Increasing the Performance of OFDM-OQAM Communication Systems through Smart Antennas Processing

Nizar Zorba[1], Stephan Pfletschinger[2], and Faouzi Bader[2]

[1] University of Jordan
EE department
11942 Amman, Jordan
`n.zorba@ju.edu.jo`
[2] Centre Tecnològic de Telecomunicacions de Catalunya
Av. Canal Olímpic S/N
08860-Castelldefels, Barcelona, Spain
{`faouzi.bader,stephan.pfletschinger`}`@cttc.es`

Abstract. A novel filter bank based multicarrier (FBMC) transmission scheme is proposed, where the transmit antennas are employed to substantially reduce the inherent inter-carrier and inter-symbol interference. Since FBMC systems do not apply a guard interval, they can achieve higher spectral efficiencies than OFDM systems, although at the cost of additional inter-symbol interference (ISI). In this paper, we present a method which reduces the number of interference terms by employing a multiantenna precoding scheme based on spatial diversity, and the system can benefit from the multiuser gain, through an opportunistic scheduler at the transmitter side.

Keywords: OFDM, OFDM-OQAM, Multiple Antennas, Filterbank, MIMO.

1 Introduction

Very high communication rates in wireless systems can be achieved by multicarrier techniques, that can be further combined with the Multiple-Input-Multiple-Output (MIMO) technology to provide both efficiency and Quality of Service to the system. The channel in these broadband systems is typically frequency selective and one of the best multicarrier techniques that can be jointly used with MIMO is the Orthogonal Frequency Division Multiplexing (OFDM), that converts the frequency selective channel into a set of parallel frequency-flat channels. Such great characteristic made OFDM to be included in several communication standards as the IEEE 802.11n WLAN standard, while its OFDM Access (OFDMA) version is considered for the IEEE 802.16e WiMAX standard.

However, OFDM has a number of drawbacks that decrease its efficiency. One of these drawbacks is the need of a Cyclic Prefix (CP) to deal with the channel

F. Granelli et al. (Eds.): MOBILIGHT 2009, LNICST 13, pp. 315–324, 2009.

impulse response, which leads to an efficiency decrease of 10% - 20% that represents a huge amount of misuse in the invested resources [1]. It also requires a block processing to maintain orthogonality among all the carriers, which is a serious handicap for scalability, as it is impossible to introduce, in a block of carriers, one or several signals that are not synchronous with the rest of the block. Keeping in mind the heterogeneous nature of modern communications with users running different applications characterized by various rates, initialization times and QoS demands; OFDM can create a problem of synchronization over the system. Clearly, OFDM is already implemented in a lot of communication standards and it is attractive due to its low complexity, and it is now familiar to both the academia and industry; but to further increase the system efficiency, further research is developed in the communications arena to find alternative multicarrier schemes.

One of most promising proposals is the Filter Bank based Multicarrier (FBMC) transmission [2], that shows both enhanced performance and operational flexibility by exploiting the spectral efficiency of filter banks and the independence of the subchannels. While in OFDM, the subcarrier spectra have a strong overlap with adjacent subcarriers, in FBMC the transmission channel is divided into subchannels, providing a control over the allocation process, together with the scalability advantage. FBMC benefits from the OFDM advantages and combines them with the Offset Quadrature Amplitude Modulation (OFDM-OQAM), where no CP is needed, achieving higher spectral efficiency than the classical CP-OFDM as all the system resources are devoted to increase the whole system throughput.

As OFDM-OQAM (i.e. FBMC) does not use the CP, then the main complex task in this technique resides in the combat of the InterSymbol Interference (ISI) and the InterCarrier Interference (ICI), where these tasks are usually performed by the receiver through some complex operations, that have handicapped its implementation. The study of OFDM-OQAM was initially proposed more than 25 years ago [3], and its complexity was the main drawback behind the consideration of FBMC in realistic systems. But current processing capabilities at both the transmitter and the receiver make the objections to the FBMC approach to be unfounded. And recently, an increasing interest in FBMC has again emerged [2][4][5].

With the implementation of MIMO in almost all commercial standards, the system designer has an additional resource that can be employed to cancel the interference terms, and therefore to decrease the complexity related to FBMC schemes. Moreover, the availability of multiple users in the system is beneficial to enable the transmitter to select the user with the best channel conditions at each time, and by this way to increase its sum rate. This scheme is known as the Opportunistic scheduler [6], which has been commercially introduced in the UMTS-HSDPA standard.

Therefore, the objective of this paper is to propose a spatial diversity scheme through MIMO to cancel the ISI and ICI in the system, so that the implementation of the FBMC technique can be possible. In other words, MIMO will be in charge of the required interference mitigation in the system. Besides that, the system multiuser gain [6][7] is employed to increase the rate behaviour. To the best of the authors' knowledge, no such scheme is previously proposed in literature, so that the result of our work will be a communication technique that provides all the advantages of MIMO and FBMC with a complexity that enables for its consideration in practical systems.

2 System Model

We focus on the Downlink channel where V receivers, each one of them equipped with a single receiving antenna, are being served by a transmitter at the Base Station (BS) provided with n_t transmitting antennas. The case of $n_t = 2$ is considered along the paper for easiness in the results presentation and to align with all commercial implementations of the IEEE 802.11 *pre-n* and the proposals for all LTE systems, where its upgrade to any number n_t is straightforward. A wireless multiantenna channel $\mathbf{h}_{[1\times n_t]} = [h_1(t)\ h_2(t)]$ is considered between the transmitter and each one of the users, where a quasi-static block fading model is assumed, which keeps constant through the coherence time, and independently changes between consecutive time intervals with independent and identically distributed (i.i.d.) complex Gaussian entries $\sim \mathcal{CN}(0, 1)$. Let $\mathbf{x}(t) = [x_1(t)\ x_2(t)]^T$ be the $n_t \times 1$ transmitted vector, while denote $r_v(t)$ as the received signal at the v^{th} receiver as

$$r_v(t) = \mathbf{h}_v(t)\mathbf{x}(t) + z_v(t) = h_{1(v)}(t)x_1(t) + h_{2(v)}(t)x_2(t) + z_v(t) \qquad (1)$$

where $z_v(t)$ is an additive Gaussian complex noise component with zero mean and a variance of σ^2. The transmitted signal $\mathbf{x}(t)$ is a coded version of the i.i.d. data symbols $s_i(t)$ with $E\{|s_i|^2\} = 1$. For ease of notation, both the user and time indexes are dropped whenever possible.

3 Opportunistic Transmission

One of the main transmission techniques in multiuser scenarios is the opportunistic technique [6][7], where during the acquisition step, a known training sequence is transmitted for all the users in the system, and each one of the users calculates the received SNR, and feeds it back to the BS. The BS scheduler chooses the user with the largest SNR value for transmission to benefit from its current channel situation, and therefore improving the global system performance. This opportunistic strategy is proved to be optimal [6][7] as it obtains the maximum rate point.

4 OFDM-OQAM

In conventional OFDM systems each carrier from a total of M carriers is modulated using QAM, where a rectangular window is employed to shape each QAM

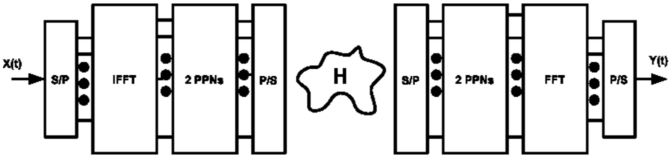

Fig. 1. System model for FBMC

symbol. To avoid ISI in the system a CP is used, so that thanks to the CP, no complex channel equalizers are needed at the receiver side, thus decreasing the system complexity, but at expenses of a lower system efficiency due to the 10% - 20% of resources that are employed for CP.

OFDM-OQAM is an alternative modulation that introduces an efficient pulse shaping in its modulation scheme through the use of accurately non-rectangular pulse shaping and thus, it generates less out-of-band radiation and provides better frequency localization. Therefore it can be employed without the need of a CP, so that it overcomes the loss of resources of conventional OFDM. But to employ non-rectangular pulse shaping, the OQAM is needed, where this modulation introduces through each of the carriers, a time offset between the real part and the imaginary part of the sent symbols. Removing the CP increases the system performance, but it requires for an alternative processing to remove ISI, which together with the accurate pulse shaping requirement, drives some complexity in the system that has been considered excessive for its implementation.

But thanks to current receivers processing capabilities, the complexity increase is affordable, so that along the complexity-performance tradeoff, the optimization goes to the performance side, which motivates the recent large interest in FBMC systems in realistic systems [2][4]. Remember that such employment of OFDM-OQAM also enables the system administrator to benefit from other advantages, mainly in terms of scalability and synchronization.

Fig. 1 shows a schematic of the FBMC system where two PolyPhase Networks (PPN), with a total of $N = 2 \times M$ subchannels, are included in the processing at both the transmitter and the receiver. The PPN is composed of a set of filters that are obtained by shifting the response of a low pass filter on the frequency axis; where the low pass filter is named the Prototype Filter in the research community [5][8]. As previously commented, the OQAM accomplishes a signal

Table 1. Example of OQAM symbols mapping to the PPNs

subchannel\time	t	t+1	t+2	...
SubChn.1 (PPN_1)	Re. part	Img. part	Re. part	...
SubChn.2 (PPN_2)	Img. part	Re. part	Img. part	...
SubChn.3 (PPN_1)	Re. part	Img. part	Re. part	...
...	...	...	...	...

separation between the real and the imaginary parts of the signal and performs an offset on them, so that 2 PPNs are employed in the transmission process, one for transmitting the real part of the symbol and the other one for the imaginary part, and performing a continuous switch between their roles, thus making the transmitted data along the PPNs to be as shown in Table 1. A main characteristic of OFDM-OQAM is that the data are transmitted as real numbers at twice the conventional Nyquist rate associated with the prototype filter. Therefore, the number of PPN subchannels (i.e branches) are twice that of OFDM carriers to separately account for both the real and imaginary parts of the symbol. The output of each two adjacent subchannels (over one time instant) are added and transmitted over a single OFDM carrier.

However, large values of ICI and ISI are generated in the system, and some processing at the transmitter and/or the receiver side must be accomplished to mitigate them. In addition, two neighbouring subchannels overlap, in order to fully exploit the available frequency spectrum. The consequence is an interference pattern between the subchannels as follows

Table 2. Example of an OFDM-OQAM interference pattern

	t-1	t	t+1
SubChn.1	Interference	Interference	Interference
SubChn.2	Interference	Desired signal	Interference
SubChn.3	Interference	Interference	Interference

As just commented, in the current State of the Art related to OFDM-OQAM (only with a single antenna), a symbol s is decomposed into its real part $d_1 = Re\{s\}$ and imaginary part $d_2 = Im\{s\}$, so that two adjacent subchannels are employed for its transmission in the same time instant, as follows:

Table 3. OFDM-OQAM setup in a single antenna scenario

	subchannel 1	subchannel 2
$antenna_1$	d_1 on PPN_1	d_2 on PPN_2

In the following time instant the order is reversed, so that the real part of the next symbol is transmitted in subchannel 2 and its imaginary part in the subchannel 1, to comply with the Offset philosophy.

To the best of the authors' knowledge, such interference mitigation is only proposed through some processing over different time samples [2], which beyond the introduced time delay, it does not show attractive results. In [2], an initial study of two transmitting antennas is performed, but the final result is still time dependant. In the current paper, we will propose some spatial interference mitigation that is jointly performed with a selection of the most appropriate user through the Opportunistic scheduler, as now shown in the next section.

5 Spatial Diversity in OFDM-OQAM

One of the drawbacks for the consideration of OFDM-OQAM in current commercial systems is the generated interference in the system due to the non-employment of the CP. On the other hand, the MIMO technology is already available in almost all OFDM-based wireless standards (e.g. IEEE 802.11n and IEEE 802.16e). Joining the two factors, notice that MIMO can be employed to carry out some interference mitigation in the system, which has its challenges when applied to the OFDM-OQAM interference pattern in Table 2, but such interference mitigation stands as one of the main milestones to make the OFDM-OQAM to be attractive, and to reduce its complexity as it avoids extra interference cancellation mechanisms at the receiver side, that use to be very complex.

Thanks to the consideration of MIMO, two simultaneous symbols can travel in the channel at the same time and through the same subchannel, so that a possible setup for the OFDM-OQAM transmission over the subchannels and on a single time instant is shown in Table 4, where the PPN order is switched over the two antennas.

Table 4. OFDM-OQAM setup in a two antennas scenario

	subchannel 1	subchannel 2
$antenna_1$	d_1 on PPN_1	d_2 on PPN_2
$antenna_2$	d_1 on PPN_2	d_2 on PPN_1

The two antennas are employed to provide the system with a Space Time scheme to enable interference mitigation at the receiver side through some signal processing. It is worth noting that with this approach, the second antenna is employed to transmit the same information as in the first antenna, implementing the same principle as the very well-known Alamouti scheme [9], but with some modification to enable its application to the OFDM-OQAM technology with all the challenges behind its consideration, mainly the large amount of generated interference in OFDM-OQAM.

Considering this setup, the received signal r_1 in the first subchannel states as

$$r_1 = (d_1 + jf_1)h_1 + (d_1 + jf_1)h_2 + z_1 \tag{2}$$

where z_1 is the noise term received in the subchannel 1, and f_1 accounts for all the interference components [8] that arise from the filterbank usage at the first subchannel, where as shown in Table 2 this interference comes from the two adjacent subchannels and time instants. On the other hand, the received signal in the second subchannel is as

$$r_2 = (jd_2 + f_2)h_1 + (jd_2 + f_2)h_2 + z_2 \tag{3}$$

with f_2 as the interference terms in the second subchannel.

The reader can wonder that if h_1 and h_2 are equal in magnitude and opposed in phase, then no signal will reach the receiver, but this is a hypothetical case with negligible probability. Even that, this case fails in the system outage consideration, exactly as the Alamouti scheme does [9].

5.1 Receiver Processing

The receiver now has two different arriving signals r_1 and r_2, one on each subchannel. Notice that two antennas operating on two subchannels (i.e. one single OFDM carrier) and on one time instant are employed to transmit a whole symbol (i.e. both its real and imaginary parts), then a full diversity rate [9] is obtained. The antennas are efficiently employed in the system with their diversity gain to help mitigating the generated OFDM-OQAM interference, thus decreasing the OFDM-OQAM complexity.

At the receiver side, some processing can be accomplished to obtain the following expression from r_1, as follows

$$y_1 = Re\{h_1^* r_1 + h_2 r_1^*\} = \left(|h_1|^2 + 2Re(h_1^* h_2) + |h_2|^2 \right) d_1 + Re(h_1^* z_1) + Re(h_2 z_1^*) \quad (4)$$

where we can see that all the interference terms f_1 are removed thanks to the receiver processing. This is actually a great step for OFDM-OQAM as 8 interfering terms have disappeared. The price for that is some dependence on the channel phase due to the $2Re(h_1^* h_2)$ term, that can show positive and negative values depending on the instantaneous channel conditions of both h_1 and h_2. Notice that the information in d_1 is received with a great spatial antenna gain as it benefits from both h_1 and h_2. Moreover, the data component d_1 is received without any other data components, so that with the simple Matched Filter (MF) receiver, the data can be efficiently extracted. Obviously, this single equation is enough for the detection of d_1 but we still need another one for d_2. Remind that d_1 and d_2 are the real and imaginary parts of the same symbol, so that the symbol is correctly received only if its both parts are properly detected.

Thus we need for an additional equation for d_2, and applying a different processing for subchannel 2 at the receiver side, we get the following expression

$$y_2 = Im\{h_1^* r_2 + h_2^* r_2\} = \left(|h_1|^2 + 2Re(h_1^* h_2) + |h_2|^2 \right) d_2 + Im(h_1^* z_2) + Im(h_2^* z_2) \quad (5)$$

where we also notice that there is not any interference term in the equation.

From the previous two equations, the detection of d_1 and d_2 seems to be solved as no more OFDM/OQAM interfering terms are shown in the equations. The problem that remains to be solved is the channel phase effect due to the $Re(h_1^* h_2)$ term. Notice that the channel phase effect can be positive or negative, where the receiver is interested in a positive value for the channels phase effect, so that the decoding process is improved.

To increase the performance of any wireless communication system, the Multiuser gain has to be taken into consideration [6], so that the system administrator can benefit from the channel conditions of the available users in the system to select the user with the best channel conditions. As OFDM/OQAM is targeted to high data rate systems, then it seems straightforward to tackle the opportunistic scheduling in its operation. This objective can be accomplished if we define the user with the best channel conditions as the one who shows a positive and high value for the $Re(h_1^* h_2)$ term, so that its selection enables the following condition

$$\left(|h_1|^2 + 2Re(h_1^* h_2) + |h_2|^2\right) > \left(|h_1|^2 + |h_2|^2\right) \tag{6}$$

to guarantee that the phase channel effect is always beneficial to the system performance. Therefore, the opportunistic scheduling is looking for scheduling the user showing

$$\max_{v=1:V} \left(|h_{1(v)}|^2 + 2Re(h_{1(v)}^* h_{2(v)}) + |h_{2(v)}|^2\right) \tag{7}$$

which is later shown to offer higher multiuser gain than the standard Alamouti scheme. The latter can be also operated with an opportunistic scheduler, where the selected user will be the one showing

$$\max_{v=1:V} \left(|h_{1(v)}|^2 + |h_{2(v)}|^2\right) \tag{8}$$

where the Alamouti scheme is shown [10] to highly benefit from the multiuser gain.

6 Simulations

The performance of the studied scheme is presented by Monte Carlo simulations, where the objective is to see the sum rate behaviour of the proposed scheme. We

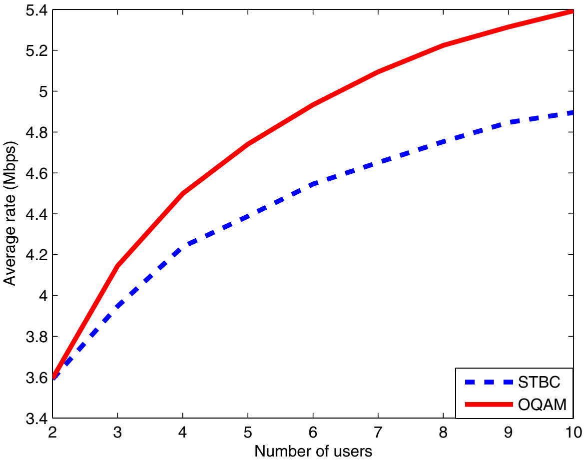

Fig. 2. Rate performance of Classical OFDM and OFDM-OQAM, both operated in the spatial diversity philosophy

consider a wireless scenario with $n_t = 2$ transmitting antennas, and a variable number of users each one equipped with a single-antenna. The transmitter runs a spatial diversity scheme over OFDM-OQAM, where a total transmitted power $P_t = 1$ is assumed with noise power $\sigma^2 = 1$. A total system bandwidth of $20MHz$ is considered in this scenario.

In Fig. 2, a scenario with a variable number of users is simulated, where the BS carries out the scheduling of the user with the best channel conditions following the selection algorithms in section 5.1. The comparison between the classical Alamouti scheme and our proposed multiuser OFDM/OQAM shows the better performance of or proposal, showing a higher benefit from the multiuser system capabilities. Remind that the OFDM-OQAM system operates without CP, then an additional 10%-20% gain is presented in the system and it is not included in the plots. Obviously, this gain comes at expenses of a higher complexity for the OFDM-OQAM strategy through its prototype filtering, but as we already commented along this paper, this complexity increase is more than affordable in current communication systems.

7 Conclusions

The paper proposed a spatial diversity scheme over OFDM-OQAM, where the generated interference is cancelled through some processing mainly at the receiver side of the communication process. The transmitter accomplishes a user scheduling to select the user with the best channel conditions to increase the systems performance. To the authors' knowledge, no previous proposals have been presented in the literature to deal with such scenario setup.

The obtained results show that OFDM-OQAM stands as a potential alternative to the classical OFDM, as its presents better rate behaviour thanks to the opportunistic scheduler to select the user with good phase component at each instant. Moreover, the proposed scheme does not employ the CP, which is a further increase in the system efficiency. Its advantages in terms of scalability and synchronization can be also attractive for the system. Therefore, OFDM-OQAM can be employed in certain scenario upon the requirements and restrictions for the system designer.

Acknowledgement

This work was partially supported by the European ICT-2008-211887 project PHYDYAS.

References

1. 802.16e-2005 IEEE Standard for Local and Metropolitan Area Networks Part 16, 3GPP (2006)
2. Bellanger, M.: Transmit Diversity in Multicarrier Transmission using OQAM Modulation. In: IEEE-ISWPC, Santorini (May 2008)

3. Hirosaki, B.: A Maximum Likelihood Receiver for an Orthogonally Multiplexed QAM System. In: IEEE-JSAC, September 1984, vol. (5) (1984)
4. ElTabach, M., Javaudin, J.P., Helard, M.: Spatial Data Multiplexing Over OFDM/OQAM Modulations. In: IEEE-ICC, Glasgow (June 2007)
5. Fusco, T., Tanda, M.: Blind Frequency-Offset Estimation for OFDM/OQAM Systems. IEEE Trans. on Signal Processing 55(5) (May 2007)
6. Viswanath, P., Tse, D.N., Laroia, R.: Opportunistic beamforming using dumb antennas. IEEE Trans. Inform. Theory 48, 1277–1294 (2002)
7. Knopp, R., Humblet, P.: Information capacity and power control in single-cell multiuser communications. In: IEEE-ICC, Seattle, USA (1995)
8. Bellanger, M.: Specification and Design of a Prototype Filter for Filter Bank Based Multicarrier Transmission. In: IEEE-ICASSP, Salt Lake City (May 2001)
9. Alamouti, S.: A Simple Transmit Diversity Technique for Wireless Communications. IEEE JSAC 16(8) (October 1998)
10. Akhtar, J., Gesbert, D.: Extending Orthogonal Block Codes With Partial Feedback. IEEE Transactions on Wireless Communications (November 2004)