A Hybrid Downlink NOMA With OFDM and OFDM-IM for Beyond 5G Wireless Networks

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***Abstract*—In this paper, a hybrid power domain non-orthogonal multiple accessing (NOMA) scheme by the superposition of orthogonal frequency division multiple accessing (OFDM) and index modulated OFDM (OFDM-IM) technologies is presented and named IM-NOMA. It is shown via both computer-based simulations and mathematical analysis that IM-NOMA outperforms the classical OFDM-NOMA in terms of bit error rate (BER) under a total power constraint and achievable sum rate. The system performance of IM-NOMA not only depends on the power difference between the overlapping users but also on features of the OFDM-IM signal. Hence, this scheme is robust against possible catastrophic error performance in case similar power is assigned to the users.**

***Index Terms*—NOMA, OFDM, index modulation, OFDM-IM, SIC, user pairing, ML receiver.**

I. Introduction

THE rapid growth of data traffic with emerging applications and use-cases increases the need for new technologies in beyond 5 G wireless multiple accessing (MA) networks [1]. Orthogonal frequency division MA (OFDMA) is the most commonly used technique in downlink transmission. It provides high system throughput for near user equipment (UE) due to assignment of distinct resources and high signal-to-noise ratio (SNR). Unfortunately, throughput of edge UEs significantly reduces with the decay of SNR due to path-loss. Hence, unequal achievable rate is provided to UEs which significantly reduces system fairness.

Non-orthogonal multiple accessing (NOMA) via superposition of different UEs over the same resources (i.e., time and frequency) is actively investigated to enhance achievable rate while considering UE fairness [2]. In NOMA, power domain multiplexing is utilized at transmitter, and successive interference cancellation (SIC) is used to separate the superposed signals at receiver [3]. However, this scheme needs signals that possess significant power difference to have a successful multi-user detection (MUD). In case of insufficient power difference between UEs, SIC can not eliminate inter-user interference (IUI), and thus multiplexing of UEs by means of power becomes infeasible. Consequently, signal separability appears as a very challenging task due to low signal-to-interference plus noise ratio (SINR) stemming from high IUI. In the literature, plenty of work attempts to maximize the achievable sum rate of OFDM-NOMA systems without compromising reliability. In [4], an appropriate power domain user pairing is suggested to enhance sum rate of system for a given user service quality. Differently, in [5], multi-numerology multiplexing along with power domain multiplexing is proposed for both increasing sum rate and mitigating IUI. Recently, the use of OFDM and index modulated OFDM (OFDM-IM) is introduced for the coexistence of grant-free ultra-reliable low-latency communication (URLLC) and grant-based latency-tolerant service, respectively [6]. Available resources are shared among the services when URLLC occurs. K-repetitions transmission and maximum ratio combining (MRC) receiver are adopted to provide URLLC. Moreover, NOMA concept is incorporated with space-domain IM in [7], [8].

In this paper, a new hybrid NOMA scheme exploring power domain multiplexing of OFDM and OFDM-IM is introduced and termed IM-NOMA. Inherent power difference between OFDM and OFDM-IM subcarriers exists due to partial subcarrier activation in OFDM-IM. Hence, the performance of MUD in downlink IM-NOMA depends not only on the UEs' power differences but also on the subcarrier activation ratio of OFDM-IM. It is demonstrated that IM-NOMA is superior to the conventional OFDM-NOMA in terms of achievable sum rate and system reliability while guaranteeing target rate of far UE. Additionally, a novel receiver design is provided to enhance MUD performance when the UEs have similar power.

The rest of the paper is organized as follows. Section II describes the proposed transceiver design of IM-NOMA. Section III shows a closed-form expression of achievable sum rate and average bit error probability (ABEP). Section IV presents numerical and simulation results. Section V contains the concluding remarks.[1]

II. Proposed Transceiver Design

The system model of proposed IM-NOMA is illustrated in Fig. 1, where near UE (N_{UE}) and far UE (F_{UE}) perform OFDM and OFDM-IM transmission, respectively. A single antenna is used at transmitter and receiver, while UEs share N subcarriers

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[1]Capital and lowercase boldface letters are used for matrices and column vectors, respectively. $(.)^T$ and $(.)^H$ denote transposition and Hermitian transposition, respectively. $\mathrm{E}\{.\}$ stands for expectation and $||.||$ denotes Frobenius norm operation. $C(b, a)$ denotes the binomial coefficient and $\lfloor . \rfloor$ is the floor function. $\mathbf{I_{b \times b}}$ is an b × b identity matrix. diag$\{\mathbf{x}\}$ is a diagonal matrix with diagonal elements drawn from $\mathbf{x}$ and det$\{\mathbf{x}\}$ is its determinant.

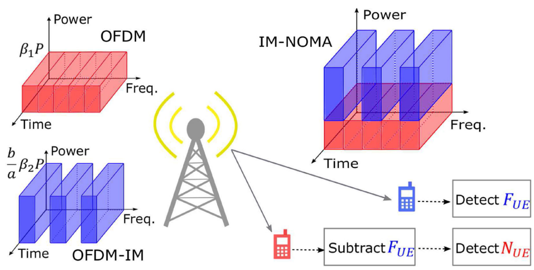


Fig. 1. Downlink IM-NOMA by superposition of OFDM and OFDM-IM.

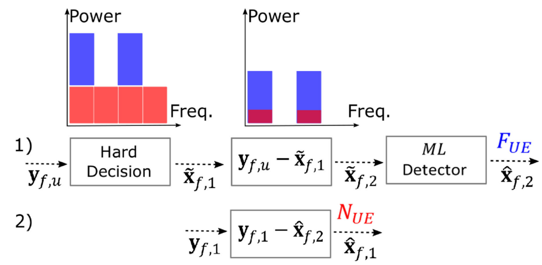


Fig. 2. Proposed receiver for IM-NOMA with symmetric channel gains.

of an OFDM block via superposition coding. Total power P is fractionally split among UEs considering UEs' channel gains and target rate of F_{UE} ($R_{F_{UE}}$). Corresponding power allocation factors for N_{UE} and F_{UE} are β_1 and β_2, respectively, with $P = \sum_{u=1}^{2} \beta_u P$. After superposition, the resultant signal is expressed as follows

$$\mathbf{x}_f = \sum_u \sqrt{\beta_u P}\mathbf{x}_{f,u}, \quad u \in [1,2], \tag{1}$$

where $\mathbf{x}_{f,u} = [x_{f,u}(1)\, x_{f,u}(2)\, \ldots\, x_{f,u}(N)]^T$ denotes the frequency domain signal of u-th UE. N_{UE} with OFDM ($\mathbf{x}_{f,1}$) modulates all subcarriers to convey data bits and thus $x_{f,1}(k) \in S$, where $\mathcal{S}$ is the set of M-ary symbols $\mathcal{S} = \{s_0\ s_1\ \cdots\ s_{M-1}\}$. Differently, F_{UE} with OFDM-IM ($\mathbf{x}_{f,2}$) carriers information not only by subcarriers but also by indices of active ones with $x_{f,2}(k) \in \{0, S\}$[9]. In OFDM-IM, OFDM block is equally split into G subblocks of $b = \frac{N}{G}$ subcarriers each, where only a out of b subcarriers are utilized. A given subblock realization of selected subcarrier indices is given as $\eta_g = \{i_{g,1}, \ldots, i_{g,b}\}$ with $i_{g,l} \in [1, \ldots, b]$, $g = 1, \ldots, G$, and $l = 1, \ldots, a$. This partial resource activation of $\frac{a}{b}$ increases the power of active subcarriers to $\frac{b}{a}\beta_2 P$. The total bit number conveyed by F_{UE} equals $m = G(\lfloor \log_2 C(b,a) \rfloor + a\log_2(M)) = Gp$. $\mathbf{x}_{f,2}$ is generated after combination of all G subblocks.

Later, inverse Fast Fourier Transform (IFFT) is applied to obtain time domain samples of $\mathbf{x}_f$. A cyclic prefix (CP) is added to eliminate the influence of Rayleigh channel $\mathbf{h}_{t,u} = [h_{t,u}(1)\, h_{t,u}(2)\, \ldots\, h_{t,u}(L)]^T$ with L Gaussian random variable taps following $\mathcal{CN}(0, \frac{1}{L})$ distribution. After channel propagation, the received frequency domain signal is expressed as

$$\mathbf{y}_{f,u} = \mathbf{X}_f \mathbf{h}_{f,u} + \mathbf{w}_{f,u}, \tag{2}$$

where $\mathbf{X}_f = \mathrm{diag}\{\mathbf{x}_f\}$. $\mathbf{w}_{f,u}$ and $\mathbf{h}_{f,u}$ denote additive noise $w_{f,u} \sim \mathcal{CN}(0, \sigma_{o,u}^2)$ and channel $h_{f,u} \sim \mathcal{CN}(0, \sigma_{f,u}^2)$ for u-th UE, respectively.

A. MUD for $\beta_1 < \beta_2$

In case of $\beta_1 < \beta_2$ to meet $R_{F_{UE}}$ considering the channel gains of UEs, MUD of $\mathbf{y}_{f,u}$ is performed via SIC by utilizing the power difference between UEs under the assumption of known channel state information (CSI) at BS and receiver. The received signals at N_{UE} and F_{UE} are given as

$$\mathbf{y}_{f,1} = \left(\sqrt{\beta_1 P}\mathbf{X}_{f,1} + \sqrt{\beta_2 P}\mathbf{X}_{f,2}\right)\mathbf{h}_{f,1} + \mathbf{w}_{f,1}, \tag{3}$$

$$\mathbf{y}_{f,2} = \left(\sqrt{\beta_1 P}\mathbf{X}_{f,1} + \sqrt{\beta_2 P}\mathbf{X}_{f,2}\right)\mathbf{h}_{f,2} + \mathbf{w}_{f,2}. \tag{4}$$

In IM-NOMA, communication reliability lays in the detection of F_{UE} carrying additional IM data. Thus, maximum likelihood (ML) decoder is applied in a subblock-wise manner, and it can jointly estimate data bits carried not only by the M-ary symbols but also by the active indices. ML criterion for g-th subblock is given as

$$\hat{\mathbf{x}}_{f,2,1}^g = \arg\min_{\mathbf{x}_{f,2}^g} ||\mathbf{y}_{f,1}^g - \mathbf{X}_{f,2}^g \mathbf{h}_{f,1}^g||^2, \tag{5}$$

$$\hat{\mathbf{x}}_{f,2,2}^g = \arg\min_{\mathbf{x}_{f,2}^g} ||\mathbf{y}_{f,2}^g - \mathbf{X}_{f,2}^g \mathbf{h}_{f,2}^g||^2. \tag{6}$$

In order to get $\mathbf{x}_{f,1}$, N_u needs to detect $\mathbf{x}_{f,2}$ and remove from $\mathbf{y}_{f,1}$. In case of correct detection $\hat{\mathbf{x}}_{f,2,1} \cong \mathbf{x}_{f,2}$, the signal of N_{UE} (3) with SIC can be written as follows

$$\mathbf{y}_{f,1} = \sqrt{\beta_1 P}\mathbf{X}_{f,1}\mathbf{h}_{f,1} + \mathbf{w}_{f,1}. \tag{7}$$

N_{UE} applies classical M-ary demodulation after removing $\hat{\mathbf{x}}_{f,2,1}$ by SIC and channel effect via zero-forcing technique.

B. MUD for $\beta_1 \cong \beta_2$

In OFDM-NOMA, SIC leads to a catastrophic error performance in case comparable $\beta_1 \cong \beta_2$ are assigned to UEs. Due to partial subcarrier activation of F_{UE}, $y_{f,1}(k)$ for $x_{f,2}(k) \neq 0$ mathematically can be rewritten as

$$y_{f,1}(k) = h_{f,1}(k)\left(\sqrt{\beta_1 P}x_{f,1}(k) + \sqrt{\frac{b}{a}\beta_2 P}x_{f,2}(k)\right) + w_{f,1}(k), \tag{8}$$

where both users provide transmission over the same radio resources, otherwise ($x_{f,2}(k) = 0$)

$$y_{f,1}(k) = h_{f,1}\sqrt{\beta_1 P}x_{f,1}(k) + w_{f,1}(k), \tag{9}$$

where N_{UE} performs orthogonal transmission. In this way, the performance of proposed IM-NOMA not only depends on the power difference but also on the portion of non-orthogonal transmission between UEs. It is important to emphasize that F_{UE} with OFDM-IM has higher power than N_{UE} only due to partial subcarrier activation, as seen in (8). However, this power difference is not higher than the power of N_{UE} on the subcarriers, where ($x_{f,2}(k) = 0$). This leads to wrong detection of active subcarriers and M-ary data symbols for F_{UE} when the conventional SIC is utilized. Motivated from this, a new receiver design is proposed for IM-NOMA to sustain the communication when power multiplexing is inapplicable. It is illustrated in Fig. 2 and explained below.

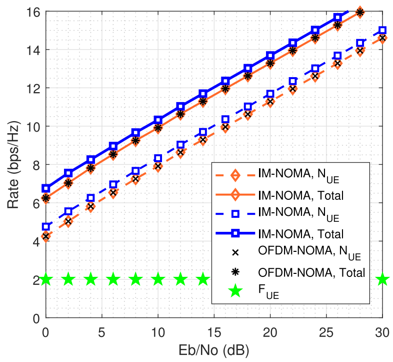


Fig. 3. Achievable rate vs. SNR for proposed IM-NOMA and OFDM-NOMA schemes. Orange and blue lines correspond to F_{UE} with (b = 4, a = 2) and (b = 8, a = 4), respectively.

1) Since N_{UE} experiences partial interference, $\tilde{\mathbf{x}}_{f,1}$ is detected and removed from $\mathbf{y}_{f,u}$ while treating F_{UE} as noise. In this way, $\tilde{\mathbf{x}}_{f,2}$ signal format is similar to $\mathbf{x}_{f,2}$.
2) ML detector is applied by F_{UE} to estimate $\hat{\mathbf{x}}_{f,2} \cong \mathbf{x}_{f,2}$.
3) Lastly, N_{UE} removes $\hat{\mathbf{x}}_{f,2}$ from $\mathbf{y}_{f,1}$ to get $\hat{\mathbf{x}}_{f,1} \cong \mathbf{x}_{f,1}$.

Due to ML receiver, the total complexity of F_{UE} and N_{UE} equal $\mathcal{O}(2^{p_1}M^a)$ and $\mathcal{O}(M(1+2^{p_1}M^{a-1}))$ while $\beta_1 < \beta_2$, and an additional complexity $\mathcal{O}(M)$ is introduced due hard decision process while $\beta_1 \cong \beta_2$.

III. Performance Analysis

In order to provide beneficial insights for the proposed IM-NOMA, theoretical analysis of achievable sum rate and ABEP are evaluated for both N_{UE} and F_{UE}.

A. Achievable Rate Analysis

According to (7), under the assumption of successful decoding of F_{UE}'s signal, mathematical expression for N_{UE}'s achievable rate is written as

$$R_{N_{UE}} = \log_2\left(1 + \frac{|h_{f,1}(k)|^2 |x_{f,1}(k)|^2 \beta_1 P}{\sigma_{o,1}^2}\right). \tag{10}$$

On the other hand, the rate calculation of F_{UE} is not straightforward since OFDM-IM signal performs a subblock-based modulation. Hence, achievable rate of F_{UE} is given as [10]

$$\begin{aligned} R_{F_{UE}} &= \frac{1}{b}\mathbf{I}\left(\mathbf{x}_f^g; \mathbf{y}_{f,2}^g | \mathbf{h}_{f,2}^g\right) \\ &= \frac{1}{b}\left(p - E_h[H(\mathbf{x}_f^g | \mathbf{y}_{f,2}^g, \mathbf{h}_{f,2}^g)]\right) \end{aligned} \tag{11}$$

considering the mutual information between $\mathbf{x}_f^g$ and $\mathbf{y}_{f,2}^g$. In order to drive $H(\mathbf{x}_f^g|\mathbf{y}_{f,2}^g, \mathbf{h}_{f,2}^g)$, probability density functions of $f(\mathbf{y}_{f,2}^g|\mathbf{x}_f^g, \mathbf{h}_{f,2}^g)$ and $f(\mathbf{y}_{f,2}^g|\mathbf{h}_{f,2}^g)$ are needed and given as

$$\begin{aligned} f(\mathbf{y}_f^g|\mathbf{x}_f^g, \mathbf{h}_{f,2}^g) &= \frac{1}{(\pi\sigma_{o,2}^2)^b}\exp(||\mathbf{y}_{f,2}^g - \mathbf{X}_f^g\mathbf{h}_{f,2}^g||^2) \\ f(\mathbf{y}_f^g|\mathbf{h}_{f,2}^g) &= \frac{1}{2^p}\sum_{i=k}^{2^p} f(\mathbf{y}_{f,2}^g|\mathbf{x}_f^g(i), \mathbf{h}_{f,2}^g), \end{aligned} \tag{12}$$

where $\mathbf{x}_f^g(i)$ represents the i-th observation of $\mathbf{x}_f^g$ realization. Since the utilization of (12) into (11) can not give a closed form for R_{UE}, mathematical evaluation of lower bound achievable rate is used as

$$\begin{aligned} R_{F_{UE}} &\triangleq \frac{p}{b} - \log_2(e) - 1 \\ &\quad - \frac{2^{-p}}{b}\sum_{i=1}^{2^p}\left(\log_2\sum_{j=1}^{2^p} 1 + \frac{1}{\det(\mathbf{I}_b + \vartheta_{i,j})}\right), \end{aligned} \tag{13}$$

with $\vartheta_{i,j} = \frac{1}{2\sigma_{o,2}^2}\mathrm{diag}\{\mathbf{x}_f^g(i) - \mathbf{x}_f^g(j)\}^H \mathrm{diag}\{\mathbf{x}_f^g(i) - \mathbf{x}_f^g(j)\}$. Total lower bound achievable rate equals $R = R_{N_{UE}} + R_{F_{UE}}$.

B. Average Bit Error Probability Analysis

Sharing of radio resources between multiple UEs gives rise to IUI, which significantly decays transmission reliability, in NOMA. Hence, in order to determine error probability of a given UE, the energy of received signal should be considered according to superposition coding principles.

1) Far User: In order to derive error performance of F_{UE}, impact of interference coming from N_{UE} must be considered. First, conditional pairwise error probability (CPEP) is evaluated to determine ABEP. F_{UE} makes decision error in case $\mathbf{X}_f$ is sent and erroneously detected as $\hat{\mathbf{X}}_f$, which can be a decision error on M-ary symbols or indices of active subcarriers. Since data information carried by IM-NOMA is independent from one block to another, a single subblock is considered for CPEP, which is given as

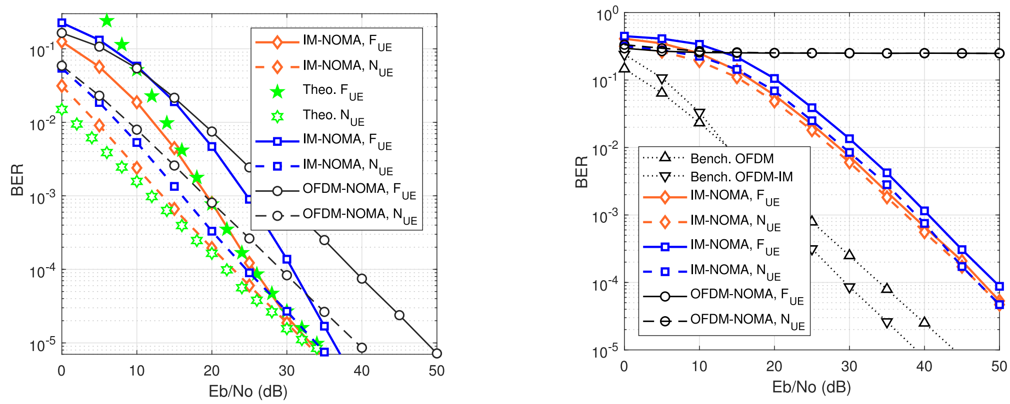
$$P\left(\mathbf{X}_f^g \rightarrow \hat{\mathbf{X}}_f^g | \mathbf{h}_{f,2}^g\right) = Q\left(\sqrt{\frac{||(\mathbf{X}_f^g - \hat{\mathbf{X}}_f^g)\mathbf{h}_{f,2}^g||^2}{2\sigma_{o,2}^2}}\right), \tag{14}$$

where $||(\mathbf{X}_f^g - \hat{\mathbf{X}}_f^g)\mathbf{h}_{f,2}^g||^2 = (\mathbf{h}_{f,2}^g)^H\mathbf{R}\mathbf{h}_{f,2}^g$, and $\mathbf{R}=(\mathbf{X}_f^g - \hat{\mathbf{X}}_f^g)^H(\mathbf{X}_f^g - \hat{\mathbf{X}}_f^g)$. A well-known approximation of Q-function $(Q(v) = (1/\sqrt{2\pi}\int_v^\infty \exp(-(v^2/2))dv))$ is adopted in this work as $Q(v) \cong \frac{1}{12}e^{-\frac{v^2}{2}} + \frac{1}{4}e^{-\frac{2v^2}{3}}$ [11]. It is important to note that this approximation provides a very tight result in case of the conventional OFDM-IM is used, and thus Craig's formula-based analysis can be performed for the advanced IM scenarios [12]. Thus, unconditional pairwise error probability (UPEP) is obtained by averaging over instantaneous channel states as

$$\begin{aligned} P\left(\mathbf{X}_f^g \rightarrow \hat{\mathbf{X}}_f^g\right) &\cong \mathrm{E}_{\mathbf{h}_{f,2}^g}\left\{\frac{e^{-\frac{E_s\delta}{4\sigma_{o,2}^2}}}{12} + \frac{e^{-\frac{E_s\delta}{3\sigma_{o,2}^2}}}{4}\right\} \\ &\cong \frac{1/12}{det(\mathbf{I}_b + q_1\mathbf{C}_b\mathbf{R})} + \frac{1/4}{det(\mathbf{I}_b + q_2\mathbf{C}_b\mathbf{R})}, \end{aligned} \tag{15}$$

where $\mathbf{C}_b = \mathrm{E}\{\mathbf{h}_{f,2}^g(\mathbf{h}_{f,2}^g)^H\}$, $q_1 = \frac{1}{4\sigma_{o,2}^2}$, and $q_2 = \frac{1}{3\sigma_{o,2}^2}$. Finally, upper bound ABEP of F_{UE} using ML detection is calculated as

$$P_e \leq \frac{1}{p\xi}\sum\sum P\left(\mathbf{X}_f^g \rightarrow \hat{\mathbf{X}}_f^g\right)\varepsilon(\mathbf{X}_f^g, \hat{\mathbf{X}}_f^g), \tag{16}$$



(a) $\beta_1 = 0.2$, $\beta_2 = 0.8$. (b) $\beta_1 = 0.5$, $\beta_2 = 0.5$.

Fig. 4. BER vs. SNR for proposed IM-NOMA and OFDM-NOMA schemes. Orange and blue lines correspond to F_{UE} with (b = 4, a = 2) and (b = 8, a = 4), respectively.

where $\varepsilon(\mathbf{X}_f^g, \hat{\mathbf{X}}_f^g)$ is the bit errors that $\mathbf{X}_f^g$ differs from $\hat{\mathbf{X}}_f^{\mathbf{g}}$ and ξ is the number of possible realizations considering both UEs.

2) Near User: By applying closed-form expressions of BER performances to $\mathbf{y}_{f,1}$ in (7), lower bound ABEP of N_{UE} for binary phase shift keying (BPSK) is obtained as [13]

$$P_e = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma_1}{1+\gamma_1}}\right), \tag{17}$$

where $\gamma_1 = \frac{|h_{f,1}(k)|^2|x_{f,1}(k)|^2\beta_1 P}{\sigma_{o,1}^2}$ is SNR of N_{UE} after correct detection of F_{UE}. For M-QAM, readers are referred to [13].

IV. Numerical and Simulation Results

In this section, a simulation study through Monte Carlo model is adopted to investigate the performance of proposed IM-NOMA for different configurations and make comparison with the classical OFDM-NOMA. System parameters used in all simulations are $N = 64$, $L = 10$, $L_{CP} = 16$, and BPSK modulation.

Fig. 3 provides the achievable rate of OFDM-NOMA and IM-NOMA with two different configurations $(b = 4, a = 2)$ and $(b = 8, a = 4)$ under target of $R_{F_{UE}} = 2$ bps/Hz as a function of transmitted power. Average channel gains of N_{UE} and F_{UE} are set to $\Omega_{f,1} = 20$ dB and $\Omega_{f,2} = 10$ dB, respectively. Full search algorithm is used to split transmit power (P) between UEs while meeting strict rate constraints and maximizing total achievable sum rate. In this study, the step size between two consecutive power factors is 0.01. Both IM-NOMA and OFDM-NOMA satisfy the rate need of F_{UE}. Moreover, IM-NOMA with $(b = 8, a = 4)$ provides 2 dB gain over the OFDM-NOMA for a total system rate of $R = 6$ bps/Hz. IM-NOMA with $(b = 4, a = 2)$ offers the same sum rate with OFDM-NOMA since equal number of data bits is transmitted over the same resources. In Fig. 4, the average BER performances of IM-NOMA and OFDM-NOMA are presented. The power allocation coefficients in Fig. 4(a) correspond to $\beta_1 = 0.2$ and $\beta_2 = 0.8$ to meet $R_{F_{UE}}$ for the given $\Omega_{f,1}$ and $\Omega_{f,2}$. Theoretical calculation for IM-NOMA with $(b = 4, a = 2)$ is obtained to validate computer-based simulations. It is clearly seen that OFDM-NOMA offers the worst performance due to full overlapping between UEs. Specifically, to achieve 10^{-4} BER, N_{UE} and F_{UE} require 30 dB and 40 dB SNR, respectively. IM-NOMA with $(b = 4, a = 2)$ provides the same error performance for N_{UE} and F_{UE} at 22 dB and 25 dB SNR, while maintaining the same system sum rate. IM-NOMA with $(b = 8, a = 4)$ increases achievable rate at the cost of reducing reliability with respect to IM-NOMA with $(b = 4, a = 2)$, but still much better than OFDM-NOMA. Lastly, performance of the proposed receiver is evaluated when similar power is assigned to UEs for a given $(\Omega_{f,1}, \Omega_{f,2})$ and $R_{F_{UE}}$, as shown in Fig. 4(b). In OFDM-NOMA, neither F_{UE} nor N_{UE} is able to detect its own signal since MUD is not feasible in scenarios with zero SINR. On the other hand, the proposed receiver exploits not only power multiplexing but also partial spectrum utilization. Hence, it offers significant BER gain for a reliable communication even when power multiplexing fails. Note that use of interleaved IM-NOMA will further improve the achieved reliability [10]. Consequently, IM-NOMA concept can provide higher achievable sum rate and system reliability by different configurations of power allocation and subcarrier activation of OFDM-IM. Moreover, instead of ML, log-likelihood ratio (LLR) detector can be used to achieve the same complexity compared with the conventional OFDM-NOMA system with a slight compromise on error performance.

V. Conclusion

In this work, a hybrid power domain NOMA scheme utilizing OFDM and OFDM-IM is proposed for downlink transmission with two UEs. It is shown that IM-NOMA is superior to OFDM-NOMA in terms of BER performance operating on frequency selective channels and can further enhance total system achievable rate. Moreover, the proposed receiver design considering the physical feature of IM-NOMA can make MUD feasible even for UEs with similar power factors. As future research, presence of more than two UEs, use of various M-ary constellations and different subcarrier activation ratios will be considered.

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