Power and Spectral Efficiency Advantages of OFDM/OQAM over OFDM/QAM for PHY in Wireless and Cognitive Radio Networks

Slobodan Nedic, Robert Vallet

Abstract — This paper addresses aspects of power and spectral efficiency advantages of OFDM/OQAM over the conventional OFDM (with QAM) signaling and accessing format for wireless networks and cognitive radio (CR) applications. The emphasis is on the ability of the OFDM/OQAM format to work without cyclic-prefix (CP), and to have a relatively small number of subchannels without incurrence of power and spectral losses inherent to OFDM/QAM heavy reliance on it. Specifically, the following aspects are elucidated: 1) exponentially increasing Eb/No degradation in OFDM with increasing QAM constellations size, and 2) reduced PAPR in OFDM/OQAM and consequently better PSD mask fitting. These two aspects are supported by computer simulation results. Additional OFDM/OQAM advantages, as the multipath diversity gains, are also briefly discussed.

***Keywords* — Cognitive Radio, OFDM/OQAM, OFDM/QAM, Power Efficiency, Spectral Efficiency, Wireless Networks.**

I. Introduction

Development of the (coded) Orthogonal Frequency Division Multiplex (OFDM) modulation for Digital Audio and Video Broadcasting [1] had paved the way for its adoption, as physical layer accessing format, by a number of WLAN, MAN and cellular systems, as well as the 4-th generation (4G) development, [2]. Although its advantages over the CDMA have largely been appreciated, it still may not represent an optimal system in terms of overall system performance and complexity ratio, mainly due to an inherent spectral and power inefficiency caused by utilization of the cyclic prefix (CP), and a considerable performance loss due to transmission impairments and implementation imperfections. Lack of subchannels' spectral confinement especially makes its applicability to unsynchronized mobile networks quite problematic.

After the introduction of the orthogonally multiplexed sub-channels with the Nyquist-type spectral shaping [3], its staggered, or OQAM (Offset QAM) form was proposed in [4], and the first digital implementation of modulation and demodulation by using IFFT/FFT and poly-phase filter banks was done in [5]. It was followed by the first sub-channel based linear equalization [6], with its alternative and improved configuration [7], to compensate for inter-symbol and inter-subchannel interference arising from linear distortions. Much work has been done on efficient implementation of pertinent filter-banks [8][9], various aspects of transceiver design, such as synchronization [10], channel estimation [11], and non-linear distortions [12], including multi-antenna and MIMO configurations [13][14]. After earlier sporadic and unsuccessful attempts to promote OFDM/OQAM for wireless applications as an alternative to conventional OFDM, including the 3GPP2 standardization proposals, recently a special interest has been shown for this form of Filter-Bank based Multi-Carrier (FBMC) for both spectrum sensing, and the secondary users PHY signaling applications in the context of Cognitive Radio, and in particular within the FP7 PHYDYAS Project, [15][16].

The most fundamental feature of the OFDM/OQAM format is that it allows for fully taping onto the unexploited segment of the signaling/accessing concepts space laying between the Single-Carrier (including CDMA) and the Multi-Carrier format with relatively large number of subchannels, as the two extremes.

Regarding combined power and spectral efficiencies, first the CP related Eb/No degradation increase with the increase of QAM constellation size will be analyzed in Section 2 both from the theoretical point of view, and by computer simulations of a practical transmit-end constrained signaling set-up. After that, in Section 3 the ability to use a relatively small number of subchannels is valorized by the reduced PAPR (resulting in smaller HPA back-off). In Section 3 additional potential advantages of OFDM/OQAM of OFDM/QAM are briefly touched upon, followed by conclusions.

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II. CP Induced SNR Degradation in OFDM

The main parameters of an OFDM/QAM modulation are the effective symbol duration T (orthogonality interval), the number of active subchannels K out of N available, and the time guard interval (GI), usually denoted by CP, of duration Δ. The signal bandwidth is then $B_s = K/T$. The channel delay spread τ_D is the inverse of the channel coherence bandwidth $B_{coh} = 1/\tau_D$, and he CP duration is supposed to satisfy $\Delta > \tau_D$. A drawback of this 'noble' property of transforming dispersive channel to a set of independents frequency-flat Rayleigh fading subchannels free of inter-symbol or inter-subchannel interference is a loss in basic spectrum efficiency by factor $T/(T+\Delta)$. Thus, with CP, the combined modulation and coding efficiency has to be proportionally increased, $\eta' = \eta(T+\Delta)/T$, (1), where η is the spectral efficiency of the OFDM/OQAM modulation with sufficiently large number of carriers and/or sufficiently low subchannels' spectral roll-off factor and the associated channel code. In addition to that, for the same average power, there is essentially reduced bit-energy, $\left(\frac{E_b}{N_0}\right)' = \frac{E_b}{N_0}\frac{T}{T+\Delta}$, (2) due to the wasted power in the CP part of the OFDM/QAM signal. For the transmission over an AWGN channel, from the capacity theorem, the signal to noise ratio satisfies the relation $\frac{E_b}{N_0} > \frac{2^{\eta}-1}{\eta}$, (3). Then by using the two losses introduced by the guard interval, by first combining (2) with primed (3), $\left(\frac{E_b}{N_0}\right)' > \frac{2^{\eta'}-1}{\eta'}$, as an equivalent capacity limit for the OFDM/QAM, and further expressing η' through η, from (1), the bit energy to noise spectral density ratio for the case with CP satisfies relation,

$$\left(\frac{E_b}{N_0}\right) > \frac{T+\Delta}{T}\frac{2^{\eta\frac{T}{T+\Delta}}-1}{\eta\frac{T+\Delta}{T}} = \frac{2^{\eta\frac{T+\Delta}{T}}-1}{\eta} \quad . \qquad (4)$$

Fig. 1 shows how the SNR loss (the ratio of (4) and (3), i.e. $(E_b/N_0)^{(\prime)}/(E_b/N_0)$ in dB) depends on the targeted modulation/coding efficiency η where the CP duration is a parameter. For larger spectral efficiencies the loss in signal to noise ratio becomes important compared to the one obtained with a spectrally maximal efficient modulation.

To corroborate on this finding, Fig. 2 shows the bit-error probability curves produced by simulation for three QAM constellation sizes, without and with convolutional coding of constraint length 8, as defined in the IEEE 802.11a standard, with the CP length of a quarter of T interval for the OFDM/QAM case.

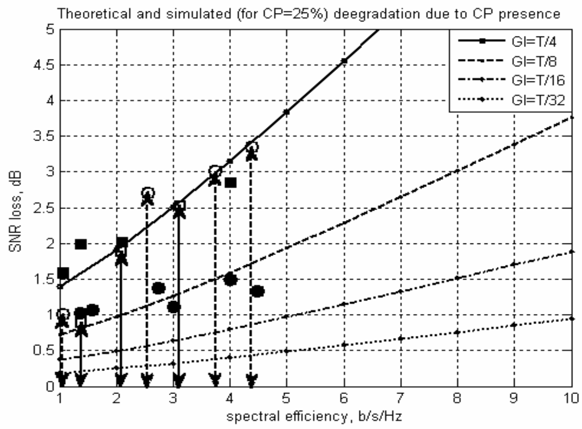

Figure 1 – Power efficiency reduction of OFDM/QAM as function of targeted spectral efficiency.

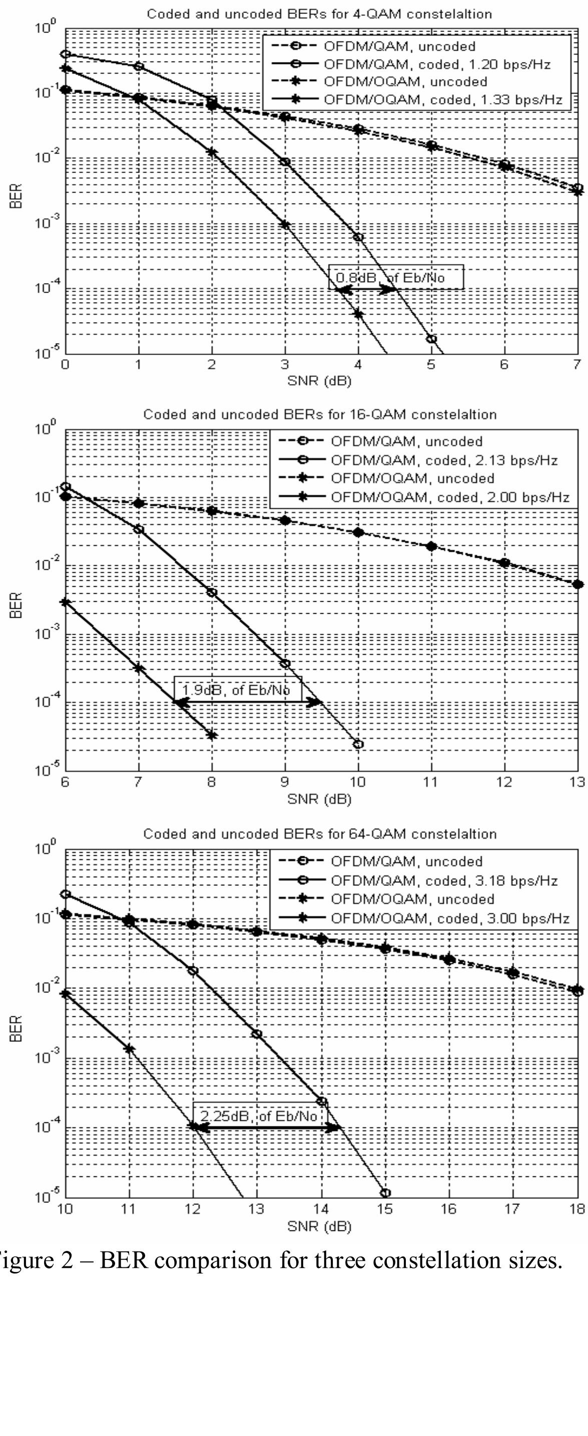

Figure 2 – BER comparison for three constellation sizes.

Simulation results correspond to AWGN case and comparison of OFDM/QAM and OFDM/OQAM both with 48 active out of 64 subchannels, with ideal channel estimations, and the rather similar overall spectral efficiencies. The latter were achieved by using larger coding rates, 3/4 vs. 2/3, 2/3 vs. 1/2 and 2/3 vs. 1/2, for OFDM/QAM 4-, 16- and 64-QAM cases, respectively. The upper, middle and lower parts of Fig. 2 present results for each of these constellation sizes for the two signaling formats. The SNR difference[1] between coded OFDM/QAM and OFDM/OQAM is larger for larger QAM constellation sizes, i.e. spectral efficiencies, incrementally from 0.8 to 2.25 dBs, while the uncoded BERs are same[2]. The SNR value differences very well correspond to the theoretical ones of Fig. 1 for the 25% CP case, as marked by double arrows and empty squares. Deviations are consistent with the differences in spectral efficiencies as result of the limited set of coding rates used, and the Eb/No difference values from Fig. 2 are indicated by full-line double arrows in Fig. 1. The results shown by dashed double arrows and empty circles are for the case of Turbo code produced by pairing the CSIs 107/8, 116/9, 121/5, & 124/7 of LTE Matlab simulator, [24]. Full squares and full circles are for simulation of the ETSI DVBT standard 330 744, respectively for 25% and 12.5 CP lengths.

III. Spectral occupancy with HPA

The combined spectral and power inefficiency of OFDM/QAM and the related advantage of the OFDM/OQAM format discussed above apply as well to the cases with different number of subchannels used in the two cases. However, when it comes to the impact of non-linear distortions introduced by the high power amplification (HPA), depending on the amplifier type, i.e. its non-linearity model, the advantage of the OFDM/OQAM over OFDM/QAM can be achieved only for smaller number of subchannels in the former.

The OFDM/OQAM advantages for same (relatively large) number of subchannels for the polynomial HPA models have been demonstrated in [12][17].

In the case of solid-state HPA with the output-input signal envelope characteristic given by Rapp's model

$$r_{out} = r_{in} / \left(1 + (r_{in} / V_{sat})^{2p}\right)^{1/2p}, \qquad (5)$$

the power spectral densities of undistorted and distorted (with p=2.5) OFDM/QAM with 52 out of 64 subchannels (including four pilots), and OFDM/OQAM with 7 out of 8 subchannels are shown in Fig. 3. It can be seen that the OFDM/OQAM format has (in relative terms) by 7.7% (7/8 vs. 52/64) better basic spectral utilization than the OFDM/QAM one.

Besides on the number of subchannels, the PAPR of the OFDM/OQAM signal depends also on the length of the referent impulse response, which in this case is four T intervals, produced by the optimization in [18].

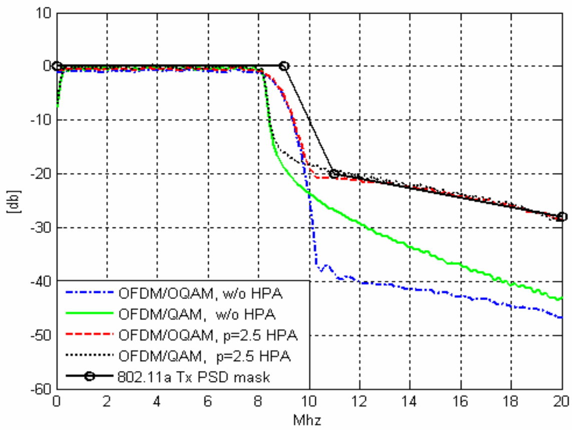

Figure 3 – Comparison of the 802.11a PSD mask fitting.

IV. Discussion of other advantages

Soon after its early inception, the (single-carrier) non-linear decision feed-back (DFE) equalization has demonstrated the ability to implicitly exploit the frequency selectivity within the transmit signal bandwidth caused by multipath propagation, [19]. The OFDM/QAM system only passively counteracts the resulting (subchannel-wise flat) frequency selectivity by using FEC with interleaving (to randomize errors), and the multipath propagation is considered as a nuisance to live with. On the other hand, since the OFDM/OQAM can use relatively wide-band subchannels, the frequency selectivity within the subchannel bandwidth can be taken to an advantage by applying subchannel DFE structure, as shown in [20], and illustrated in Fig. 4.

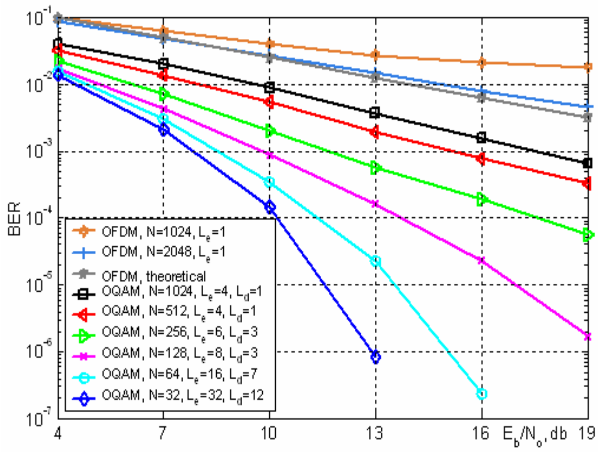

Figure 4 – OFDM/OQAM multipath diversity gains.

These results are produced for the following channel impulse response given by delays/amplitudes (with delay in samples): 0/1, 5/0.75, 10/0.75, 30/0.75, 90/0.5, 120/0.5, 150/0.25, 155/0.25, 160/0.25, 180/1, 240/0.75, 270/0.5, 300/0.5, 305/0.5, 310/0.5, 330/0.25, 390/0.1, and number of subchannels fitting into the available bandwidth is given by N. For wider subchannels (smaller N), larger equalizer span is used to cover the

[1] Same as dB difference in Eb/No for equal spectral efficiencies.

[2] SNR values on the abscissas have been retained also for coded cases, since Eb/No dB differences are essentially same.

correspondingly larger frequency selectivity within the subchannel, with the lengths feed-forward (FFF) and feed-back (FBF) T/2-spaced filters[3] given by values of L_e and L_d. It can be seen that with larger frequency selectivity within the subchannel bandwidth, the BER curves are more and more waterfall-shaped, strongly indicating the presence of SNR gains of diversity type.

Wideband subchannels can be also advantageous for MIMO implementation in the form of a rather traditional multiantenna system, as in [21], where the antenna array spatial resolution features are used.

It has long been known that DFE is quite efficient in suppressing the co-channel cyclostationary interference, [22]. The effectiveness of its application to adjacent channel interference can also be conjectured. With the underlying mechanism of using additional degrees of freedom based on spectral redundancy of interfering and useful signals, the interference suppression is enhanced by increased Nyquist excess bandwidth, that is the roll-off factor. Since even with a moderate number of subchannels roll-off factors of 100% can be used without reduced spectral efficiency, a per-subchannel DFE may eliminate the need for separation of adjacent users altogether in unsynchronized networks applications.

The framework of the successive interference cancellation (SIC) as applied to OFDM/OQAM, [23], and particularly in the turbo-mode iterations with FEC decoding, offers ultimately optimal and effective means to exploit multipath diversity gains, interference suppression, as well as generally colored noise prediction/cancellation without any causality constraints. Preliminary results on prediction and cancellation of ideally estimated noise indicate some 3dB of SNR improvement through its prediction.

V. Conclusions

In this paper we addressed a number of advantageous features of OFDM/OQAM format as compared with the OFDM/QAM, which have not been taken into account in previous comparative evaluations. The accent was on pointing to the OFDM/QAM CP-related SNR degradation exceeding by a few dBs the widely perceived one, and the utilization of relatively small number of subchannels bringing almost ten percents of the increased nominal spectral occupancy in presence of HPA non-linear distortions. The analysis results, as well as the other discussed potentials may provide compelling enough indications of the need to include these aspects in conducting link- and network-level data throughput analyzes, to possibly even more convincingly demonstrate the superiority of the OFDM/OQAM for wireless and CR networks.

[3] Feed-back filter was driven by ideal decisions, including the non-causally produced T/2-spaced quadrature components complementing the data-carrying ones, to enhance diversity effect.

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