Power Allocation for Frequency-Modulated OFDM Wireless Systems

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***Abstract*—Frequency-modulated orthogonal frequency division multiplexing (FM-OFDM) is a recently proposed waveform which overcomes the notoriously high peak-to-average power ratio (PAPR) of traditional OFDM wireless systems. Employing this new FM-OFDM waveform, however, will demand a redesign of certain signal processing mechanisms, since those tailored to traditional OFDM waveforms may no longer be optimal or even applicable. This paper proposes two novel power allocation schemes for FM-OFDM systems, both of which take into account this new waveform's unique interactions with noise and with the propagation channel. We analytically derive and optimize closed-form expressions for both of the proposed power allocation schemes, the first of which improves average bit error rate (BER) while the second maximizes spectral efficiency. Our simulation results illustrate the improvements in BER and in data rate when employing our power allocation schemes over conventional benchmarks but also underscore what regimes they should be employed to maximize these gains.**

***Index Terms*—New waveform, post-OFDM, FM-OFDM, power allocation**

I. Introduction

The demand for more efficient and more robust waveform technologies is unrelenting in the ever-evolving landscape of wireless communication [1]. Orthogonal frequency division multiplexing (OFDM) offers a multitude of undeniable strengths and, as a result, has been a staple in cellular networks for over a decade and in Wi-Fi systems for over two decades [2], [3]. However, the use of OFDM does introduce a few noteworthy drawbacks, with one of the most notable being its high peak-to-average power ratio (PAPR) [4], [5]. Frequency-modulated OFDM (FM-OFDM) has recently emerged as a promising alternative to circumvent the high PAPR of traditional OFDM waveforms [6].

This new FM-OFDM waveform uses a conventional OFDM signal to modulate the phase of a complex exponential, hence its allusion to frequency modulation (FM). Consequently, FM-OFDM waveforms exhibit a constant envelope and thus have a PAPR of 0 dB, which relaxes power amplifier requirements and improves energy efficiency. Furthermore, compared to traditional OFDM, FM-OFDM also exhibits remarkable robustness to highly time-varying channel conditions [6].

To fully leverage FM-OFDM signaling, however, new signal processing mechanisms must be developed, since existing ones for conventional OFDM are no longer necessarily optimal or applicable. In particular, this paper focuses on new schemes for allocating transmit power across subcarriers, which, to our knowledge, has not yet been considered in the open literature, given the recent introduction of FM-OFDM in early 2023 [6]. We analytically derive and optimize two novel power allocation schemes, each of which incorporates two defining characteristics of FM-OFDM systems pertaining to how the signal is impacted by noise and by the propagation channel.

Both of the power allocation schemes we propose importantly account for the frequency-dependent noise power spectral density in FM-OFDM systems [6]. This frequency-dependent noise stems from differentiation of the signal at the receiver; this was compensated for in traditional FM radio systems by employing pre-emphasis and de-emphasis filters [7]. Both proposed schemes also account for the fact that the channel gain on each subcarrier no longer has a multiplicative effect (as in OFDM) but rather an additive one, courtesy of FM modulation [6]. Consequently, so-called *waterfilling* power allocation [8]–[10] in its traditional form is no longer necessarily optimal.

By taking these characteristics of noise and of the channel into account, the first of two power allocation schemes we propose ensures that all subcarriers enjoy equal signal-to-noise ratio (SNR). We show that this approach enhances bit-error rate (BER) compared to conventional equal power allocation, particularly at high SNR. The second power allocation scheme we propose in this work is a modified version of waterfilling, which we analytically derive—using convex optimization—as the optimal power allocation scheme in maximizing spectral efficiency. Through simulation, we confirm its ability to improve data rate compared to conventional equal power allocation by 38% at modest SNR, for instance.

II. System Model

In this paper, we consider a wireless communication system employing FM-OFDM signaling, whose functional block diagram is shown in Fig. 1. For FM transmission, the time-domain OFDM signal must consist of real components only. The

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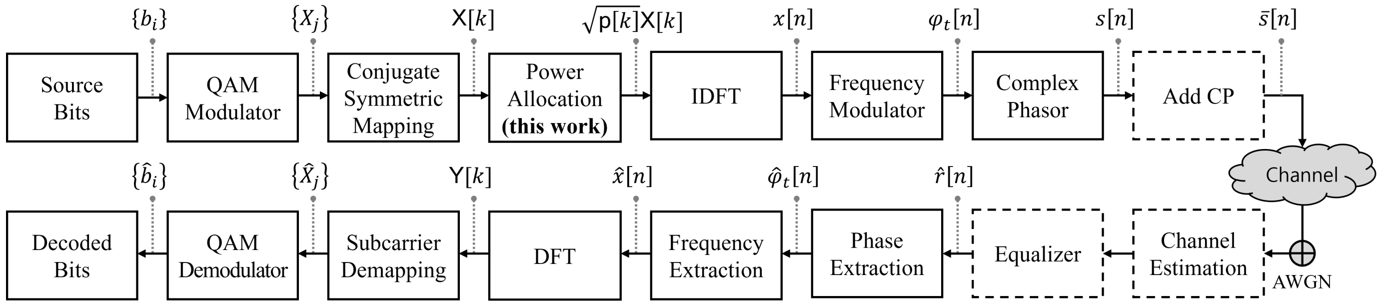

Fig. 1. The functional block diagram of an FM-OFDM system, with the focus of this being on power allocation. Blocks with dashed outlines are only necessary in a frequency-selective fading channel. Figure inspired by [6].

transmitted symbol $\mathsf{X}[k]$ on k-th subcarrier in the frequency domain is therefore constructed as follows to ensure that the entire symbol vector is conjugate symmetric[1]:

$$\mathsf{X}[k] = \begin{cases} X_{k-1}, & k = 1, \ldots, N_s \\ X^*_{N-2-k}, & k = N - N_s - 1, \ldots, N-2 \\ 0, & \text{else}, \end{cases} \tag{1}$$

where X_k and N_s are the k-th modulated QAM symbol with unit power and the number of transmit symbols, respectively.

The frequency-domain symbol vector undergoes power allocation and an N-point inverse discrete Fourier transform (IDFT) to construct the time-domain samples $\{x[n]\}$ as

$$x[n] = \frac{1}{\sqrt{N_a}} \sum_{k=0}^{N-1} \sqrt{\mathsf{p}[k]}\mathsf{X}[k] e^{\mathrm{j}\frac{2\pi kn}{N}}, \tag{2}$$

where N_a and $\mathsf{p}[k]$ are, respectively, the number of active subcarriers and the power allocation coefficient of k-th subcarrier. Here, $N_a = 2N_s$ for conjugate symmetry. This work will propose two schemes for allocating power $\mathsf{p}[k]$ on each subcarrier k under a total power constraint

$$\frac{1}{N_s} \sum_{k=1}^{N_s} \mathsf{p}\,[k] = 1. \tag{3}$$

To employ FM-OFDM, the time-domain OFDM signal is then transmitted via FM as follows. The generated OFDM signal $x[n]$ in (2) is modulated into an instantaneous phase signal through a cumulative sum as

$$\varphi_t[n] = \varphi_0 + 2\pi m \sum_{n'=0}^{n} x[n'], \tag{4}$$

where m is the *modulation index* and $\varphi_t[n]$ is the n-th instantaneous phase signal sample, respectively. Here, the modulation index m plays an important role in dictating the rate at which the transmitted signal's frequency changes and thus the bandwidth it occupies [11], [12]. The initial phase φ_0 is an arbitrary constant [13] and is therefore taken to be 0.

[1]To ensure that the transmitted signal achieves a constant envelope, the signal modulating the complex phasor in (5) must be real-valued. To satisfy this condition, we employ the property that a Fourier transform of a real-valued vector is conjugate symmetric.

$\varphi_t[n]$ is then modulated into a constant envelope signal through a complex exponential as

$$s[n] = A_c \cdot \exp(\mathrm{j}\varphi_t[n]), \tag{5}$$

where A_c is the amplitude of the constant envelope signal $s[n]$ after transmit power amplification. When the cyclic prefix (CP) is appended to $s[n]$, the transmitted signal $\bar{s}[n]$ effectively transforms a multi-tap channel into a parallel bank of single-tap subchannels.

The multi-path channel impulse response vector is [10]

$$h[n, z] = \sum_{\ell=0}^{L-1} b_\ell[n]\; e^{\mathrm{j}\alpha_\ell}\; \delta[z - z_\ell], \tag{6}$$

where n and z denote the discrete time and delay indices. L is the number of paths in the channel, and b_ℓ, α_ℓ, and z_ℓ are the amplitude, phase shift, and delay of the ℓ-th tap, respectively.

The received signal after the channel is

$$r[n] = \sum_{\ell=0}^{L-1} b_\ell[n] e^{\mathrm{j}\alpha_\ell} \bar{s}[n - z_\ell] + w[n], \tag{7}$$

where the noise sample follows $w[n] \sim \mathcal{N}_{\mathbb{C}}(0, N_0)$, with N_0 being the one-sided noise power spectral density.

Due to the circularity obtained through the CP, it is possible to employ one-tap frequency-domain equalization to remove multi-path effects. The FM-OFDM received signal obtained after channel equalization $\hat{r}[n]$ is [6]

$$\hat{r}[n] = \hat{b}[n] \cdot s[n] \cdot \exp\left(\mathrm{j}(\hat{\varphi}_{\mathrm{e}}[n] + \hat{\psi})\right) + \hat{w}[n], \tag{8}$$

where $\hat{b}[n]$, $\hat{\varphi}_{\mathrm{e}}[n] + \hat{\psi}$, and $\hat{w}[n]$ are respectively the residual amplitude, residual phase shift, and noise term after equalization.

At the receiver, phase extraction determines the instantaneous phase of the received signal $\hat{r}[n]$ as

$$\begin{aligned} \hat{\varphi}_t[n] &= \mathrm{unwrap}\left(\mathrm{angle}(\hat{r}[n])\right) && (9) \\ &= \varphi_t[n] + \hat{\varphi}_{\mathrm{e}}[n] + \hat{\psi} + \tilde{w}[n], && (10) \end{aligned}$$

where the angle operation is defined as

$$\mathrm{angle}(\hat{r}[n]) = \arctan\left(\frac{\Im\{\hat{r}[n]\}}{\Re\{\hat{r}[n]\}}\right), \tag{11}$$

and $\tilde{w}[n]$ is the noise in the instantaneous phase. Here, the phase unwrapping operation unwrap is employed to remove abrupt discontinuities due to 2π phase wraps, ensuring a continuous and equivalent representation of the phase information [14], [15].

Obtaining the instantaneous frequency from the instantaneous phase involves a backward difference operation ∇ between consecutive phase values by taking (4) and (10) into account as

$$\hat{x}[n] = \frac{1}{2\pi m} \cdot \nabla \hat{\varphi}_t[n] \tag{12}$$

$$= \frac{1}{2\pi m} (\hat{\varphi}_t[n] - \hat{\varphi}_t[n-1]) \tag{13}$$

$$= x[n] + \frac{1}{2\pi m} \cdot \nabla \left(\tilde{w}[n] \right), \tag{14}$$

where the initial instantaneous frequency is

$$\hat{x}[0] = \frac{1}{2\pi m} \cdot (\hat{\varphi}_t[0] - \hat{\varphi}_t[N-1]). \tag{15}$$

In this process, the constant residual phase shift term vanishes, and the channel has an additive impact rather than multiplicative, which supplies FM-OFDM with robustness to the wireless channel. A previous study has demonstrated that, in scenarios involving AWGN and Rayleigh flat fading, channel estimation and subsequent equalization are not required at all [6]. However, the goal of this paper is not to focus on the channel robustness of FM-OFDM but rather to assume scenarios where time-varying terms are disregarded, and thus successful equalization is assumed for multi-path channels.

Performing a discrete Fourier transform (DFT) on this signal yields the demodulated signal

$$\mathsf{Y}[k] = \frac{\sqrt{N_a}}{N} \sum_{n=0}^{N-1} \hat{x}[n] e^{-\mathrm{j}\frac{2\pi k n}{N}} \tag{16}$$

$$= \sqrt{\mathsf{p}[k]} \mathsf{X}[k] + \mathsf{n}[k], \tag{17}$$

where $\mathsf{n}[k]$ is the received noise at the k-th subcarrier and is distributed as $\mathcal{N}_{\mathbb{C}}(0, \mathsf{N}[k])$ whose variance $\mathsf{N}[k]$ is [6]

$$\mathsf{N}[k] = \frac{N_0 N_a}{4\pi^2 m^2 A_c^2 N} \cdot (1 - \cos(2\pi k/N)). \tag{18}$$

The resulting SNR at k-th subcarrier $\gamma[k]$ is then derived as

$$\gamma[k] = \frac{4\pi^2 m^2 A_c^2 N}{N_0 N_a} \frac{\mathsf{p}[k]}{1 - \cos(2\pi k/N)}. \tag{19}$$

Unlike conventional OFDM systems, the sub-channel strength variations due to non-uniform noise PSD in FM-OFDM introduce new possibilities for power allocation, even in the absence of fluctuations caused by fading channels.

III. Proposed Power Allocation Strategies

Power allocation is an important mechanism in communication systems that adjusts or distributes transmit power strategically to enhance desired sense of performance. In conventional systems, including those employing OFDM, power allocation was tailored to the variability in the channel over time and across frequency, as the channel had a direct multiplicative impact on the signal strength being transmitted, with the noise power essentially constant across both time and frequency. As mentioned, the effects of the channel and of noise differ in the context of FM-OFDM systems: the channel has an additive effect and noise is frequency-dependent. With these factors in mind, we propose two novel power allocation strategies. The first is one aims to improve BER performance while the second one optimizes spectral efficiency.

A. BER Enhancement Strategy: Emphasis Filter Equivalent

In traditional analog FM systems, so-called pre-emphasis and de-emphasis filters are employed to prevent high-frequency components of a signal from being plagued by higher noise [7], [16]. Put simply, the pre-emphasis filter at the transmitter emphasizes high-frequency components, whereas the de-emphasis filter at the receiver inverts this process. Together, this renders a received noise which exhibits, more desirably, a uniform power spectral density.

Akin to this notion of pre-/de-emphasis filtering, the first power allocation scheme we propose digitally compensates for the frequency-dependency of received noise. Since higher-frequency subcarriers will experience higher noise and are thus prone to more noise-induced bit errors, our proposed scheme centers on allocating more power to them. We mitigate the effects of this frequency-dependent noise by allocating power on each subcarrier proportional to its noise PSD, subject to a total power constraint, which effectively equalizes the SNR across all subcarriers. Conveniently, this can be implemented with low complexity in the digital domain when taking the IDFT in (2) without the need for additional circuitry.

This proposed *emphasis filter equivalent* power allocation scheme is derived as follows.

Lemma 1. *The emphasis filter equivalent power allocation coefficients are derived as*

$$\mathsf{p}_{\mathrm{EFE}}[k] = \frac{N_s \cdot (1 - \cos(2\pi k/N))}{\sum_{i=1}^{N_s} (1 - \cos(2\pi i/N))}, \tag{20}$$

yielding an SNR on the k-th subcarrier of

$$\gamma_{\mathrm{EFE}}[k] = \frac{4\pi^2 m^2 A_c^2 N}{N_0 N_a} \frac{N_s}{\sum_{i=1}^{N_s} (1 - \cos(2\pi i/N))}, \tag{21}$$

which does not depend on the subcarrier index k and is thus constant across subcarriers.

Proof. To yield a constant SNR, the signal power should be adjusted proportionally to the noise PSD. In (18), the noise PSD is proportional to $(1 - \cos(2\pi k/N))$. Thus, the desired power allocation coefficients are

$$\mathsf{p}'_{\mathrm{EFE}}[k] = \eta \cdot (1 - \cos(2\pi k/N)), \tag{22}$$

where η is a power normalization constant chosen to maintain total power consumption. To abide by an average subcarrier power constraint of 1 as per (3), η must satisfy

$$\sum_{k=1}^{N_s} \eta \cdot (1 - \cos(2\pi k/N)) = N_s. \tag{23}$$

Then, η is determined to be

$$\eta = \frac{N_s}{\sum_{k=1}^{N_s}(1-\cos(2\pi k/N))}. \tag{24}$$

By substituting (22) and (24) into (19), the SNR on each subcarrier becomes a constant equal to

$$\gamma_{\mathrm{EFE}}[k] = \frac{4\pi^2 m^2 A_c^2 N}{N_0 N_a} \cdot \eta. \tag{25}$$

□

Through Lemma 1, it is confirmed that the proposed power allocation scheme equalizes the SNR for all subcarriers. Now, with the same SNR across all subcarriers, there is no concentrated bit error occurrence on specific subcarriers.

While Gaussian signaling is the capacity-achieving scheme, practical systems employ discrete modulation and coding schemes (MCSs) and adapt such dynamically based on channel quality. In 5G cellular systems, this adaptation is done across subcarriers, since only a single 4-bit wideband channel quality indicator (CQI) is fed back, resulting in a uniform MCS across the entire sub-band [17]. The above proposed approach is tailored to cases such as this where the same MCS is employed across all subcarriers.

B. Capacity Enhancement Strategy: Modified Waterfilling

Nonetheless, it is still meaningful to maximize capacity to analyze the achievable maximum information rate in FM-OFDM. The capacity of a conventional OFDM system is attained through *waterfilling* by allocating power across subcarriers according to their strength, which can vary widely in wireless channels that are highly frequency-selective [18]. For FM-OFDM systems, we formulate the rate maximization problem as follows, considering only the noise PSD without accounting for channel gain. In FM-OFDM systems, the traditional form of waterfilling is no longer capacity-achieving since each subcarrier sees a unique noise power due to its dependence on frequency, as evidenced by (18). This motivates us to formulate the following power allocation problem to maximize the spectral efficiency subject to a total power constraint.

$$\max_{\mathsf{p}[1],\ldots,\mathsf{p}[N_s]} \quad \frac{1}{N_s}\sum_{k=1}^{N_s}\log_2(1+\gamma[k]) \tag{26a}$$

$$\text{s.t.} \quad \frac{1}{N_s}\sum_{k=1}^{N_s}\mathsf{p}[k] = 1 \tag{26b}$$

$$\mathsf{p}[k] \geq 0,\ k = 1,\ldots,N_s \tag{26c}$$

$$\gamma[k] = \frac{4\pi^2 m^2 A_c^2 N}{N_0 N_a}\frac{\mathsf{p}[k]}{1-\cos(2\pi k/N)}. \tag{26d}$$

Here, under the assumption that the receiver applies channel equalization to remove multi-path effects, the noteworthy difference between this problem and that of traditional waterfilling is the fact that each subcarrier sees a unique noise power. We solve this problem to obtain the optimal power allocations which maximize the sum-rate across subcarriers.

Lemma 2. *Solving problem* (26) *results in the optimal power allocation coefficient on subcarrier* k *being*

$$\mathsf{p}_{\mathrm{MWF}}[k] = \left(\frac{1}{\lambda} - \frac{N_0 N_a}{4\pi^2 m^2 A_c^2 N}(1-\cos(2\pi k/N))\right)^+, \tag{27}$$

where $1/\lambda$ *is the so-called water level and* $x^+ = \max(x,0)$.

Proof. Since (26) is a convex problem, it can be solved using the Lagrangian multiplier method. We formulate the Lagrangian function [9] as

$$L(\lambda, \mathsf{p}[1],\ldots,\mathsf{p}[N_s]) = \frac{1}{N_s}\sum_{k=1}^{N_s}\log_2(1+\gamma[k]) - \lambda\left(\frac{1}{N_s}\sum_{k=1}^{N_s}\mathsf{p}[k]-1\right), \tag{28}$$

where λ is the Lagrange multiplier and $\gamma[k]$ is as in (19). By taking the derivative of the Lagrangian function with respect to each power coefficient and setting it to zero, a solution satisfying the Karush-Kuhn-Tucker (KKT) conditions can be obtained as

$$\begin{cases} \dfrac{\partial L}{\partial \mathsf{p}[k]} = 0, & p[k] > 0, \\ \dfrac{\partial L}{\partial \mathsf{p}[k]} \leq 0, & p[k] = 0. \end{cases} \tag{29}$$

The optimal power allocation coefficient is then derived as

$$\mathsf{p}^\star[k] = \left(\frac{1}{\lambda} - \frac{N_0 N_a}{4\pi^2 m^2 A_c^2 N}\cdot(1-\cos(2\pi k/N))\right)^+, \tag{30}$$

where λ is determined to satisfy $\sum_{k=1}^{N_s} p^\star[k] = N_s$. □

Through Lemma 2, we have analytically shown that our proposed modified waterfilling scheme will maximize the achievable sum spectral efficiency, and in the next section, we empirically evaluate such, along with the emphasis filter equivalent scheme.

IV. Simulation Results

Simulations are conducted to observe the noise characteristics of FM-OFDM and evaluate the performance of the proposed power allocation schemes. In order to highlight the key idea of this paper, we conducted simulations in AWGN channels, under the assumption that multi-path effects have been removed at the receiver by channel equalization. We conducted our simulation using a transmit amplitude of $A_c = 1$, an FFT size of $N = 512$, a total number of data subcarriers as $N_s = 255$, and a subcarrier spacing of 15 kHz with QPSK modulation. We consider modulation indices of $m = 0.1/(2\pi)$ and $m = 0.6/(2\pi)$, the latter of which is the maximum allowed to avoid phase ambiguities, as highlighted in [6]. We will evaluate our results in terms of energy per bit E_b/N_0 to evaluate the system performance under various input power levels. Here, E_b/N_0 is defined as

$$E_b/N_0 = \frac{N}{N_s \log_2(M)}\frac{A_c^2}{N_0}, \tag{31}$$

where M is the modulation order.

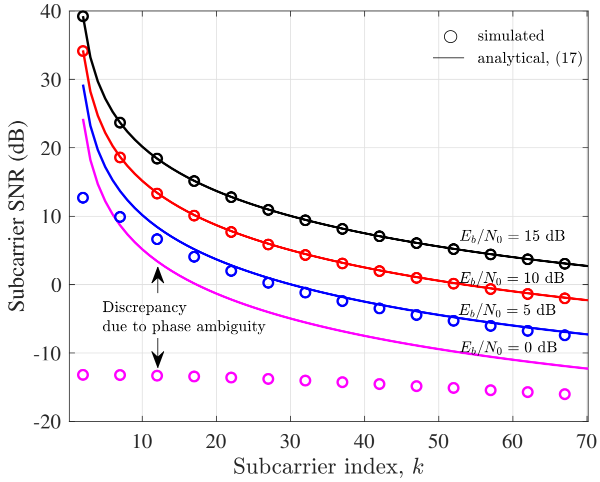

Fig. 2. For $m = 0.6/(2\pi)$, shown is a comparison of the SNR across subcarriers between theoretic and simulated values. Theoretic values are depicted as lines and simulated values are depicted as circles. E_b/N_0 is distinguished by color. The discrepancies between theory and simulation are due to noise-induced phase ambiguity inherent to FM.

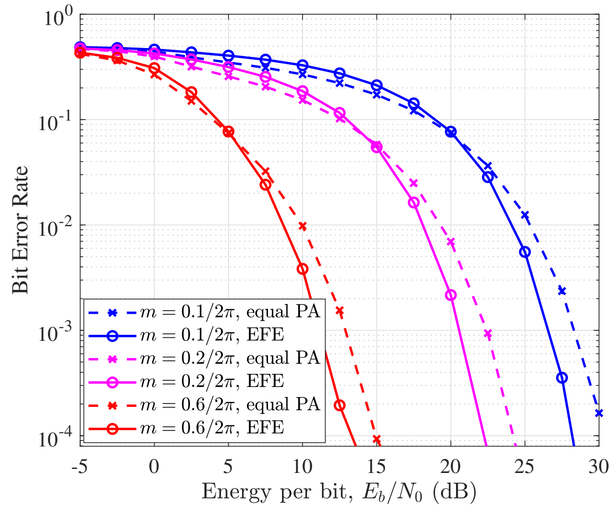

Fig. 3. BER performance comparison of the proposed emphasis filter equivalent (EFE) power allocation with equal power allocation (equal PA). The modulation index m is distinguished by color.

It is important to first verify the validity of (19), since the proposed schemes are based on theoretically derived SNR closed-form expressions, which may differ from implementation due to the phase ambiguity commonly observed in FM systems. Fig. 2 shows the SNR of each subcarrier as a function of E_b/N_0, according to both (19) and the results of Monte-Carlo simulations. When E_b/N_0 is high, the results of SNR obtained from Monte-Carlo simulations precisely match the theoretical SNR values. However, at low E_b/N_0, a significant discrepancy arises between simulation results and theoretical values. This is due to the fact that, when noise is strong, it has a greater likelihood of inducing phase ambiguity which leads to poor phase extraction at the receiver.

Fig. 3 illustrates BER performance as a function of E_b/N_0 with our first proposed power allocation scheme, the emphasis filter equivalent approach (denoted as EFE). We compare performance against equal power allocation across subcarriers, $p[k] = 1$ for all k, denoted as equal PA. In the high E_b/N_0 regime, the proposed EFE approach significantly improves BER performance. By design, this is because intensive bit errors are mitigated on subcarriers where noise is strong. However, in the low E_b/N_0 region, the proposed EFE scheme exhibits a slight performance degradation compared to equal power allocation. The reason for this lies in the interpretation that, when E_b/N_0 is low, it is advantageous to have no errors on specific subcarriers with lower noise, rather than equalizing the SNR for all subcarriers. This is further compounded by the discrepancy between theoretical and simulated SNR due to phase ambiguity, as mentioned. Therefore, it can be concluded that the proposed emphasis filter equivalent power allocation is most suitable in modestly high SNR conditions.

Fig. 4 demonstrates the theoretic and simulated data rate results based on the proposed modified waterfilling power allocation scheme (denoted as MWF). Data rates are derived by multiplying subcarrier spacing to the sum of spectral efficiency. The difference between the results based on simulation and those based purely on theory can be attributed to the aforementioned phase ambiguity inherent to FM systems. First, the theoretical results show an improvement in data rate regardless of the modulation index. On the other hand, in the simulation results, due to the phase ambiguity, a significant performance improvement can only be observed for low modulation index cases. At an $E_b/N_0 = 7.5$ dB, about a 38% gain is achieved, for instance, with the lower modulation index. This implies that, for the modified waterfilling power allocation to be effective, a low modulation index should be used with an appropriate E_b/N_0 value such that phase ambiguity is not severe.

It is worth noting that the two proposed schemes are effective in different environments. The EFE power allocation scheme proposed in Lemma 1 effectively improves the BER performance at high SNR. The MWF power allocation scheme proposed in Lemma 2, on the other hand, improves the spectral efficiency at moderate E_b/N_0 and with a low modulation index. This suggests that an appropriate power allocation design in FM-OFDM systems must be done so according to the environment.

V. Conclusion

In this paper, we introduced two novel power allocation schemes for FM-OFDM systems. The first proposed scheme, akin to emphasis filters in FM systems, effectively equalizes frequency-dependent noise across subcarriers in an effort to improve BER. The second proposed scheme modifies the traditional form of waterfilling power allocation to account for this frequency-dependent noise when maximizing sum spectral efficiency across subcarriers. The proposed power allocation

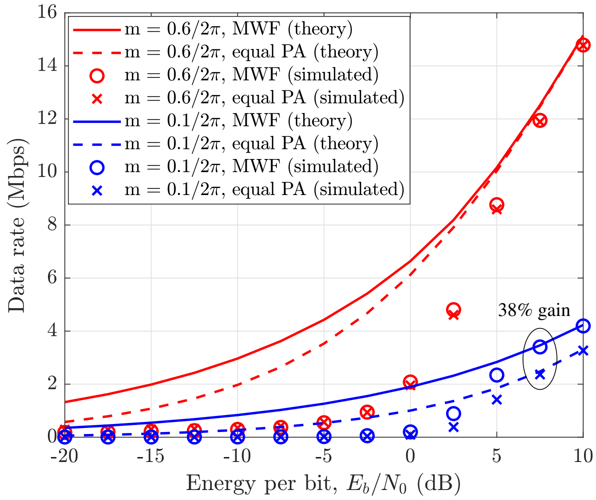

Fig. 4. Data rate comparison of the proposed modified waterfilling (MWF) power allocation with equal PA. Theoretic results are depicted as lines and simulated results are depicted as circles. The modulation index m is distinguished by color. The discrepancies between theory and simulation are due to noise-induced phase ambiguity inherent to FM.

strategies are capable of outperforming benchmarks but must be employed under particular SNR regimes to obtain the most gain in either BER or in spectral efficiency. The exploration of this paper underscores the importance of designing novel signal processing techniques, such as power allocation, based on the unique characteristics of these new waveforms that continue to be proposed in the literature, such as FM-OFDM. Valuable future work would examine how other mechanisms, such as equalization, may be tailored specifically for FM-OFDM waveforms and how to improve robustness to noise-induced phase ambiguity.

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