FASTER THAN NYQUIST-AN ENABLER FOR ACHIEVING MAXIMUM SPECTRAL EFFICIENCY IN COEXISTENCE SCENARIOS?

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ABSTRACT

In the context of spectrum sharing, a loss in spectral efficiency is incurred due to required guard bands needed for a desired co-channel interference level between systems. Our main interest is to show whether FTN signaling can recover the loss of spectral efficiency (SE) due to guard bands by adjusting the symbol duration and tolerating ISI in practical coexistence scenarios. In this paper, the SE of FTN signaling is investigated taking into account a practical multi-access channel, where a single-carrier system based on Nyquist or FTN signaling shares spectrum with a multi-carrier system. A single-user based on OQAM/OFDM system is considered as reference system. Simulation results show that by choosing an appropriate symbol duration, FTN signaling can recover the loss of SE at high SNRs. Furthermore, in coexistence scenarios with small guard bands, using FTN the SE curve is very close to that of the single-user reference system.

Index Terms— Faster than Nyquist (FTN) signaling; Spectral efficiency; Multi-access channel

1. INTRODUCTION

FTN signaling is considered as a promising technique to improve the bandwidth efficiency of conventional Nyquist rate modulation schemes in future communication systems. In FTN signaling systems, information symbols are transmitted at a rate higher than that suggested by the Nyquist theorem for having an ISI free transmission. As a result, inter-symbol interference (ISI) is induced.

The concept of FTN signaling was proposed and evaluated first by Mazo in 1975, [1]. In this study, the minimum Euclidean distance at the receiver of a single-carrier FTN signaling system using the sinc pulse shape is investigated. It is shown that the information symbols can be transmitted at a rate up to 25% higher than Nyquist signaling without having any loss in the Euclidean distance resulting in the same BER. Accordingly, a symbol duration of $0.802T$ is specified as Mazo limit for the sinc pulse shape with binary input.

The constrained Shannon capacity of FTN signaling was investigated first by Rusek and Anderson in [3]. They prove that the loss in capacity due to the excess bandwidth can be regained using FTN signaling. Therefore, using non-sinc pulse shaping FTN delivers higher capacities compared to the Nyquist signaling. Furthermore, the study in [6] confirms the results of FTN capacity presented in [3] and additionally indicates that the asymptotic capacity gain achieved by FTN tends to be equal to the excess bandwidth for high SNRs. However, in practice the asymptotic region (for large SNRs) is not of main interest. It is much more important to consider the SNR region (operational SNRs), where a given system is able to achieve a target Block Error Ratio (BLER).

In this paper, we consider a coexistence scenario, where multiple heterogeneous devices communicate with the base station, including mobile services and machine-type communication (MTC) devices. A certain fraction of the frequency band is allocated to each user/service. Due to low complexity and low peak-to-average power ratio, single carrier technique is a promising candidate for MTC. In in-band coexistence scenarios, where a single carrier system is operated in a band adjacent to a multicarrier system, a loss in spectral efficiency is incurred due to a required guard band needed to keep the co-channel interference under a predefined level. In our work, we focus on the question whether FTN signaling can recover loss of SE caused by guard bands and excess bandwidth by adjusting the data rate higher than the rate known from the Nyquist criterion under practical conditions of use.

The rest of this paper is organized as follows. In Section II, we describe the considered system models. An overview of the considered pulse shaping filters is given in Section III. The considered scenarios and related performance evaluation are described in Section IV. Section V presents the simulation results and finally a conclusion is drawn.

2. SYSTEM MODEL

In this section, we provide first a description of a single-carrier system model, followed by the OQAM/OFDM system model.

2.1. Single Carrier System Model

At the transmitter side, after the modulation block the FTN mapper is applied. The discrete transmit signal for a single-

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carrier FTN system is given as follows

$$s(n) = \sum_m d_m p(n - m\tau P), \;\; 0 < \tau \leq 1 \tag{1}$$

with the oversampling factor $P = TF_s$. Here, T and F_s are the symbol period and the sampling frequency, respectively. $p(n)$ stands for a real-valued discrete pulse shape having unit energy. A system with $\tau = 1$ corresponds to the Nyquist signaling for an orthogonal transmission scheme. For FTN signaling $\tau < 1$ and the pulse shapes are no longer orthogonal.

In the considered system model, the signal is transmitted through an AWGN channel, so that the received signal $y(n)$ is given by

$$y(n) = s(n) + w(n), \tag{2}$$

where $w(n)$ is the noise signal. At the receiver side, the received signal $y(n)$ passes through the FTN demapper, which consist of a matched filter $p^*(-n)$ having the same pulse shape used at the transmitter side and a pre-whitening filter applied to decolor noise. To eliminate the ISI resulted by FTN, a FTN detection based on the Viterbi algorithm is applied after the FTN demapper. Finally, the deinterleaving and channel decoder blocks are deployed. Since Nyquist signaling guarantees an ISI free transmission, the pre-whitening process and FTN detection are not required at the receiver side in the case of Nyquist signaling over AWGN channel.

2.2. OQAM/OFDM System Model

A multi-carrier based on OQAM/OFDM technology is considered as a promising candidate for future communication system due to better spectral properties compared to OFDM technology. In OQAM/OFDM systems, the discrete transmit signal $s(n)$ can be expressed as

$$s(n) = \sum_{m=-\infty}^{\infty} \sum_{k=-K/2}^{k=K/2-1} j^{m+k} d_{k,m} p_k(n - m\tau_0 K), \tag{3}$$

where $d_{k,m}$ is a real valued OQAM/OFDM symbol, which is mapped to the kth subcarrier at the mth OQAM/OFDM symbol. The parameter K represents the total number of subcarriers and $p_k(n - m\tau_0 K)$ is the real valued and even transmit pulse shape modulated to subcarrier k at the mth symbol. In general, the transmit pulse shape $p_k(n)$ is given by

$$p_k(n) = p(n) e^{-2j\nu_0 k \frac{n}{K}}. \tag{4}$$

Here, the normalized symbol duration $\tau_0 = 0.5$ and the normalized subcarrier spacing $\nu_0 = 1$ are specified for the OQAM/OFDM system. At the receiver side, after applying the modulated receiver pulse shape $q_{\widetilde{k}}(n) = p^*_{\widetilde{k}}(-n) = p_{\widetilde{k}}(n)$, the estimated real-valued OQAM symbol $\widehat{d}_{\widetilde{k},\widetilde{m}}$ can be calculated using

$$\widehat{d}_{\widetilde{k},\widetilde{m}} = \Re \left\{ j^{-(\widetilde{k}+\widetilde{m})} \sum_{n=-\infty}^{\infty} r(n) q_{\widetilde{k}}(n - \widetilde{m}\tau_0 K) \right\}, \tag{5}$$

where $r(n)$ is the received signal. More detail information about the OQAM/OFDM transmission scheme and related implementation structures are presented in [5] and [7].

3. PULSE SHAPING OVERVIEW

In a single-carrier system, a pulse shape $g(n)$ is used to minimize ISI that meets the Nyquist criterion. In practical implementations, $g(n)$ is the convolution of the transmitter side pulse shaping filter $p(n)$ and related matched filter at the receiver side $p^*(-n)$, i.e. $g(n) = p(n) * p^*(-n)$. Based on the characteristics of the mobile radio channel, pulse shaping filters can be designed and optimized to minimize ISI and intercarrier interference (ICI).

In this paper, we consider the Nyquist pulse shapes such as the rRC, Phydyas and extended Gaussian Functions (EGF) pulse shapes. The Phydyas and EGF pulse shapes are under discussion for future wireless communication systems. More descriptions about these pulse shapes are presented in [8]. The excess bandwidth of a pulse shape indicates how much the spectrum of a pulse shape extends over a given Nyquist bandwidth $W_0 = \frac{1}{T}$ and is defined as $W - W_0$, whereby W is the total bandwidth of the pulse shape. Therefore, the excess bandwidth factor can be expressed as follows:

$$\beta = \frac{W - W_0}{W_0}. \tag{6}$$

The related equivalent excess bandwidth factor of the applied pulse shapes is evaluated and summarized in [8].

4. CONSIDERED SCENARIOS

In this section, we provide a description of the considered coexistence scenarios and derive the metrics for analyzing the coexistence performance. The considered coexistence scenario is illustrated in Fig. 1, assuming that the multi-carrier system occupies a frequency band of bandwidth W_{MC}. A frequency band of bandwidth $W_{sc} = \mathrm{B} - W_{MC}$ is allocated for the single-carrier system including the guard band (GB) between the two systems. The available frequency band B is divided into K virtual subcarriers with a carrier spacing of Δf, and K_{ac} subcarriers are active for the multi-carrier system. The following scenarios are considered:

- Scenario 1: the frequency band B is occupied completely by an OQAM/OFDM system with $K_{ac} = K$
- Scenario 2: the frequency band B is occupied by an OQAM/OFDM and a single-carrier Nyquist system
- Scenario 3: the frequency band B is occupied by an OQAM/OFDM and a single-carrier FTN system

In scenario 1, we assume that the multi-carrier system achieves the maximum SE for a given bandwidth B. In scenario 2 and 3, a guard band is required between the two systems to keep the co-channel interference under a given level. As a result, the SE decreases with increasing the required guard band. The main aim of this study is to show whether FTN signaling can compensate the SE loss, so that

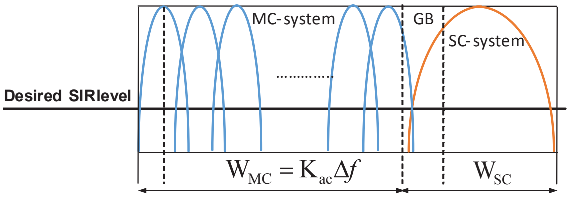

Fig. 1. Coexistence Scenarios

scenario 3 achieves the same SE as in scenario 1. In the following, the analysis of the co-channel interference is presented first, followed by the SE analysis of the considered scenarios.

4.1. Analysis of Multi-access Interference

In the coexistence scenarios 2 and 3, the received signal at the OQAM/OFDM receiver for the ideal transmission is given by

$$r_{oqam}(n) = s_{oqam}(n) + s_{sc}(n) + w(n), \tag{7}$$

where $s_{oqam}(n)$ and $s_{sc}(n)$ are the transmit OQAM/OFDM and single-carrier signals, which are given by (3) and (1), respectively. The signal $w(n)$ stands for the noise at the OQAM/OFDM receiver. In order to determine the required guard band between the two systems, we are interested in the interference caused from the single-carrier system to the edge subcarrier of the OQAM/OFDM system, which is denoted as the neighbor subcarrier of the single-carrier system. Assuming that f_{sc} is the center frequency of the single-carrier system and that it corresponds to the lth subcarrier in the virtual subcarrier grid of K carriers and $\widetilde{k}$ is the neighbor subcarrier of the single-carrier system, the transmit signal of the single-carrier system can be expressed as

$$s_{sc}(n) = s_{ftn}(n)e^{-j2\pi n\frac{l}{K}} \tag{8}$$

where the signal $s_{ftn}(n)$ is given by (1). Inserting (3) and (8) into (7) results in the following general expression for the estimation of the received OQAM/OFDM symbol $d_{\widetilde{k},\widetilde{m}}$

$$\widehat{d}_{\widetilde{k},\widetilde{m}} = \Re\left\{j^{-(\widetilde{k}+\widetilde{m})}\sum_{n=-\infty}^{\infty} r_{oqam}(n)q_{\widetilde{k}}(n-\widetilde{m}\tau_0 K)\right\}. \tag{9}$$

Consequently, the caused interference power from the single-carrier system to the estimated real-valued OQAM/OFDM symbol $\widehat{d}_{\widetilde{k},\widetilde{m}}$ is determined using

$$I_{re}(\widetilde{m}) = \left|\Re\left\{j^{-(\widetilde{k}+\widetilde{m})}\sum_{n=-\infty}^{\infty} s_{sc}(n)q_{\widetilde{k}}(n-\widetilde{m}\tau_0 K)\right\}\right|^2 \tag{10}$$

where $\nu = l - \widetilde{k}$ is the subcarrier offset, which corresponds to the frequency distance between the two coexisting systems. Inserting (1) and (8) into (10), we obtain

$$I_{re}(\widetilde{m}) = \left|\Re\left\{j^{-(\widetilde{k}+\widetilde{m})}\sum_{n=-\infty}^{\infty}\sum_{m} d_m p(n-\mu)q(n)e^{-j2\pi n\frac{\nu}{K}}\right\}\right|^2, \tag{11}$$

where $\mu = m\tau P - \widetilde{m}\tau_0 K$ represents the time offset between the two systems. Assuming $E\{|d_m|^2\} = 1$ and utilizing the cross-ambiguity function $A(\mu,\nu)$ given by

$$A(\mu,\nu) = \sum_{n=-\infty}^{\infty} p(n-\mu)q^*(n)e^{-j2\pi n\frac{\nu}{K}}, \tag{12}$$

equation (11) can be rewritten as

$$I_{re}(\widetilde{m}) = \left|\Re\left\{j^{-(\widetilde{k}+\widetilde{m})}A(\mu,\nu)\right\}\right|^2 \tag{13}$$

Since transmitted symbols of the single-carrier system are complex and the transmitted PAM symbol of the OQAM/OFDM system is either in-phase (real part) or the quadrature (imaginary part) components of complex QAM symbols, the interference power is calculated using

$$I(\widetilde{m}) = \max\left\{I_{re}(\widetilde{m}), I_{im}(\widetilde{m})\right\}, \tag{14}$$

where $I_{im}(\widetilde{m}) = \left|\Im\left\{j^{-(\widetilde{k}+\widetilde{m})}A(\mu,\nu)\right\}\right|^2$.

4.2. Spectral Efficiency Analysis

For a given allocated bandwidth $[-W, W]$, the optimal Nyquist pulse shape is a sinc pulse shape with a symbol duration of $T = 1/2W$. However, a sinc pulse shape is impractical and typically the rRC pulse shape with the excess bandwidth factor β is used. If an rRC pulse occupies the same bandwidth $[-W, W]$, a symbol duration of $T = (1+\beta)/2W$ can be chosen for having ISI free transmission. Thus, in comparison to sinc pulse, the rRC pulse suffers a loss in SE of $1/(1+\beta)$. In FTN signaling, by setting $\tau T < (1+\beta)/2W$ the loss may be reduced. For a given bandwidth B, the achieved SE (the normalized data rate) at high SNRs is calculated according to

$$\eta = \frac{R}{B} = \frac{R_c \log_2 M}{TB}, \tag{15}$$

where R stands for the achieved sum rate and R_c represent the channel code rate. The parameters M and T are the modulation order and the symbol duration, respectively. In scenario 1, where only an OQAM/OFDM system operates in the whole frequency band B, the SE is given as

$$\eta_1 = \frac{KR_c \log_2 M}{T_{oqam}B}. \tag{16}$$

Here, T_{oqam} is the OQAM/OFDM symbol duration. Assuming that $B = \frac{K}{T_{oqam}}$ and $\Delta f = \frac{B}{K}$, we obtain

$$\eta_1 = R_c \log_2 M. \tag{17}$$

In the coexistence scenario 2 and 3, it is assumed that both systems have the same code rate and modulation order, the achieved sum rate at high SNRs is calculated using

$$R = \underbrace{\frac{\left(K - \frac{KW_{sc}}{B}\right)R_c \log_2 M}{T_{oqam}}}_{\text{Rate of OQAM system}} + \underbrace{\frac{R_c \log_2 M}{\tau T_{sc}}}_{\text{Rate of SC system}}. \tag{18}$$

where $W_{sc} = B - W_{MC}$ is allocated bandwidth for the single-carrier system including the required guard band, and T_{sc} is the Nyquist symbol duration of the single-carrier system. Inserting (18) into (15) with $B = F_s$ and $T_{sc} = PF_s$ results in

$$\eta_C = \left(1 - \frac{W_{sc}}{B} + \frac{1}{\tau P}\right) R_c \log_2 M, \qquad (19)$$

where η_C with $\tau = 1$ and $\tau < 1$ stand for the SE of scenario 2 and 3, respectively. According to (19), it can be seen that in the considered multi-access channel a loss in SE is incurred due to the guard band between the two systems using Nyquist signaling. In scenario 2 the loss in SE increases with increasing the guard band. Furthermore, in the single-carrier system the excess bandwidth of the used pulse shape also results in a SE loss. In scenario 3 by choosing an appropriate FTN factor τ, the loss in SE may be compensated.

5. SIMULATION RESULTS

To evaluate the coexistence performance in terms of co-channel interference and SE, all simulations are performed for 1000 frames, each consisting of 10^4 bits, and different modulation pulse shaping filters are used. For the single-carrier system an oversampling factor of 8 is considered for the used pulse shapes. All pulse shapes have an overlapping factor of 4. The whole frequency band B is divided into 128 virtual subcarriers. We assume that both systems use the same modulation scheme, channel coding and pulse shape. In the following, the simulation results are shown and discussed in depth.

5.1. Coexistence Performance in term of Interference

In this section, the interference from the single-carrier Nyquist signaling system to the edge subcarrier of the OQAM/OFDM system depending on the frequency distance ν is investigated. Fig. 2 depicts the coexistence performance in terms of interference leakage for different pulse shapes, where the frequency distance ν is counted in number of virtual subcarriers. It can be seen that the frequency distance and the required guard band between the two systems scales with the excess bandwidth of the applied pulse shape. More specifically, for an interference value of around -22 dB the frequency distance ν is equivalent to $\frac{(1+\beta)K}{2P}$, which corresponds to $W_{SC} = \frac{(1+\beta)K}{P}$.

5.2. Spectral Efficiency

For the SE evaluation, both systems use a convolutional coder (177, 131). The achieved SE, $\eta = R/B$ is calculated by $\eta = (1 - BLER)R_c \log_2 M$. In order to perform the spectral efficiency improvement achieved by FTN signaling, a single user based on OQAM/OFDM system is considered as the reference system (scenario 1). Assuming that in the single user system, the OQAM/OFDM system achieves the maximum SE, our goal here is to investigate whether FTN

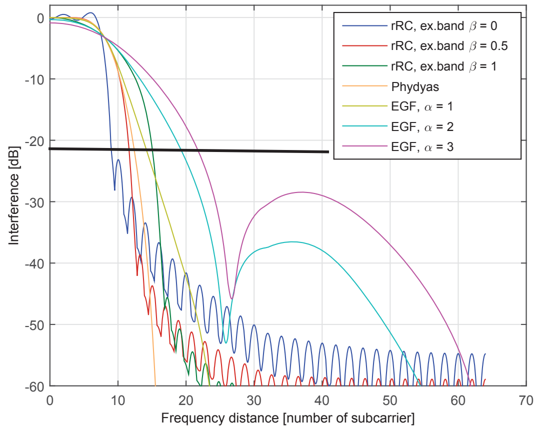

Fig. 2. Interference power versus frequency distance

can enable achieving the same SE given by the single-user OQAM/OFDM system. Note that for any W_{SC}, in order to compensate the SE loss in coexistence scenarios we have to adjust the FTN factor τ according to (19). For keeping the interference power below -22 dB, in order to recover the SE loss we have to set the FTN factor $\tau = 0.7692 \approx 0.75$ and $\tau = 0.5$ for the case of using an rRC pulse shape with $\beta = 0.3$ and $\beta = 1$, respectively.

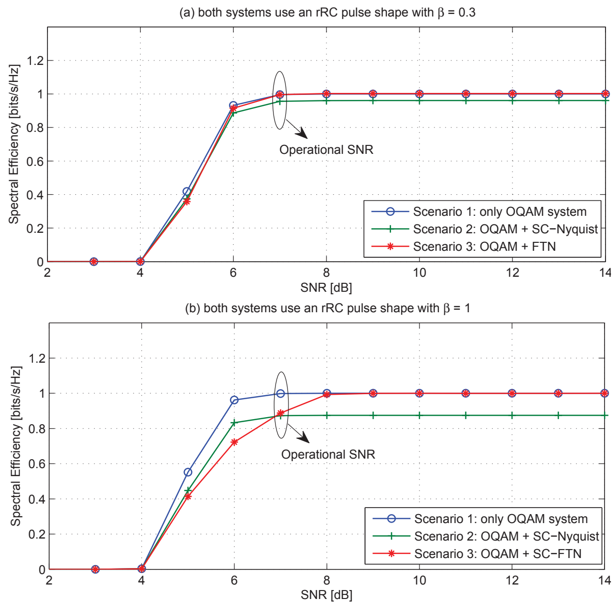

Fig. 3. SE of three considered scenarios at an interference power of -22 dB with a code rate of 0.5

Fig. 3 illustrates the SE for the cases that both system use an rRC pulse shape of $\beta = 0.3$ and $\beta = 1$, respectively. Here, a code rate of 1/2 is used. Fig. 3 indicates that in coexistence scenario 2 the excess bandwidth and guard band result in SE loss. Furthermore, in scenario 3 FTN signaling can recover completely the loss in SE at high SNRs. An interesting observation is that FTN signaling can start to recover the SE loss from a SNR value of 6 dB and 7 dB for the case of $\beta = 0.3$

and $\beta = 1$, respectively, and after that the spectral efficiency loss is completely recovered. More specifically, the SE loss and the corresponding equivalent guard band at a SNR value of 7 and 8 dB are given in Table 1. It can be seen that in the case of $\beta = 0.3$, due to small guard band the SE curve of scenario 3 is very close to that of scenario 1, and from a SNR value of 7 dB, where the OQAM/OFDM system starts to achieve the maximum SE (operational SNR), the loss is already recovered. However, in case of $\beta = 1$, due to large guard band at a SNR value of 7 dB only 1% the SE loss can be recovered using FTN. The reason for this is that for large guard band, in order to recover the SE loss we have to set a smaller value for τ, which leads to more ISI in the FTN system. This in turn leads to poor BLER performance of the system.

Table 1. SE loss and related equivalent guard band of coexistence scenarios

Pulse shape	Performance	Scenario 2		Scenario 3	
rRC	SNR	7 dB	8 dB	7 dB	8 dB
$\beta = 0.3$	SE loss	$\approx 4\%$	4%	0%	0%
	Eq.Guard band (nCarr)	≈ 6	≈ 6	0	0
rRC	SNR	7 dB	8 dB	7 dB	8 dB
$\beta = 1$	SE loss	13%	12.5%	12%	0.6%
	Eq.Guard band (nCarr)	≈ 17	≈ 16	≈ 15	≈ 1

We consider now the SE performance at an interference power of -15 dB. At this interference level, the frequency distance ν is about 13 virtual subcarriers (see Fig. 2) corresponding to $W_{sc} \approx 29$ subcarriers. According to (19), in order to recover the SE loss we have to set FTN signaling factor $\tau = 0.552 \approx 0.6$. The SE for this case is shown in Fig. 4. It can be seen that due to the smaller guard band correspondingly a larger τ is needed, thus the SE curve of scenario 3 is close to that of scenario 1. However, due to the rounding applied for factor τ FTN does not fully achieve the maximum SE.

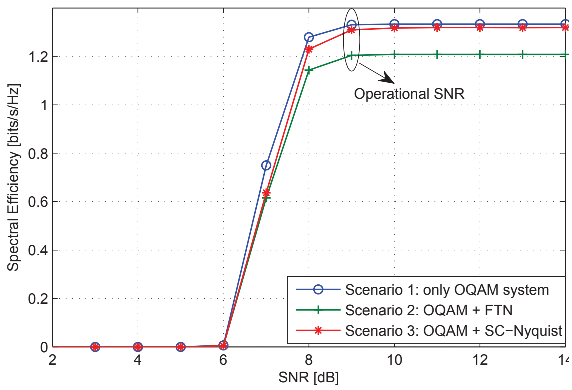

Fig. 4. SE of three considered scenarios at an interference power of -15 dB using a rRC pulse shape $\beta = 1$ with a code rate of 2/3

6. CONCLUSION

In this paper, we investigated spectral efficiency of coexistence scenarios, where a single-carrier system using Nyquist or FTN signaling shares spectrum with a multi-carrier system. Simulation results show that FTN signaling can recover completely the loss of SE due to guard bands between systems and excess bandwidth of the applied pulse shape in high SNR regime. For any other operational SNR, the spectral efficiency loss can be regained by choosing an appropriate FTN rate. Furthermore, in coexistence scenarios with small guard band and excess bandwidth, using FTN signaling the SE curve is close to that of the single-user reference system. This leads to the conclusion that FTN signaling technique is able to improve the overall spectral efficiency in coexistence scenarios.

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