frequency Division Multiplexing with Index Modulation in the Presence of High Mobility

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***Abstract*—In this paper, a novel orthogonal frequency division multiplexing (OFDM) scheme, which is called OFDM with index modulation (OFDM-IM), is proposed for frequency-selective fading channels in the presence of high mobility. In this scheme, inspiring from the recently introduced spatial modulation concept for multiple-input multiple-output (MIMO) channels, the information is conveyed not only by M-ary signal constellations as in classical OFDM, but also by the indices of the subcarriers, which are activated according to the incoming bit stream. Different low complexity transceiver structures based on maximum likelihood (ML) detection or log-likelihood ratio (LLR) calculation are proposed. It is shown via computer simulations that the proposed scheme achieves significantly better error performance than classical OFDM.**

I. Introduction

In frequency selective fading channels with mobile terminals reaching high vehicular speeds, the subchannel orthogonality is lost due to rapid variation of the wireless channel during the transmission of the OFDM block, and this leads to a well-known phenomenon known as inter channel interference (ICI) which considerably affects the system implementation and performance. Consequently, the design of the OFDM systems which can effectively work under mobility conditions appears as a challenging problem considering the fact that mobility support is considered one of the key features of next generation wireless communication systems to provide broadband services at high mobility. Recently, the channel estimation and equalization problems have been comprehensively studied in the literature for high mobility [1], [2].

A novel concept known as spatial modulation (SM), which uses the spatial domain to convey information in addition to the classical signal constellations, has emerged as a promising MIMO transmission technique [3]–[5]. The fundamental principle of SM is an extension of two dimensional signal constellations to a new third dimension, which is the spatial (antenna) dimension. Therefore, in the SM scheme, the information is conveyed by both of the amplitude/phase modulation techniques and by the antenna indices.

More recently, a novel transmission scheme called *OFDM with index modulation (OFDM-IM)* has been proposed for frequency selective channels [6]. In this scheme, information is conveyed not only by M-ary signal constellations as in classical OFDM, but also by the indices of the subcarriers, which are activated according to the incoming information bits. A general method, by which the number of active subcarriers can be adjusted, and the incoming bits can be systematically mapped to these active subcarriers, is presented for the OFDM-IM scheme.

In this paper, OFDM-IM scheme has been significantly modified to operate on channels in which mobile terminals can reach high mobility. Different detection techniques are proposed for the new scheme. Considering the special structure of the channel matrix for the mobility case, three novel ML detection based detectors, which can be classified as interference unaware or aware, are proposed for the OFDM-IM scheme. In addition to these detectors, a minimum mean squared error (MMSE) detector, which operates in conjunction with an LLR detector, is proposed for the new scheme to successfully detect the higher number of transmitted information bits in the spatial domain. It has been shown via computer simulations that significant gains can be achieved by the OFDM-IM scheme compared to the classical OFDM in the presence of high mobility.

The rest of the paper can be summarized as follows. In Section II, the system model of OFDM-IM is overviewed. In Section III, we present different detector types for OFDM-IM. The computer simulation results are given in Section IV. Finally, Section V concludes the paper.*

II. System Model of OFDM-IM

The block diagram of the OFDM-IM transmitter is given in Fig. 1. A total of m information bits enter the OFDM-IM transmitter for the transmission of each OFDM block. These m bits are then split into g groups each containing p bits, i.e., $m = pg$. Each group of p-bits is mapped to an *OFDM subblock* of length n, where $n = N_{av}/g$ and N_{av} is the number of available subcarriers for $N_{av} < N$, where N is the total number of OFDM subcarriers, i.e., the size of the fast Fourier transform (FFT). For each subblock, only k out of n available indices are employed for this purpose

*Notation: Bold, lowercase and capital letters are used for column vectors and matrices, respectively. $(\cdot)^T$ and $(\cdot)^H$ denote transposition and Hermitian transposition, respectively. $\mathbf{I}_{N\times N}$ and $\mathbf{0}_{N_1\times N_2}$ are the identity and zero matrices with dimensions $N \times N$ and $N_1 \times N_2$, respectively. $\|\cdot\|_F$ stands for the Frobenius norm. $X \sim \mathcal{CN}\left(0,\sigma_X^2\right)$ represents the distribution of a circularly symmetric complex Gaussian r.v. X with variance σ_X^2. $C(n,k)$ denotes the binomial coefficient and $\lfloor\cdot\rfloor$ is the floor function. $\mathcal{S}$ denotes the complex signal constellation of size M.

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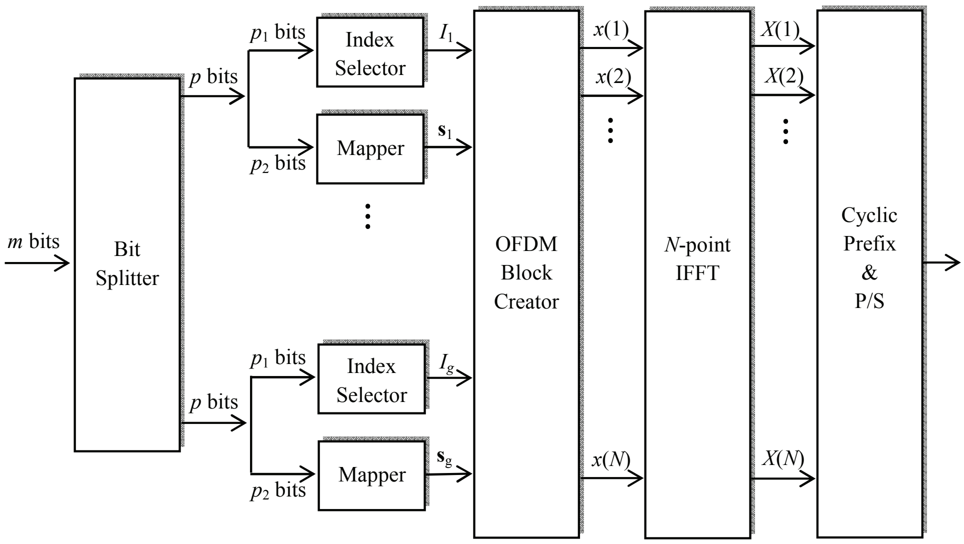

Fig. 1. Block Diagram of the OFDM-IM Transmitter

and they are determined by a selection procedure from a predefined set of active indices, based on the first p_1 bits of the incoming p-bits sequence. For each subblock β, the incoming p_1 bits are transferred to the index selector, which chooses k active indices out of n available indices, where the selected indices are given by $I_\beta = \{i_{\beta,1}, \ldots, i_{\beta,k}\}$ where $i_{\beta,\gamma} \in [1, \ldots, n]$ for $\beta = 1, \ldots, g$ and $\gamma = 1, \ldots, k$. Therefore, for the total number of information bits carried by the spatial position of the active indices in the OFDM block, we have $m_1 = p_1 g = \lfloor \log_2 (C(n,k)) \rfloor g$. In other words, I_β has $c = 2^{p_1}$ possible realizations. The remaining $p_2 = k \log_2 M$ bits of this sequence are mapped on to the M-ary signal constellation to determine the data symbols that modulate the subcarriers having active indices, therefore, we have $p = p_1 + p_2$. The total number of information bits carried by the M-ary signal constellation symbols are given by $m_2 = p_2 g = k (\log_2 (M)) g$ since the total number of active subcarriers is $K = kg$ in our scheme. Consequently, a total of $m = m_1 + m_2$ bits are transmitted by a single block of the OFDM-IM scheme. The vector of the modulated symbols at the output of the M-ary mapper (modulator), which carries p_2 bits, is given by $\mathbf{s}_\beta = \left[s_\beta (1) \ldots s_\beta (k) \right]$ where $s_\beta (\gamma) \in \mathcal{S}$, $\beta = 1, \ldots, g$, $\gamma = 1, \ldots, k$. We assume that $E\{\mathbf{s}_\beta \mathbf{s}_\beta^H\} = k$, i.e., the signal constellation is normalized to have unit average power. The OFDM block creator creates all of the subblocks by taking into account I_β and $\mathbf{s}_\beta$ for all β first and it then forms the $N \times 1$ main OFDM block

$$\mathbf{x}_F = \left[x(1)\, x(2) \cdots x(N) \right]^T \tag{1}$$

where $x(\alpha) \in \{0, \mathcal{S}\}, \alpha = 1, \ldots, N$, by concatenating these g subblocks. Unlike the classical OFDM, in our scheme $\mathbf{x}_F$ contains some zero terms whose positions carry information.

After this point, the same procedures as those of classical OFDM are applied. The OFDM block is processed by the inverse FFT (IFFT) algorithm: $\mathbf{x}_T = \text{IFFT}\{\mathbf{x}_F\} = \mathbf{W}_N^H \mathbf{x}_F$, where $\mathbf{x}_T$ is the time domain OFDM block, $\mathbf{W}_N$ is the discrete Fourier transform (DFT) matrix with $\mathbf{W}_N^H \mathbf{W}_N = N \mathbf{I}_N$. At the output of the IFFT, a cyclic prefix (CP) of length L samples is appended to the beginning of the OFDM block. After parallel to serial (P/S) and digital-to-analog conversion, the signal is sent through a frequency-selective Rayleigh fading channel for which the equivalent frequency domain input-output relationship of the OFDM scheme is given by [7]

$$\mathbf{y}_F = \mathbf{G} \mathbf{x}_F + \mathbf{w}_F \tag{2}$$

where $\mathbf{y}_F$ and $\mathbf{w}_F$ represent the vector of the received signals and the noise samples in the frequency domain respectively, and

$$\mathbf{G} = \mathbf{W}_N \mathbf{H} \mathbf{W}_N^H \tag{3}$$

where $\mathbf{H}$ is the equivalent channel matrix at the time domain. The entries of $\mathbf{w}_F$ are distributed as $\mathcal{CN}(0, N_{0,F})$, where $N_{0,F}$ is the noise variance in the frequency domain, which is related by the noise variance in the time domain by $N_{0,F} = N N_{0,T}$. We define the signal-to-noise ratio (SNR) as $\rho = E_b / N_{0,T}$, where $E_b = \|\mathbf{x}_T\|^2 / m$ is the average transmitted energy per bit. We assume that perfect channel state information is available at the receiver.

The receiver's task is to detect the indices of the active subcarriers and the corresponding information symbols by processing $\mathbf{y}_F$. Different detector types will be presented in the next section. Due to space limitations, we refer readers to [6] for the details of the mapping/demapping operations (look-up table and combinadics methods) for the OFDM-IM scheme.

III. OFDM-IM Detector Types

In this section, we present OFDM-IM detector structures which work in conjuction with the mapping/demapping algorithms given in [6]. Considering that the first and the last $N_{zp}/2$ elements of the main OFDM block have been padded with zeros, we define the meaningful received signal vector, OFDM block and the channel matrix, respectively, as follows $\tilde{\mathbf{y}}_F = \mathbf{y}_F(\mathcal{J})$, $\tilde{\mathbf{x}}_F = \mathbf{x}_F(\mathcal{J})$, and $\tilde{\mathbf{G}} = \mathbf{G}(\mathcal{J},\mathcal{J})$, where $\mathcal{J} = \frac{N_{zp}}{2} + 1 : N - \frac{N_{zp}}{2}$. For the mobility case, due to the structure of the modified channel matrix $\mathbf{G}$ given in (2), different OFDM subblocks interfere with each other; therefore, sophisticated signal processing algorithms are required in order to detect the active indices as well as corresponding constellation symbols. In the following, we propose different detection methods for the OFDM-IM scheme under mobility:

1) MMSE Detector: MMSE detector of the OFDM-IM scheme filters the received signal vector given in (2) as follows

$$\mathbf{y}_{MMSE} = \tilde{\mathbf{G}}^H \left(\tilde{\mathbf{G}}\tilde{\mathbf{G}}^H + \frac{\mathbf{I}_{N_{av}}}{\rho_F}\right)^{-1} \tilde{\mathbf{y}}_F \tag{4}$$

where $\mathbf{y}_{MMSE}$ is the MMSE filtered signal, ρ_F is the average SNR at the frequency domain. After MMSE equalization, one can consider either of LLR or reduced complexity ML detectors to determine the active indices and corresponding constellation symbols depending on the system configuration.

ii) Log-likelihood Ratio (LLR) Detector: The LLR detector of the OFDM-IM scheme provides the logarithm of the ratio of a posteriori probabilities of the frequency domain symbols by considering the fact that their values can be either non-zero or zero. This ratio, which is given below, gives information on the active status of the corresponding index for $\alpha = 1, \ldots, N$:

$$\lambda(\alpha) = \ln \frac{\sum_{\chi=1}^{M} P\left(x(\alpha) = s_\chi \mid y_{MMSE}(\alpha)\right)}{P\left(x(\alpha) = 0 \mid y_{MMSE}(\alpha)\right)} \tag{5}$$

where $s_\chi \in \mathcal{S}$. In other words, a larger $\lambda(\alpha)$ value means it is more probable that index α is selected by the index selector at the transmitter, i.e., it is active. Using Bayes' formula and considering that $\sum_{\chi=1}^{M} p\left(x(\alpha) = s_\chi\right) = k/n$ and $p\left(x(\alpha) = 0\right) = (n-k)/n$, (5) can be expressed as

$$\lambda(\alpha) = \ln(k) - \ln(n-k) + \frac{\left|y_{MMSE}(\alpha)\right|^2}{N_{0,F}} + \ln\left(\sum_{\chi=1}^{M} \exp\left(-\frac{1}{N_{0,F}}\left|y_{MMSE}(\alpha) - h_F(\alpha)s_\chi\right|^2\right)\right). \tag{6}$$

In order to prevent numerical overflow, the Jacobian logarithm [8] can be used in (6). As an example, for $k = n/2$ and binary-phase shift keying (BPSK) modulation, (6) simplifies to

$$\lambda(\alpha) = \max(a,b) + \ln\left(1 + \exp\left(-|b-a|\right)\right) + \frac{\left|y_{MMSE}(\alpha)\right|^2}{N_{0,F}} \tag{7}$$

where $a = -\left|y_F(\alpha) - 1\right|^2 / N_{0,F}$ and $b = -\left|y_F(\alpha) + 1\right|^2 / N_{0,F}$. After calculation of the N_{av} LLR values, for each subblock, the receiver decides on k active indices out of them which have maximum LLR values. As seen from (6), the decoding complexity of this detector is linearly proportional to M and comparable to that of classical OFDM. This detector is classified as near-ML since the receiver does not know the possible values of I_β. Although this is a desired feature for higher values of n and k, the detector can decide on a catastrophic set of active indices which is not included in I_β since $C(n,k) > c$ for $k > 1$, and $C(n,k) - c$ index combinations are unused at the transmitter. This detector is used with the combinadics algorithm which processes the active indices to find the index selecting bits.

TABLE I
A LOOK-UP TABLE EXAMPLE FOR $n = 4, k = 2$ AND $p_1 = 2$

Bits	*Indices*	*subblocks*
[0 0]	$\{1,2\}$	$\left[s_\chi\ s_\zeta\ 0\ 0\right]^T$
[0 1]	$\{2,3\}$	$\left[0\ s_\chi\ s_\zeta\ 0\right]^T$
[1 0]	$\{3,4\}$	$\left[0\ 0\ s_\chi\ s_\zeta\right]^T$
[1 1]	$\{1,4\}$	$\left[s_\chi\ 0\ 0\ s_\zeta\right]^T$

i) Reduced Complexity ML Detector: For the cases where a look-up table is considered, a reduced complexity ML decoder can be implemented which operates in conjuction with this look-up table and a special LLR detector. Let us denote the set of possible active indices by $\mathcal{I} = \left\{I_\beta^1, \ldots, I_\beta^c\right\}$ for which $I_\beta \in \mathcal{I}$, where $I_\beta^\omega = \left\{i_{\beta,1}^\omega, \ldots, i_{\beta,k}^\omega\right\}$ for $\omega = 1, \ldots, c$. As an example, for the look-up table given in Table I, we have $I_\beta^1 = \{1,2\}, I_\beta^2 = \{2,3\}, I_\beta^3 = \{3,4\}, I_\beta^4 = \{1,4\}$. After the calculation of all LLR values using (6), for each subblock β, the receiver can calculate the following c LLR sums for all possible set of active indices using the corresponding look-up table as $d_\beta^\omega = \sum_{\gamma=1}^{k} \lambda\left(n(\beta-1) + i_{\beta,\gamma}^\omega\right)$ for $w = 1, \ldots, c$. Considering Table I, for the first subblock ($\beta = 1$) we have $d_\beta^1 = \lambda(1) + \lambda(2)$, $d_\beta^2 = \lambda(2) + \lambda(3)$, $d_\beta^3 = \lambda(3) + \lambda(4)$, and $d_\beta^4 = \lambda(1) + \lambda(4)$. After calculation of c LLR sums for each subblock, the receiver makes a decision on the set of active indices by choosing the set with the maximum LLR sum, i.e., $\hat{\omega} = \arg\max_{\omega} d_\beta^\omega$ and obtains the corresponding set of indices, and finally detects the corresponding M-ary constellation symbols.

2) Submatrix Detector: This interference unaware detector assumes that $\tilde{\mathbf{G}} \approx \tilde{\mathbf{G}}_{sub}$, where $\tilde{\mathbf{G}}_{sub}$ has the following structure

$$\tilde{\mathbf{G}}_{sub} = \begin{bmatrix} \tilde{\mathbf{G}}_1 & 0 & \cdots & 0 \\ 0 & \tilde{\mathbf{G}}_2 & & \vdots \\ \vdots & & \ddots & \\ 0 & \cdots & & \tilde{\mathbf{G}}_g \end{bmatrix} \tag{8}$$

where $\tilde{\mathbf{G}}_\beta = \tilde{\mathbf{G}}\left(n\beta - n + 1 : n\beta, n\beta - n + 1 : n\beta\right)$ is an $n \times n$ matrix which corresponds to the subblock β, $\beta = 1, \ldots, g$. In other words, this detector does not consider the interference between different subblocks. Therefore, for each subblock, the receiver makes a joint decision on the active indices and the constellation symbols by minimizing the following metric

$$\hat{\mathbf{x}}_F^\beta = \arg\min_{\tilde{\mathbf{x}}_F^\beta} \left\|\tilde{\mathbf{y}}_F^\beta - \tilde{\mathbf{G}}_\beta \tilde{\mathbf{x}}_F^\beta\right\|_F^2 \tag{9}$$

where $\tilde{\mathbf{y}}_F^\beta = \tilde{\mathbf{y}}_F\left(n\beta - n + 1 : n\beta\right)$ is the corresponding received signal vector of length n for OFDM-IM subblock $\tilde{\mathbf{x}}_F^\beta =$

TABLE II
SIMULATION PARAMETERS

Channel Bandwidth	1.5 MHz
Number of Subcarriers (N)	128
Number of Occuppied Subcarriers	88
Subcarrier Spacing	15 kHz
Sampling Frequency	1.92 MHz
Carrier Frequency (f_c)	2.5 GHz
Number of Multipaths (ν)	10
Cyclic Prefix Length (L)	10
Modulation Format	BPSK or QPSK
Velocity (v)	100, 300 km/h

$\tilde{\mathbf{x}}_F\,(n\beta - n + 1 : n\beta)$, which has cM^k different realizations. Therefore, unlike the MMSE detector, the decoding complexity of this detector grows exponentially with increasing values of k.

3) Block Cancellation Detector : Block cancellation detector applies the same procedures as those of the submatrix detector; however, after the detection of $\tilde{\mathbf{x}}_F^{\beta}$, this detector updates the received signal vector by eliminating the interference of $\tilde{\mathbf{x}}_F^{\beta}$ from the remaining subblocks by

$$\tilde{\mathbf{y}}_F = \tilde{\mathbf{y}}_F - \bar{\mathbf{G}}_{\beta}\hat{\mathbf{x}}_F^{\beta} \qquad (10)$$

where $\bar{\mathbf{G}}_{\beta} = \tilde{\mathbf{G}}\,(1 : N_{av}, n\beta - n + 1 : n\beta)$. In other words, after the detection of $\tilde{\mathbf{x}}_F^{\beta}$, its effect on the received signal vector is totally eliminated by the update equation given in (10) under the assumption that $\hat{\mathbf{x}}_F^{\beta} = \tilde{\mathbf{x}}_F^{\beta}$.

3) SP Detector : Signal-power (SP) detector for the OFDM-IM scheme applies the same detection and cancellation techniques of the block cancellation detector; however, first, it calculates the SP values for all subblocks by $SP_{\beta} = \left\|\tilde{\mathbf{G}}_{\beta}\right\|_F^2$ and then sorts these SP values and starts from the subblock with the highest SP, and finally, proceeds towards the subblock with the lowest SP. In other words, SP detector starts with the detection of the subblock with the highest SP, after the detection of this subblock, then it updates the received signal vector using (10) and so on.

IV. SIMULATION RESULTS

In this section, we present computer simulation results for the OFDM-IM scheme operating under realistic channel conditions. Our simulation parameters are given in Table II. A multipath wireless channel having an exponentially decaying power delay profile with the normalized powers is assumed [9].

In Fig. 2, we compare the BER performance of three different OFDM-IM schemes employing various detectors with the classical OFDM for a mobile terminal moving at a speed of $v = 100$ km/h where all schemes use BPSK modulation. After MMSE processing, the reduced complexity ML detector is employed for the $n = 4, k = 2$ OFDM-IM scheme, which is using the look-up table given in Table I, while for the higher rate $n = 8, k = 4$ and $n = 22, k = 11$ OFDM-IM schemes,

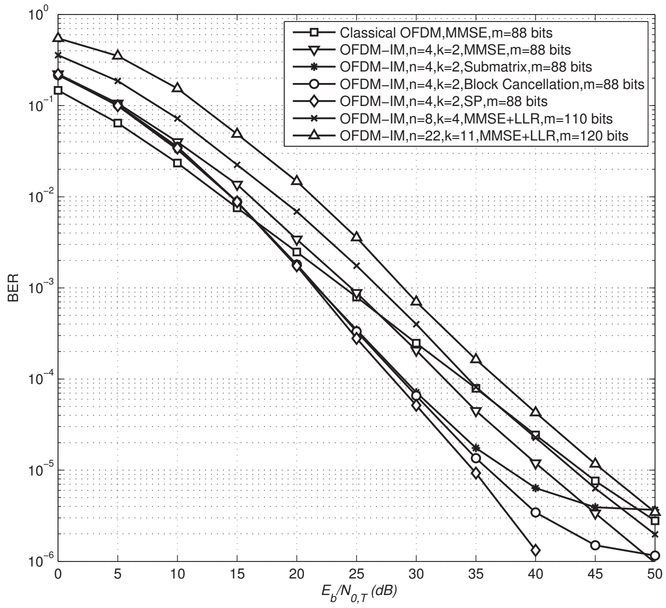

Fig. 2. Performance of OFDM-IM for a mobile terminal moving at a speed of $v = 100$ km/h, BPSK

which rely on combinadics method to determine the active indices, an LLR detector is employed. On the other hand, the classical OFDM scheme employs a MMSE detector. As seen from Fig. 2, compared to the classical OFDM, OFDM-IM cannot exhibit exceptional performance with the MMSE detector, since this detector, which works as an equalizer, does not strengthen the detection process of the OFDM-IM scheme, which relies on the differences between the channel coefficients to determine the indices of the active subcarriers. On the other hand, interference unaware submatrix receiver tends to error floor just after reaching to the BER value of 10^{-5}. This can be explained by the fact that this detector does not take into account the inference between different subblocks; therefore, the performance is limited by this interference with increasing SNR values, which causes a well-know phenomenon called as error floor. Although considering the interference, the performance of block cancellation detector is also dominated by the error floor as seen from Fig. 2; however, it pulls downs the error floor to lower BER values compared to the submatrix receiver. Meanwhile the SP detector provides the best error performance by completely eliminating the error floor in the considered BER regime. For a BER value of 10^{-5}, SP detector provides approximately 9 dB better BER performance than the classical OFDM. In the same figure, we also show the BER curves of higher rate $n = 8, k = 4$ and $n = 22, k = 11$ OFDM-IM schemes. Interestingly, our $n = 8, k = 4$ OFDM-IM scheme achieves better BER performance than the classical OFDM with increasing SNR values even if transmitting 22 additional bits per an OFDM block.

In Fig. 3, we extend our simulations to $v = 300$ km/h case. As seen from Fig. 3, by increasing mobile terminal speed, due to the increasing interference between different subblocks, which is caused by the increased banded size of the modified

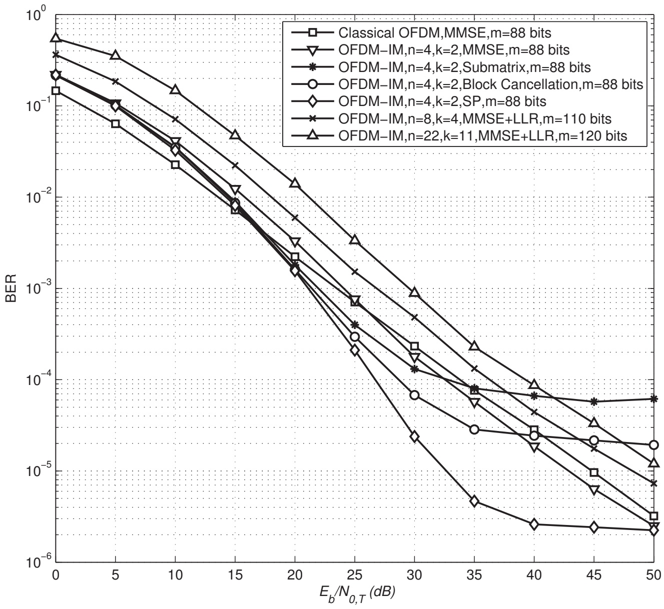

Fig. 3. Performance of OFDM-IM for a mobile terminal moving at a speed of $v = 300\,\text{km/h}$, BPSK

channel matrix $\mathbf{G}$, the detectors which do not use MMSE equalization tend to the error floor for lower BER values compared to $v = 100\,\text{km/h}$ case. OFDM-IM scheme with the SP detector provides a significant improvement (around 12 dB) compared to classical OFDM if the target BER is 10^{-5}, while for much lower target BER values, one may consider the OFDM-IM scheme with the MMSE detector, which is invulnerable to the error floor.

In Fig. 4, we compare the BER performance different OFDM-IM schemes employing MMSE and LLR detectors for a mobile terminal moving at a speed of $v = 100\,\text{km/h}$ and using QPSK modulation†. As seen from Fig. 4, in order to reach the target bit rate of the classical OFDM, four different OFDM-IM schemes are considered which employ different number of active subcarriers. We observe from Fig. 4 that for the same bit rate, the $n = 11, k = 7$ OFDM-IM scheme achieves 1.6 dB better BER performance than the classical OFDM for a BER value of 10^{-5}, and $n = 22, k = 13$, $n = 11, k = 7$ and $n = 8, k = 6$ OFDM-IM schemes exhibit close BER performance with increasing SNR. By using the lower rate $n = 8, k = 4$ OFDM-IM scheme, the BER performance can be further improved by 0.8 dB. We also observe from Fig. 4 that the higher rate $n = 22, k = 16$ OFDM-IM scheme achieves better BER performance than the classical OFDM with increasing SNR.

V. Conclusion

A novel OFDM scheme, which uses the indices of the active subcarriers to transmit data, has been proposed for high mobility. Different detectors have been proposed and their relative performances have been compared. It has been shown that the proposed scheme achieves significantly better BER performance than classical OFDM under realistic channel conditions.

† In order to prevent numerical overflow we use

$$\ln\left(e^a + e^b + e^c + e^d\right) = f_{max}\left(f_{max}\left(f_{max}\left(a,b\right),c\right),d\right) \qquad (11)$$

where $f_{max}\left(a,b\right) = \ln\left(e^a + e^b\right) = \max\left(a,b\right) + \ln\left(1 + e^{-|b-a|}\right)$

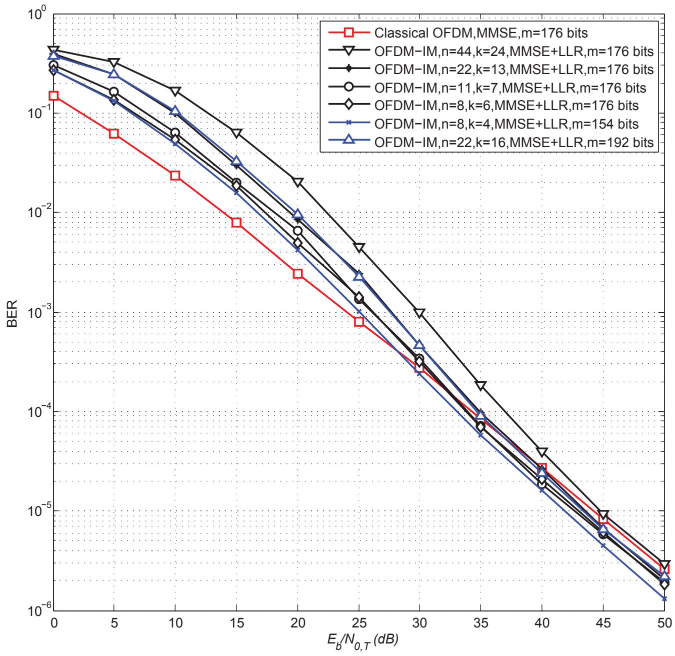

Fig. 4. Performance of OFDM-IM for a mobile terminal moving at a speed of $v = 100\,\text{km/h}$, QPSK

References

[1] H. Şenol, E. Panayırcı, and H. Poor, "Nondata-aided joint channel estimation and equalization for ofdm systems in very rapidly varying mobile channels," *IEEE Trans. Signal Process.*, vol. 60, no. 8, pp. 4236–4253, Aug. 2012.

[2] E. Panayırcı, H. Şenol, and H. Poor, "Joint channel estimation, equalization, and data detection for ofdm systems in the presence of very high mobility," *IEEE Trans. Signal Process.*, vol. 58, no. 8, pp. 4225–4238, Aug. 2010.

[3] R. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, "Spatial modulation," *IEEE Trans. Veh. Technol.*, vol. 57, no. 4, pp. 2228–2241, Jul. 2008.

[4] J. Jeganathan, A. Ghrayeb, and L. Szczecinski, "Spatial modulation: Optimal detection and performance analysis," *IEEE Commun. Lett.*, vol. 12, no. 8, pp. 545–547, Aug. 2008.

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

[6] ——, "Orthogonal frequency division multiplexing with index modulation," in *Proc. IEEE Global Telecommun. Conf.*, Dec. 2012.

[7] E. Panayırcı, H. Doğan, and H. Poor, "Low-complexity map-based successive data detection for coded ofdm systems over highly mobile wireless channels," *IEEE Trans. Veh. Technol.*, vol. 60, no. 6, pp. 2849–2857, Jul. 2011.

[8] P. Robertson, E. Villebrun, and P. Hoeher, "A comparison of optimal and sub-optimal MAP decoding algorithms operating in the log domain," in *Proc. IEEE Int. Conf. on Commun.*, Seattle, WA, USA, Jun. 1995, pp. 1009–1013.

[9] Y.-S. Choi, P. Voltz, and F. Cassara, "On channel estimation and detection for multicarrier signals in fast and selective rayleigh fading channels," *IEEE Trans. Commun.*, vol. 49, no. 8, pp. 1375–1387, Aug. 2001.