OFDM-Based Information Harvesting

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***Abstract*— Considering the current capability in hardware design, wireless power transmission enables the next stage in the current consumer electronics revolution by reducing the dependency on the lifetime of the batteries in the devices. Information harvesting (IH) introduced a novel mechanism by enabling information transmission to the existing far-field wireless power transfer mechanisms. To do so, information bits are embedded into a transmitter entity at the wireless power transmitter inspired by index modulation techniques creating a communication link without sacrificing the operational objectives of the power transmitter. This letter proposes a new IH mechanism on top of orthogonal frequency division multiplexing-based far-field wireless power transfer mechanism. The benefits of the proposed IH mechanism are investigated in terms of harvested energy, achievable rate and reliability.**

***Index Terms*— Wireless power transfer, orthogonal frequency division multiplexing, information harvesting.**

I. Introduction

WIRELESS power transfer (WPT) introduces a revolution to consumer electronics by providing ambient energy resources [1], [2] and these trends advocate the integration between WPT systems and existing wireless communication mechanisms along with carbon awareness over IoT networks in the near future. One pioneering example of this integration lies in the principle of simultaneous wireless information and power transfer (SWIPT) for RF-based systems [3] and, recently, simultaneous light information and power transfer (SLIPT) for optical-based ones [4].

In the SWIPT systems, the power and information components are mostly separable over different domains, for instance, energy domain (power splitting), time domain (time splitting), and space domain (antenna splitting) [5]. For all cases, a trade-off exists between information transfer and energy transfer and there is an extensive body of work exploring different preferences out of this trade-off [6]. While the SWIPT systems introduce novel mechanisms for addressing energy and communication needs, they sacrifice the coverage due to different sensitivity levels of energy harvesters (EHs) and information receivers (IRs) [7]. Additionally, deploying the SWIPT mechanism might be impractical in terms of hardware capability. Utilizing the same receiver circuits for both decoding information and harvesting energy from the same received signal may not be feasible in all cases [8].

As being different from these existing SWIPT efforts, *Information harvesting (IH)*, was proposed in [9] by introducing a new paradigm for information transfer on top of the existing far-field WPT mechanisms. In contrast to traditional SWIPT systems, the IH concept aims to facilitate data transmission in conjunction with far-field power transmission without compromising the coverage range of the service area. The implementations of the IH concept based on utilizing multi-antenna WPT transmitters can be found in [10] and [11].

Earlier far-field WPT studies did not integrate OFDM-based solutions since they were mainly limited to strong, non-dispersive, short-range channels. Then, considering its high peak-to-average-power ratio (PAPR) characteristics resulting in high energy conversion efficiency [12], OFDM-based wireless power transfer was investigated in [13] and [14]. Within this direction, [15] considered a joint information and power transmission mechanism where Zadoff-Chu sequences are adopted as WPT signals due to their small PAPR value under OFDM transmission. In the context of OFDM-SWIPT systems, a hybrid time switching/power-splitting scheme was proposed in [16], where a cyclic prefix was utilized for generating artificial noise as well as for energizing the legitimate receiver. Also, [17] introduced a novel architecture to extract the cyclic prefix (CP) of the signal for energy harvesting and selectively harvest a fraction of the received signal to increase energy capability.

Motivated by the existing interest on OFDM-based power transfer, this letter introduces the implementation of Information Harvesting concept [9] into an OFDM-based far-field power transfer mechanism after utilizing OFDM with index modulation (OFDM-IM) structure. To do so, a novel data transmission mechanism on top of OFDM-based far-field power transmitter has been implemented, where information transmission is carried out through an active OFDM subcarrier set that emits WPT waveforms. The benefits of the proposed mechanisms are investigated from the energy harvester's and information receiver's perspectives in terms of harvested energy amount, achievable rate, and error performance, respectively. Besides, dual-mode OFDM-based IH is also introduced where all subcarriers are active with two different waveforms. The presented results validates the superiority of the OFDM-based IH in energy harvesting capability compared to a time splitting-based SWIPT mechanism [17] where some parts of the data frame have been used for energy harvesting in addition to the cyclic prefix. In this respect, the presented results highlight the substantial potential of OFDM-based IH mechanism for enabling data communication in far-field power transfer scenarios.

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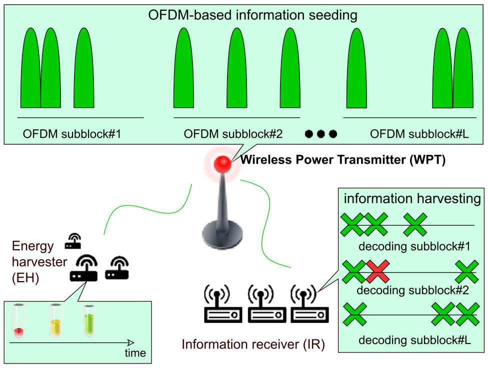


Fig. 1. The block diagram of OFDM-based IH when both EH and IR exist in the service area.

II. OFDM-Based IH System

Fig.1 represents a typical implementation of the OFDM-based IH mechanism. Herein, the WPT serves as a module supplying far-field power transfer to the energy harvesters (EHs) along with embedding the information in a choice of active subcarrier set, so-called *information seeding*, while information receivers (IRs) designed for decoding the information out of emitted WPT signal, so called *information harvesting* in [9]. Note that the IR and EH are not necessarily separate devices, so the IR can act as an EH device provided that it is in the WPT service area and the details regarding each module of the implementation will be described in the following subsections.

A. OFDM-Based WPT Transmission

In the considered scenario, the WPT mechanism is assumed to operate over a frequency-selective Rayleigh fading channel. The WPT transmitter emits OFDM waveforms where N_{FFT} is the number of OFDM subcarriers, in other words, the size of the fast Fourier transform (FFT). Each OFDM block is divided into G subblocks, $G = N_{\text{FFT}}/N$, and the localized subcarrier grouping is applied to N subcarriers in each subblock as in [18]. Unlike the conventional OFDM approach, the proposed IH mechanism considers only a subgroup of active subcarrier indices. The mapping operation is then performed for the indices of the active subcarriers, K in a considered subblock as in [18], so the available information block is mapped into an active subcarrier set such that $K \leq N$. It was known that the maximum number of information bits per channel use, spectral efficiency, η, can be mapped into the active subcarrier set indices can be expressed as $\eta = \left\lfloor \log_2 \binom{N}{K} \right\rfloor$ along with floor operation, $\lfloor \cdot \rfloor$. Under this assumption, even if the emitted OFDM waveform does not have any information component itself, the information can be carried inside the indices of the corresponding active subcarrier set out of $L = 2^{\eta}$ possibilities.

Particularly, the gth OFDM subblock can be expressed as $\mathbf{x}^g = \left[x^g(1), \ldots, x^g(N)\right]$ where $x^g(i)$ is the emitted WPT signal corresponding to ith subcarriers when it is active. For an inactive subcarrier, $x(i) = 0$ holds for $i \in \{1, \ldots, N\}$. For the WPT signal, Zadoff-Chu sequences [15] and real Gaussian [19] are used in K active subcarriers. For the first one, the amplitude is constant, and the phase is expressed by [15]

$$\theta_x = \exp\left(-j\frac{\pi M_{\text{ZC}} i(i+1)}{K}\right), \quad i = 0, 1, \ldots, N_{\text{ZC}} \quad (1)$$

where M_{ZC} indicates the Zadoff-Chu sequence root index, and N_{ZC} indicates the Zadoff-Chu sequence length, which is K times the number of the OFDM subblock. It was shown in [15] that employing Zadoff-Chu sequences results in higher rectification efficiency and lower peak-to-average-power ratio (PAPR) than M-QAM and continuous waveform (CW) for high input power region.

Then, the OFDM subblock is processed by the inverse FFT algorithm where the output is the time-domain version of $\mathbf{x}$ such that $\mathbf{x}_T = \text{IFFT}\{[\mathbf{x}^1, \ldots, \mathbf{x}^G]\} = \frac{N}{\sqrt{K}}\mathbf{W}_{N_{\text{FFT}}}^H \mathbf{x}$ giving N_{FFT} time samples. Herein, $\mathbf{W}_{N_{\text{FFT}}}$ is the discrete Fourier transform (DFT) matrix such that $\mathbf{W}_{N_{\text{FFT}}}^H \mathbf{W}_{N_{\text{FFT}}} = N_{\text{FFT}} \mathbf{I}_{N_{\text{FFT}}}$ where $\mathbf{I}_{N_{\text{FFT}}}$ is the identity matrix with the dimension of $N_{\text{FFT}} \times N_{\text{FFT}}$ and $(\cdot)^H$ is the Hermitian transposition. Then, the cyclic prefix (CP) samples with length of P can be added at the beginning of $\mathbf{x}_T$. Finally, after parallel to serial (P/S) and digital-to-analog conversion, the OFDM waveform is transmitted from the WPT.

The channel between the WPT-EH is considered a slowly time-varying multipath Rayleigh fading channel where a channel impulse response can be expressed as $\mathbf{h}_T = [h_T(1), \ldots, h_T(v)]$ where v is the number of channel taps and each tap is modelled as circularly symmetric complex Gaussian random variables, $h_T(i) \sim \mathbb{CN}\left(0, \sigma_\delta^2\right)$ and $\sum \sigma_\delta^2 = 1$ along with $P > v$. Then, the equivalent frequency domain input-output relationship of the considered OFDM scheme can be expressed as

$$y_F^{\text{EH}}(i) = h_F(i)\, x(i) + \omega_F(i) \quad (2)$$

where $y_F^{\text{EH}}(i)$, $h_F(i)$ and $\omega_F(i)$ are the CP-contained received signals at the EH, the channel fading coefficients which can be formulated as $h_F(i) = \sum h_T(v)\, e^{2j\pi(i-1)(v-1)/N_{\text{FFT}}}$ and the noise samples in the frequency domain, respectively. The distribution of $\omega_{\mathbb{F}}$ is $\mathbb{CN}\left(0, N_{0,F}\right)$, and its variance in frequency domain relates with noise variance in the time domain such that $N_{0,F} = K N_{0,T}/N$.

For a more spectrally efficient design, the unused subcarriers in the proposed IH mechanism can be utilized for transmitting a set of symbols selected from a different constellation as in dual-mode OFDM mechanism [20]. In this case, K subcarriers emit the WPT signal and the remaining $N - K$ subcarriers can be reserved for modulated symbols where the modulation order of the selected constellation is M.

B. Decoding at the IR

Similar to the WPT-EH link, the WPT-IR link is modeled with a slowly time-varying multipath Rayleigh channel denoted as $\mathbf{g}_T$. The goal of the IR is to retrieve the information that was mapped into active transmit indices from the received OFDM waveform so the IR can decode the information bits. To do so, the IR first removes the appended CP from the received signal and then implements a decoding mechanism to estimate the active subcarrier index set used in the WPT for a given OFDM subblocks. Herein, two different detection algorithms can be implemented based on the implementation complexity constraint in the IR:

1) Maximum Likelihood (ML) Decoding: The ML detector considers all possible active subcarrier index combinations for a given OFDM subblock so it aims to find an active subcarrier set, $\hat{\mathbf{I}}_{\mathrm{IR}}$, out of L possibilities which minimizes the following metric:

$$\hat{\mathbf{I}}_{\mathrm{IR}} = \arg\min_{l \in L} ||\mathbf{y}_F^{\mathrm{IR}} - \hat{\mathbf{g}}_{l,F}\mathbf{x}||^2. \tag{3}$$

Herein, $\mathbf{y}_F^{\mathrm{IR}}$ is the received signal vector, $\hat{\mathbf{g}}_{l,F}$ corresponds to lth possible channel coefficients set in the frequency domain, and $\mathbf{x} = [x_1, 0, \ldots, x_K, 0]$ is the WPT signal in the frequency domain where zero entries correspond to inactive subcarrier. It can be easily shown that the total computational complexity of the ML detector in (5), in terms of complex multiplications, is $\mathcal{O}\left(LK^k\right)$ per subblock. Considering this, the ML detector becomes impractical for larger values of N and K.

2) Log-Likelihood Ratio (LLR) Decoding: ML decoding brings considerable computational complexity since all possible active subcarrier sets are considered for a given $\{N, K\}$ so it makes the proposed OFDM-based IH practical for only limited scenarios. Alternatively, the LLR detector carries out the logarithm of the ratio of a posteriori probabilities by estimating the status of lth subcarrier as being idle or active individually. Then, the decision metric for lth subcarrier can be formulated as $\lambda_l = \ln\left(\Pr(A_l)/\Pr\left(\bar{A}_l\right)\right)$, where A_l represents a case where the l-th subcarrier is active while $\bar{A}_l$ does idle and using [(12), [21]] λ_l can be formulated as

$$\lambda_l = \ln K - \ln(N-K) + \frac{|y_F(l)|^2}{N_{0,F}} + \ln\sum_{k=1}^{K}\left(\exp\left(-\frac{1}{N_{0,F}}|y_F(l) - g_F(l)\,x_{F,k}|^2\right)\right) \tag{4}$$

where $x_{F,k}$ corresponds to kth WPT signal where the total WPT signal set consists of K symbols. To eliminate the cases of decoding a catastrophic set in the IR, resulting from $\log_2\binom{N}{K} > \eta$ and the LLR decoder considers each subcarrier detection individually, once (4) is calculated for all subcarriers, the LLR detector can estimate active subcarrier after L possibilities are taken into consideration in the IR as in the following:

$$\hat{\mathbf{I}}_{\mathrm{IR}} = \arg\max_{\mathbf{i}_l, l \in L} \sum \lambda_l. \tag{5}$$

The computational complexity of the LLR detector in (5), in terms of complex multiplications, is $\mathcal{O}(K)$ per subcarrier is the same as that of the classical OFDM detector.

III. Performance Metrics

In this section, the performance metrics used in the evaluation of the proposed scheme from energy harvesting and data communication aspects wil be described.

A. Energy Harvesting Capability

Once the WPT transmits power transfer waveforms into a service area, the EH is expected to convert the received RF waveforms into dc-output power through a rectenna. The rectenna output DC power under perfect matching and ideal low-pass filter is directly related to the quantity [22]

$$z_{DC} = \beta_2 R_{ant}\,\mathbb{E}\left[y(t)^2\right] + \beta_4 R_{ant}^2\,\mathbb{E}\left[y(t)^4\right], \tag{6}$$

where β_2, β_4 are the parameters of the nonlinear rectifier model and R_{ant} is the antenna impedance. Note that the fraction of time exists where the rectenna cannot perform harvesting since input RF power lies below certain RF power, which is referred to as *rectenna sensitivity*. Also, after a certain received signal power level at the harvester, *rectenna saturation power*, the harvested energy stays constant as shown in [23]. After considering these realistic aspects and harvesting formulation proposed in [22], the output dc power can be expressed as a function of the received RF signal can be expressed as

$$v_{out} = \begin{cases} 0, & P_r^t \in [0, \Gamma_{in}] \\ \beta_2 R_{ant} P_r^t + \beta_4 R_{ant}^2 {P_r^t}^2, & P_r^t \in [\Gamma_{in}, \Gamma_{sat}] \\ \beta_2 R_{ant}\delta_{sat} + \beta_4 R_{ant}^2 \delta_{sat}^2, & P_r^t \in [\Gamma_{in}, \Gamma_{sat}] \end{cases} \tag{7}$$

where P_r^t is the received input power at time instant t, $P_r^t = |y(t)|^2$, Γ_{in} refers to the harvester sensitivity, and Γ_{sat} denotes the saturation level.

B. Error Performance

Now, the reliability of OFDM-based IH mechanism is investigated in terms of the bit error rate at the IR. To do so, the pairwise error probability (PEP), which considers the error event resulting from an inaccurately decoded active subcarrier set corresponding to the correct one, is considered. At this point, the channel coefficients in frequency domain can be expressed in terms of time domain channel coefficients such that $\mathbf{g}_F = \mathbf{W}_{N_{\mathrm{FFT}}}\mathbf{g}_T^0$, where $\mathbf{g}_T^0$ is the zero-padded version of $\mathbf{g}_T$. It was known that the Fourier transform of a Gaussian vector gives another Gaussian vector but the elements of $\mathbf{g}_F$ is no longer uncorrelated. The correlation matrix of $\mathbf{g}_F$ is expressed as $\mathbf{K} = \mathbb{E}_{\mathbf{g}_F}\left[\mathbf{g}_F\mathbf{g}_F^H\right]$ and because $\mathbf{K}$ is a Hermitian Toeplitz, the PEP for a single block can determine the overall PEP performance [21] and the unconditional PEP (UPEP) of the OFDM-based IH scheme can be obtained from

$$\mathrm{PEP}_{\mathbf{x}_\mathrm{F}\to\hat{\mathbf{x}}_\mathrm{F}} = \frac{1/12}{\det\left(\mathbf{I}_\mathrm{n} + \mathrm{q}_1\mathbf{K}_\mathrm{n}\mathbf{A}\right)} + \frac{1/4}{\left(\mathbf{I}_\mathrm{n} + \mathrm{q}_2\mathbf{K}_\mathrm{n}\mathbf{A}\right)} \tag{8}$$

along with $q_1 = 1/\left(4N_{0,F}\right)$, $q_2 = 1/\left(3N_{0,F}\right)$, and $\mathbf{A} = \left(\mathbf{x}_F - \hat{\mathbf{x}}_F\right)$ [21]. Herein, $\mathbf{K}_n$ is a $n \times n$ submatrix centered along the main diagonal of the matrix of $\mathbf{K}$. Then, average bit error rate (ABER) is bounded by

$$\overline{P}_b \leq \frac{1}{\eta}\frac{1}{L}\sum_{i_1=1}^{L}\sum_{i_2=1, i_1\neq i_2}^{L} N_b(i_1, i_2)\,\mathrm{PEP}_{\mathbf{x}_{\mathrm{F},\mathrm{i}_1}\to\mathbf{x}_{\mathrm{F},\mathrm{i}_2}} \tag{9}$$

where $N_b(i_1, i_2)$ is the number of erroneous bits resulting from decoding active carrier set, i_2, when i_1 is transmitted.

C. Achievable Rate

While BER analysis is insightful for assessing the error reliability of the OFDM-based IH mechanism, achievable rate analysis can truly unveil its potential and discover

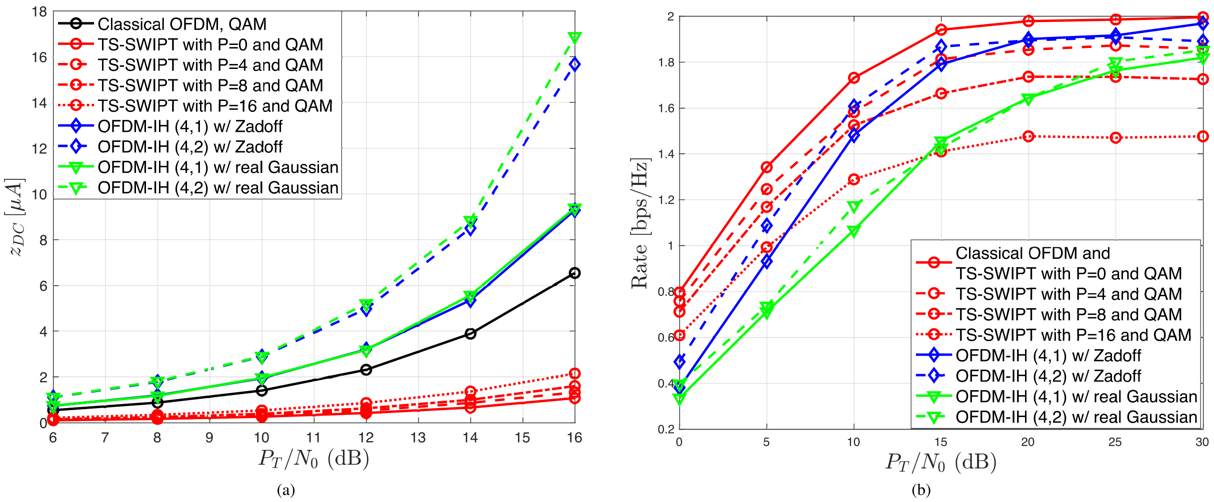


Fig. 2. (a) Energy harvesting capability (z_{DC}) when the EH is located at $d = 5$m (b) Achievable rate comparison of the proposed OFDM-based IH mechanisms deploying Zadoff-Chu and real Gaussian WPT waveform with classical OFDM and TS-SWIPT [17] with respect to varying power budget values, P_T/N_0.

the maximum information transmission capacity. To do so, the achievable rate of OFDM-based IH mechanism can be expressed as [18]

$$R_{\text{OFDM-IH}} = \frac{\log_2(L)}{N} - \left(\log_2(e) - 1\right) - \frac{1}{NL}\sum_{l=1}^{L} \times \underset{\mathbf{g}_F,\omega_F}{\mathbb{E}}\left[\log_2\left(2^N e^{-|\mathbf{w}_F|^2} + \sum_{l'=1}^{L}\prod_{i=1}^{L}\xi\left(w_F(i), g_F(i)\right)\right)\right] \tag{10}$$

where perfect channel state information at the information receiver is assumed and $\xi(\cdot,\cdot)$ is defined in [eq.(13), [18]].

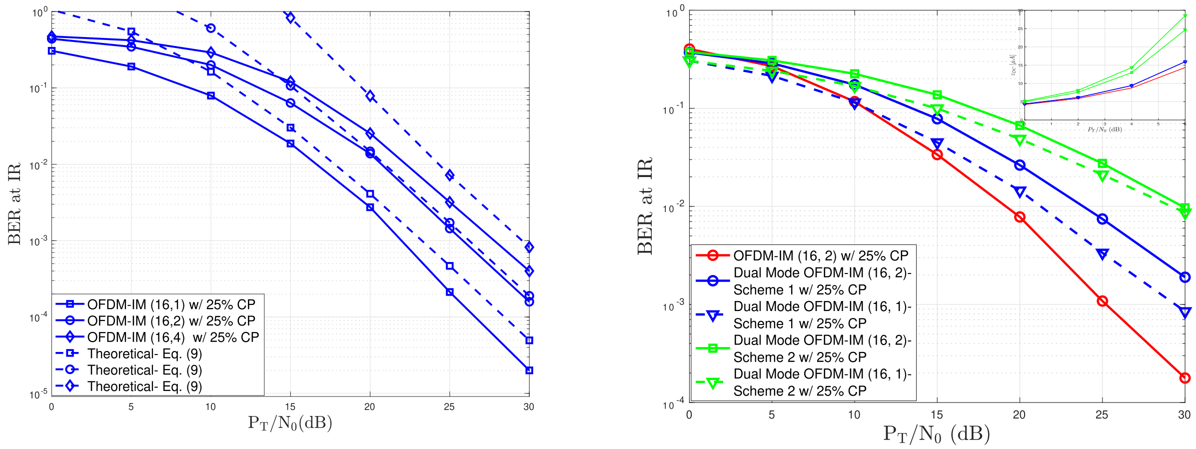
IV. Numerical Results

Now, the performance of the proposed OFDM-based IH mechanism is evaluated in terms of energy harvesting capability, achievable rate, and bit error rate over different (N, K) values. To demonstrate its superiority, classical OFDM and TS-SWIPT mechanism [17] was used as a baseline where P denotes the number of extra subcarriers taken from the OFDM data frame for energy harvesting. In the EH, the pair of $\{\beta_2, \beta_4\}$ in (7) is considered as $\{0.0034, 0.3829\}$, R_L is set to 50Ω [19] and the operation range of the input power of the rectenna is chosen based on PowerCast module [23] such that $\Gamma_{in} = 10^{-1.2}$ mW and $\Gamma_{sat} = 10$mW in (7). For the WPT signal, since the information is only conveyed through the indices of the active subcarrier set, the Zadoff-Chu sequences which have a smaller PAPR are preferred where $M_{\mathrm{ZC}} = 13$ in (1).

To start with, Fig. 2a illustrates the energy harvesting capability of the considered cases. The channels between the WPT and the EH are modeled with Rayleigh fading along with $\upsilon = 10$ taps and the following path-loss model is considered; $PL\,[\text{dB}] = 35.3 + 37.6\log_{10}(d)$, where d is the distance between the WPT and an EH in meters. In order to keep the same maximum achievable spectral efficiency, which is η for OFDM-IM scheme and $\log_2(M)$ for TS-SWIPT and classical OFDM ones, the transmitter deploys the following setting for corresponding case: $N = 4$, $K = \{1, 2\}$ and QAM modulation for those simulations. It can be clearly seen that the proposed OFDM-IH scheme outperforms classical OFDM and TS-SWIPT mechanisms by utilizing its advantage of being a far-field power transfer mechanism along with WPT waveform, whereas there is negligible difference between Zadoff-Chu and real Gaussian signaling. As expected, higher P values result in more harvested energy, but it is still far from the classical OFDM mechanism where all symbols are used for energy harvesting. Then, the achievable rates of the considered scenarios are plotted in Fig. 2b. Due to its constant amplitude, the Zadoff-Chu outperforms real Gaussian signaling from a communication perspective, and while the achievable rate of OFDM-IM is worse under lower power budget, it converges to the classical OFDM achievable rate as higher power for both signaling schemes.

Now, the quality of the bits transmitted over the indices of the active OFDM subcarrier set is investigated in terms of bit error rate (BER) in Fig. 3a where $\upsilon = 4$ is assumed. Herein, the calculation of the BER lies in comparing the transmit active subcarrier set vector and the estimated one at the IR and Gray-coded index mapping is used. Initially, the curves validate the tightness of the BER expression for higher P_T/N_0 values. Considering its practicality, LLR decoding is considered for all cases. It can be seen that a less active subcarrier during OFDM subblock transmission introduces better reliability.

Furthermore, in order to show the feasibility of dual-mode OFDM-based IH, two different schemes are considered for the choice of dual mode constellation. Scheme 1 deploys QAM constellation for $N - K$ subcarriers, inactive ones in previous cases, in each OFDM symbol. In Scheme 2, $N - K$ subcarriers are mapped into Zadoff-Chu sequences with different M_{ZC} values, $M_{\mathrm{ZC}} = 9$ for $N - K$ subcarriers, given in (1) where it is assumed that two different M_{ZC} values are known a priori at the IR. Fig. 3b illustrates that the dual-mode OFDM-based IH sacrifices reliability, whereas energy harvesting capability has been improved considerably.



(a) (b)

Fig. 3. (a) BER results of the proposed OFDM-based IH mechanism, (b) BER results and the energy harvesting capability (z_{DC}) of the proposed dual-mode IH mechanism along with given N and K values over varying power budget values P_T/N_0 at the IR.

As expected, deploying two different Zadoff-Chu sequences in Scheme 2 outperforms Scheme 1 where QAM is selected.

V. Concluding Remarks

In this letter, Information Harvesting concept has been applied to OFDM-based far-field power transfer systems. The simulation results verify that OFDM-based IH can boost energy harvesting capability at the energy harvester, and while the achievable rate may not match its energy harvesting superiority compared to its counterparts, it provides comparable performance when the power budget is relaxed. Furthermore, dual-mode OFDM introduces some sacrifice in terms of reliability along with enhanced energy harvesting capability compared to the proposed one. Following the presented results, it becomes apparent that OFDM-based IH has the potential to serve as an alternative approach in the establishment of carbon-free communication platform in future networks.

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