Gabor Expansion for Simultaneous Wireless Power and Information Transfer (SWIPT): Interference Analysis

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Abstract

Wireless power transfer (WPT) has recently appealed the research community. One application for such technology is powering up future IoT devices and sensors. This article proposes a setup where both WPT and information transfer (IT) coexist sharing the same time and frequency resources in a flexible manner while keeping the interference at a low level. The interference of WPT on IT is analyzed as a performance metric for the proposed scheme. In particular, the influence of WPT side lobes on the main lobes of the information signal is computed to assess its impact on the performance of IT. The proposed scheme uses a Gabor expansion to create both power and information signals. This structure enables to assign resources for energy and information dynamically on the time-frequency lattice providing a high flexibility in the system. We propose to use the Gaussian basis functions to create the WPT signal since they are well localized both in time and in frequency, therefore creating the lowest possible interference on the nearby subcarriers. Hence, any multi-carrier system with different modulation schemes can be used for IT in the allowed time-frequency grid such as CP-OFDM and FBMC-OQAM. The expressions of interference are computed and simulation results show the low level of interference created by the power signal on the information signals which validates the possible coexistence of both systems.

1 Introduction

The research on wireless power transfer (**WPT**) has been motivated by the growing interest in the Internet of things (IoT) electronic devices such as battery-free sensor, passive RF identification (RFID), and machine-to-machine (M2M) systems. These future devices can harvest energy from the nearby electromagnetic sources or from dedicated power heads that are designed to maximize their energy transfer. On the other hand, these devices are envisioned to perform information transfer (**IT**) with heterogeneous needs depending on their application. The demand for WPT and IT gave rise to the idea of coexistence between both systems using the same time and frequency resources allowing for greater flexibility in assigning those resources [1]. However, this coexistence faces several obstacles. One significant challenge is the interference caused from the power source on the information transfer system that would significantly affect its performance. This is particularly critical because the power signal is usually much greater than the information signal. To overcome such problem, a new waveform design is required with smart allocation of resources that can reduce the interference effect.

In this paper, we propose a structure that is based on Gabor expansion, where each waveform is represented as a linear combination of shifted basis functions in time and

frequency creating a regular grid also known as time-frequency lattice. Gaussian prototypes are used to generate the power signal which we call **Multi-Gaussian** waveform since they are characterized by their good localization both in time and in frequency. Besides, multi-Gaussian is very similar to the multisine signal and is expected to offer similar performance in terms of energy harvesting [1]. Given this good localization property of the power signal, we expect a small interference on the information signals. Any multi-carrier scheme utilizing the same time-frequency grid can then be used for information signals as long as a small guard time/band is used to separate both signals. In this paper, we consider the cyclic-prefix orthogonal frequency-division multiplexing (**CP-OFMD**) and the offset QAM filter-bank multi-carrier (**FBMC-OQAM**). The interference of the multi-Gaussian waveform on both the CP-OFDM and FBMC-OQAM systems is studied. Most interference computation in the literature are based on a Power Spectral Density (PSD) model [3, 4, 5] that considers the out-of-band radiation of the multi-carrier signal. However, the work of [6, 7] showed that the PSD-based model is not precise and proposed a more accurate approach in calculating the interference. In addition, in our case the interference is not random but its deterministic and the PSD-based model is not applicable. In this work, we derive the expressions for the interference of the IT on both aforementioned information systems. As in [8], the receiver architecture (i.e. the filtering operations and processing done at the receiver) is taken into consideration while calculating the interference expressions. Then, the expressions are simulated and the results are discussed in a practical scenario. This scenario shows that the multi-Gaussian power signal has low interference on its neighboring subcarriers and can coexist with both systems under certain conditions.

The paper is organized as follow: First, the proposed scheme and system models are demonstrated in Section 2. The expressions of the interference caused by multi-Gaussian signal on CP-OFDM and FBMC-OQAM in Section 3. Simulated results of the interference is shown in Section 4. Practical Example is presented in Section 5. Finally, the paper is concluded in Section 6.

Notations: scalars are noted as x, vectors are bold as $\mathbf{x}$, x^* is the complex conjugate of x, and sets are represented by a calligraphy letters such as $\mathcal{X}$. n is the discrete index for symbols, m indexes for subcarriers and t is for the continuous time. $*$ is the convolution operation, $\mathbf{E}_x\{y\}$ is the mathematical expectation of y with regards to the random variable x and $\Re\{x\}$ is the real part of x.

2 Proposed Scheme and System models

2.1 Gabor Expansion for coexistence

In this paper, we propose a time-frequency lattice, which is called Gabor system, where different systems with different multi-carrier schemes can coexist together. All systems in this structure share the same time separation T (the symbol duration) and same frequency separation $\Delta f = 1/T$. The proposed system provide flexibility in allocating different multi-carrier systems. However, we must avoid interference caused by frequency side lobes and time tails that would affect the performances of the other systems.

As a result, guard bands and guard periods are proposed to minimize these interference among different systems. One particular example of this proposed structure is illustrated in Fig.1 which shows flexibility of allocating resources for different multi-carrier systems within a certain time-frequency space. It is important to note that all these systems must be synchronized both in time and in frequency.

We proposed also to utilize the Gaussian basis function to generate the power signal. The reasons for that are as follows:

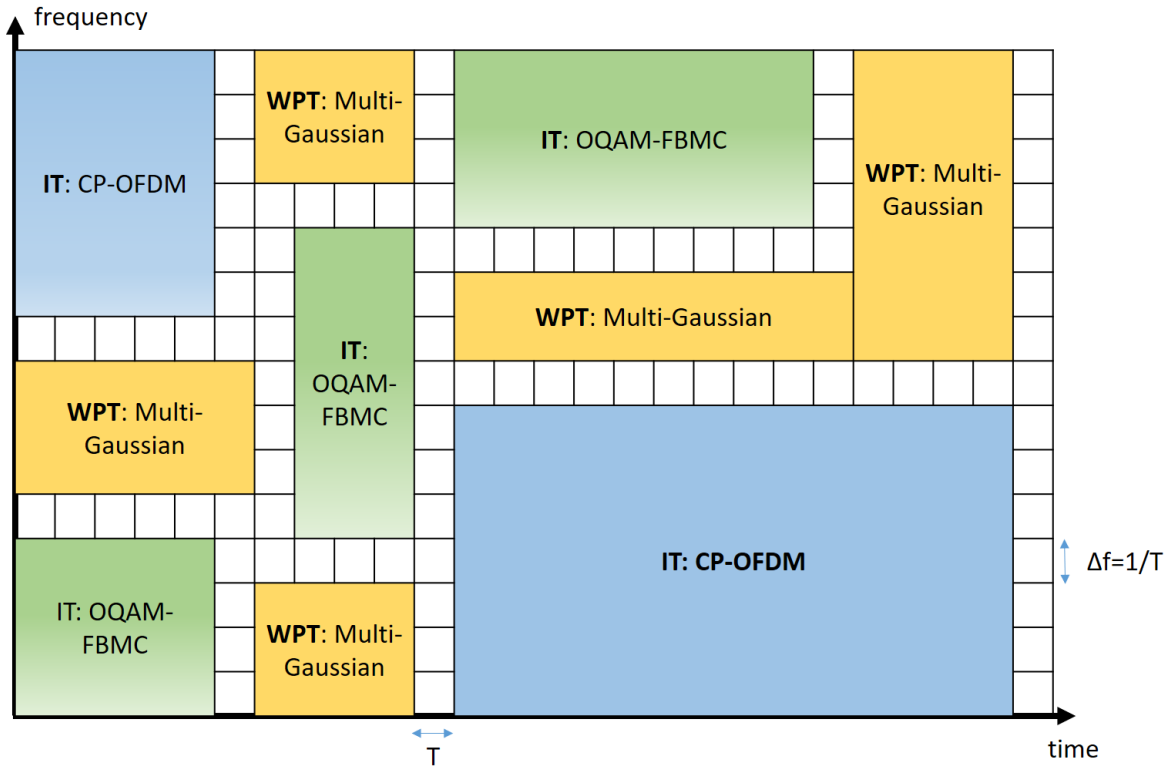


Figure 1: Example of the Proposed Structure of coexistence among different systems

- ◇ There will always be a trade-off between side lobes and time tails. Gaussian functions are well localized both in time and in frequency i.e. it has very low side lobes and time tails.
- ◇ It is expected to have good performance in terms of energy harvesting similar to that of the multisine waveform[1].

In our work, we are interested in studying the interference caused by the side lobes only (not the time tails). Therefore we assume the setup illustrated in Fig.2. The information system (whether CP-OFDM or FBMC-OQAM) and the power system share the same bandwidth $\mathcal{B}$. IT occupy a sub-band that belong to a set of information active subcarriers $\mathcal{M}_i$. Whereas, WPT occupy another sub-band that belong to a set of power active subcarriers $\mathcal{M}_p$. In our analysis, we assume we have an additive white Gaussian noise (AWGN) channel and we ignored the path-loss and shadowing of the channel, as well as any propagation delay.

2.2 Power Signal Model: Multi-Gaussian waveform

We consider that a power signal is generated using a Gaussian prototype filter using $\mathcal{M}_p$ active subcarriers out of $\mathcal{M}$ in a fixed bandwidth $\mathcal{B}$. A certain power and phase coefficient $\mathbf{d}_{m_p}[n_p]$ (n_p is the symbol time index) is allocated to a each active subcarrier m_p ($m_p \in \mathcal{M}_p$) during the symbol duration T. The normalized Gaussian prototype filter used is defined as:

$$g(t) = \frac{(2\alpha)^{1/4}}{\sqrt{T}} e^{-\pi\alpha(\frac{t}{T})^2}, \tag{1}$$

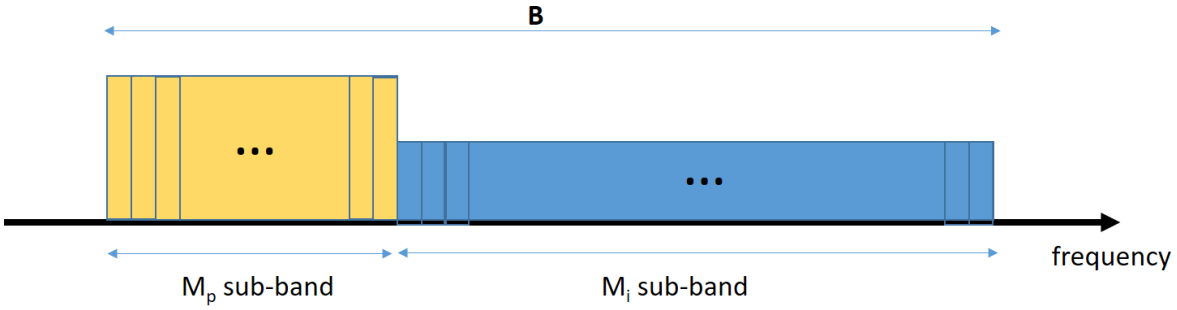


Figure 2: Bandwidth sharing among IT and WPT systems used

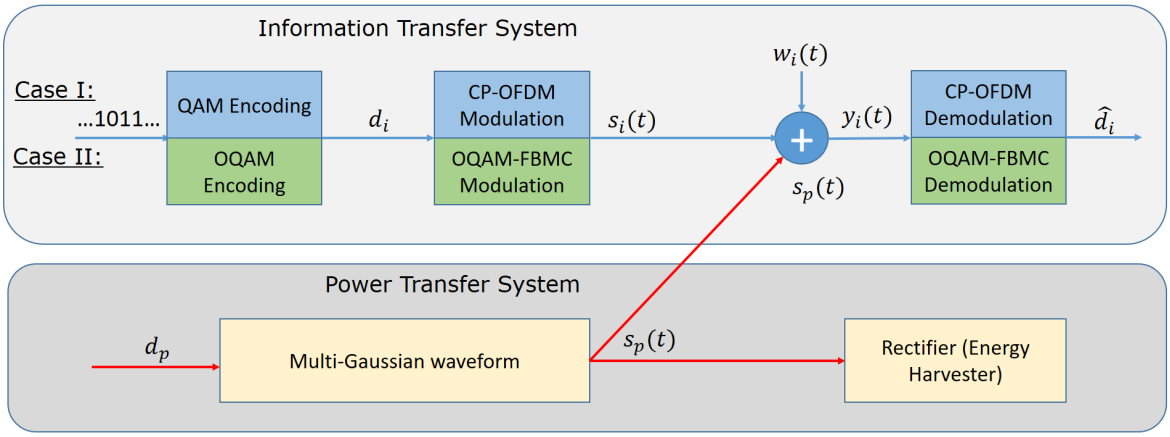


Figure 3: Block diagram representing the IT and WPT systems. Case I: CP-OFDM and Case II: FBMC-OQAM. WPT transmitter is interfering on IT receiver as shown.

where $\alpha > 0$ is the localization parameter. We choose $\alpha = 1$ to have the best localization both in time and in frequency. Using the general multi-carrier model in [2] to generate the multi-Gaussian signal, the time-domain signal transmitted on each active subcarrier $m_p \in \mathcal{M}_p$ is expressed as:

$$s_{m_p}(t) = \sum_{n_p \in \mathcal{Z}} \mathbf{d}_{m_p}[n_p] g(t - n_p T) e^{j2\pi m_p \frac{t}{T}}. \tag{2}$$

Hence, the total transmitted signal from the power source (i.e. Multi-Gaussian Waveform) is expressed as:

$$s_p(t) = \sum_{m_p \in \mathcal{M}_p} s_{m_p}(t) = \sum_{m_p \in \mathcal{M}_p} \sum_{n_p \in \mathcal{Z}} \mathbf{d}_{m_p}[n_p] g(t - n_p T) e^{j2\pi m_p \frac{t}{T}}. \tag{3}$$

2.3 Information Signal Model: CP-OFDM

Referring to case I of Fig.3, we consider that the information system that is being influenced by the power signal is a CP-OFDM system. This system has a symbol duration T, cyclic prefix duration T_{CP}, and $\mathcal{M}_i$ active subcarriers out of $\mathcal{M}$ in a fixed bandwidth $\mathcal{B}$. As mentioned above, we assume perfect channel with AWGN. Therefore, the signal at the input antenna of the CP-OFDM receiver can be expressed as:

$$y_i(t) = s_i(t) + s_p(t) + w_i(t), \tag{4}$$

where $s_p(t)$ is the interfering power signal and $w_i(t)$ is the AWGN. At the receiver, assuming perfect synchronization, the cyclic prefix is removed from the signal where only a time window ($f(t) = \frac{1}{\sqrt{T}}$ for $t \in [-\frac{T}{2}, \frac{T}{2}]$) is considered. Then, the Fast Fourier Transform (FFT) is applied to the received windowed signal. The demodulated n_i^{th} symbol on the m_i^{th} subcarrier of the receiver can be expressed as:

$$\hat{\mathbf{d}}_{m_i}[n_i] = \mathbf{d}_{m_i}[n_i] + \sum_{m_p \in \mathcal{M}_p} \eta_{m_p \to m_i}[n_i] + \mathbf{w}_i[n_i], \tag{5}$$

where $\mathbf{w}_i[n_i]$ is the filtered Gaussian noise and $\eta_{m_p \to m_i}[n_i]$ is the interference caused by the m_p^{th} subcarrier of the power source onto the m_i^{th} subcarrier of the information signal which can be expressed as:

$$\eta_{m_p \to m_i}[n_i] = \int_{-\infty}^{\infty} s_{m_p}(t) f(t - n_i(T + T_{CP})) e^{-\frac{j2\pi m_i}{T}(t - n_i T_{CP})} dt. \tag{6}$$

2.4 Information Signal Model: FBMC-OQAM

Referring to case II of Fig.3, we consider that the information system to be FBMC-OQAM with PHYDYAS normalized prototype filter [9] which is expressed as:

$$p(t) = \sqrt{\frac{2}{T}} \sum_{k=-K+1}^{K-1} \frac{G_{|k|}}{K} e^{j2\pi \frac{kt}{KT}}, \quad t \in [-\frac{KT}{2}, \frac{KT}{2}], \tag{7}$$

where $K = 4$ is the overlap factor, and $G_0 = 1$, $G_1 = 0.971960$, $G_2 = \frac{1}{\sqrt{2}}$, and $G_3 = 0.235147$. It is noted also that the filter $p(t)$ is real and symmetric (i.e. $p^*(-t) = p(t)$). The received signal in this case is modulated around the subcarrier of choice then filtered by the prototype filter $p(t)$ where only the real part of the signal is taken. Besides, the received signal is also multiplied by phase factors $\theta_{m_i}[n_i] = j^{(n_i + m_i)}$ and $(-1)^{n_i m_i}$ [9]. The received signal at the FBMC-OQAM receiver can be expressed as equation (4) above. After demodulation, the expression is also similar to equation (5) above. In this case, the interference caused by the m_p^{th} subcarrier of the power source onto the m_i^{th} subcarrier of the FBMC-OQAM signal which can be expressed as:

$$\eta_{m_p \to m_i}[n_i] = \int_{-\infty}^{\infty} s_{m_p}(t)\ p(t - n_i \frac{T}{2})\ (-1)^{n_i m_i}\ j^{(n_i + m_i)}\ e^{-\frac{j2\pi m_i}{T} t} dt. \tag{8}$$

3 Interference Expressions

The total interference inserted from all the active subcarriers of the power source onto the m_i^{th} information subcarrier of the n_i^{th} information symbol can be expressed as follows:

$$\eta_{P \to m_i}[n_i] = \sum_{m_p \in \mathcal{M}_p} \eta_{m_p \to m_i}[n_i]. \tag{9}$$

Then, the interference power caused by all active subcarriers of the power source can be expressed as:

$$I_{P \to m_i} = |\eta_{P \to m_i}[n_i]|^2. \tag{10}$$

In order to ensure fairness in comparison between the two cases (CP-OFDM and FBMC-OQAM), all filters ($f(t)$, $p(t)$, and $g(t)$) are normalized such that both systems transmit with the same energy per symbol. Besides, we assume uniform distribution of symbols $\mathbf{d}_{m_i}[n_i]$ among transmitted active power subcarriers.

3.1 Case I: CP-OFDM

We plug in the expression of the transmitted power signal of one subcarrier shown in (2) into the interference expression in (6). We use the value of the window filter $f(t)$ of the CP-OFDM receiver mentioned in section 2.3 above. Besides, we substitute the value of the Gaussian prototype filter in (1) with $\alpha = 1$. Then, from (10) we get the expression for the interference power as follows:

$$I_{P\to m_i}^{OFDM} = \frac{\sqrt{2}}{M_p T^2}\left| \sum_{l\in\{\mathcal{M}_p - m_i\}} \sum_{\tau=\frac{-KT}{2}}^{\frac{KT}{2}} \int_{\frac{-T}{2}}^{\frac{T}{2}} e^{-\pi(\frac{t-\tau}{T})^2 + \frac{j2\pi l}{T}t} dt \right|^2, \tag{11}$$

where τ is the relative time distance between all interfering power symbols onto a given information symbol, and $l = m_p - m_i$ is the spectral distance between a certain active power subcarrier m_p and a given active information subcarrier m_i.

3.2 Case II: FBMC-OQAM

We substitute the expression of the transmitted power signal of one subcarrier shown in (2) into the interference expression in (8). We use the value of the normalized PHYDYAS prototype filter of the OQAM-OFDM receiver shown in (7) above. We plug-in also the Gaussian prototype filter in (1) with $\alpha = 1$. Then, from (10) we get the expression for the interference power as follows:

$$I_{P\to m_i}^{FBMC} = \frac{\sqrt{2}}{M_p T^2 K^2}\left| \sum_{l\in\{\mathcal{M}_p - m_i\}} \sum_{\tau=(-K+1)T}^{(K-1)T} \sum_{k=-K+1}^{k=K-1} G_{|k|}\, \Re\left\{ \int_{\frac{-KT}{2}}^{\frac{KT}{2}} e^{-\pi(\frac{t-\tau}{T})^2 + \frac{j2\pi}{T}t(\frac{k}{K}+l)} dt \right\} \right|^2, \tag{12}$$

where τ and $l = m_p - m_i$ are as defined in (11). We should note that a factor of $\frac{1}{2}$ is considered since we are only taking the real part of the signal at the FBMC-OQAM receiver.

4 Simulation results

We consider two systems: the information transfer system (CP-OFDM and FBMC-OQAM) and the power transfer system (multi-Gaussian). Both systems share the same bandwidth $\mathcal{B}$ with total number of subcarriers equals to 128 ($\mathcal{M} = 128$).The WPT system uses 30 active subcarriers ($\mathcal{M}_p = 30$) such that $m_p = [1 \to 30]$. The IT system uses 98 active subcarriers ($\mathcal{M}_i = 98$) such that $m_i = [31 \to 128]$.

Given this setup, the interference expressions (11) and (12) represented above were plotted as shown in Fig.4. The following conclusions can be extracted from these results:

- ◇ Generally, the interference is higher for the CP-OFDM as compared to FBMC-OQAM which could be predicted due to the higher side lobes of CP-OFDM.
- ◇ Due to the usage of multi-Gaussian power source, there is a sharp decrease in the interference of the neighboring subcarriers close to the active power subcarriers. This is due to the good localization of the Gaussian filter.
- ◇ The interference stabilizes after subcarrier difference of 3.
- ◇ Only one guard band can be considered and the information signal can utilize subcarriers starting from spectral distance equals to 2. That is due to the sharp decrease in interference.

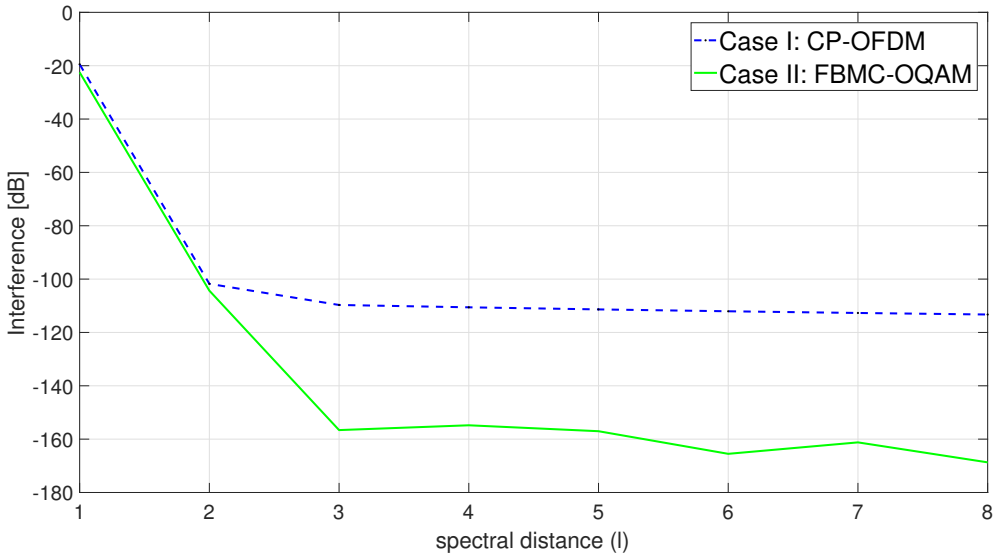


Figure 4: Interference curves for both CP-OFDM and FBMC-OQAM cases

5 Practical Example for coexistence

The simulation results show that the interference values are very low due to the good localization nature of the Gaussian filter used to generate the power signal. This helps in the coexistence of both systems: IT and WPT. A practical example is illustrated in this section to evaluate the value of interference caused by a power transmitter.

Consider a battery-free sensor that requires WPT and IT to operate (i.e. SWIPT device). We consider that both systems transmit at $f_c = 2.4GHz$ and they share the same bandwidth $\mathcal{B} = 1.92MHz$ with $\mathcal{M} = 128$ subcarriers and frequency separation $\Delta f = 15kHz$. The information source transmits at a power of $P_{I,tx} = 0dBm$ while the power source transmits at a power of $P_{P,tx} = 23dBm$. The sensor is present in a fixed place where it is located at a near distance from the power head ($d_p = 2m$) while its further away from the information transmitter ($d_i = 35m$) which potentially create a gap between the power levels of both systems. Both signals will experience a path-loss components before reaching the information receiver. We use the free space path-loss model to get: $L_p = 46.0726dB$ and $L_i = 70.9334dB$ for the power and information signals respectively. We will ignore the channel shadowing and scattering effect for both signals in this example. Hence, the received power at the antenna of the information signal and the power signal are $P_I = -70.9334dBm$ and $P_P = -23.0726dBm$ respectively.

To evaluate the performance of the information subcarrier m_i, we will use the signal-to-interference-ratio (SINR) as a performance metric which is defined as:

$$SINR(m_i) = \frac{P_{m_i,I}}{I_{P\rightarrow m_i} + N}, \tag{13}$$

where $P_{m_i,I}$ is the power allocated for subcarrier m_i of the information signal at the antenna receiver, $I_{P\rightarrow m_i}$ is the interference caused by the power signal on the information signal, and N is the power of the noise experienced by the information signal ($N = -141dBm$).

As an example, we consider the adjacent information subcarrier $m_i = 31$ to be the guard band and we want to evaluate the SINR at $m_i = 32$. Assuming uniform distribution of power among information subcarriers (98 subcarriers), hence $P_{31,I} =$

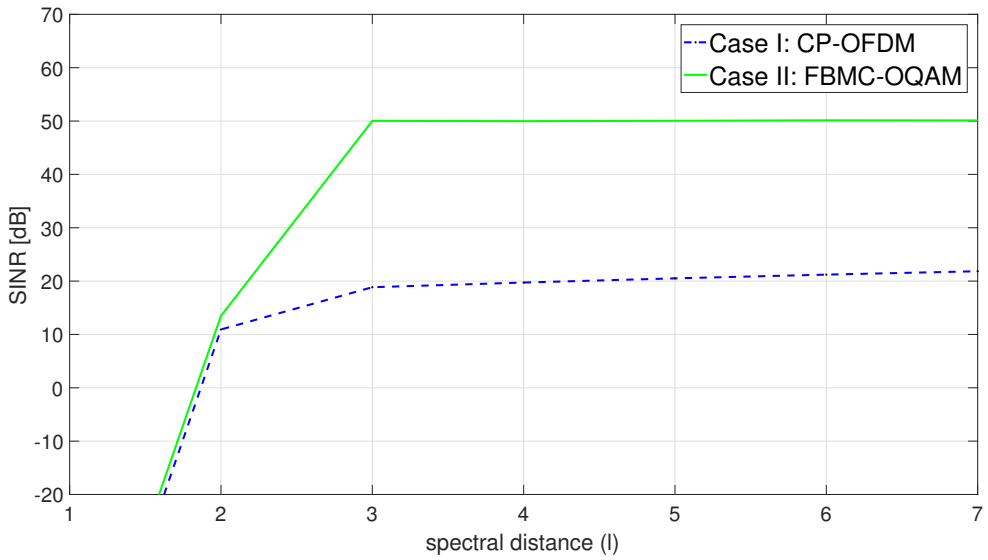


Figure 5: SINR for information subcarriers of Case I: CP-OFDM and Case II: FBMC-OQAM

$-90.8456dBm$. We evaluate the interference caused by all active subcarriers of the power signal on this particular information subcarrier from the interference curve obtained in the simulation section above ($I^{OFDM}_{P\to m_i} = -101.7777dBm$ and $I^{FBMC}_{P\to m_i} = -109.7005dBm$). Then, we calculate the SINR values for both IT cases using (13) as follows:

$$SINR^{OFDM}(32) = \frac{P_{32,I}}{I_{P\to 31} + N} = 10.9316dB, \tag{14}$$

$$SINR^{FBMC}(32) = \frac{P_{32,I}}{I_{P\to 31} + N} = 13.4862dB. \tag{15}$$

We followed the same steps to obtain the SINR curves for all other information subcarriers as shown in Fig.5. Based on the results, we observe with this practical example that the SINR of FBMC-OQAM is better than CP-OFDM. Also, one guard band only is recommended after which the information subcarriers can utilize the remaining subcarriers. SINR also becomes flat after $l = 3$.

6 Conclusion

In this work, we provided a structure where information and power signals can coexist in flexible manner sharing the same bandwidth. The power signal is proposed to be generated by a Gaussian function that is well localized in time and frequency and that is expected to have good performance in terms of energy harvesting since its similar to the multisine. The interference of the power signal is studied on two information multi-carrier systems CP-OFDM and FBMC-OQAM. Results shows low level of interference injected from the power signal onto the both cases of information signals which means that IT and WPT can coexist by considering only one guard band.

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