THE POTENTIAL OF OQAM FOR MULTICARRIER RADIOCOMMUNICATIONS

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ABSTRACT

In future wireless and cellular communication networks, flexibility of operation will be a crucial requirement. A single system should be capable of providing high speed access to a few users and low speed robust access to many users, in both downlink and uplink. Multicarrier techniques based on filter banks have the potential to meet such a requirement, due to their sub-channel separation property. High speed is obtained if different data streams are fed to different sub-channels and robustness is achieved if a single data stream is fed to several sub-channels.
It is shown that an OQAM system, based on filter banks, can be designed to have no interference between sub-channels for spread spectrum with a single user, noticeable interference with only a few codes for multiuser downlink and it can have few interference with most of the code combinations in the uplink, provided a coarse time alignment of the scattered users is carried out .

I- INTRODUCTION

In wireless networks, two kinds of multicarrier modulations are employed, namely multi-user spread spectrum and OFDM (Orthogonal Frequency Division Multiplexing). Spread spectrum is known for its flexibility and robustness, while OFDM provides high efficiency. The third generation of mobile cellular radio systems, UMTS, is based on spread spectrum and code division multiple access (CDMA), but an OFDM option is retained for high speed downlink packet access (HSDPA) [1].
The OQAM (Orthogonal Quadrature Amplitude Modulation) technique divides the total transmission bandwidth into a large number of sub-bands, just like OFDM. However, it uses a uniform filter bank instead of only a DFT (Discrete Fourier Transform) to perform the separation of the subchannels, which has two major benefits. First, the guard time between consecutive symbols is not needed, which increases the efficiency and, second, the system is more robust to channel distortion and narrow-band jammers, since the sub-channel separation is enhanced. An OQAM option is also included in the UMTS standard for HSDPA [2].
The OFDM approach is used for frequency spreading in the so-called multicarrier (MC)-CDMA scheme. The OQAM technique as well can be employed for the two kinds of multicarrier transmission. It performs frequency spreading if the same data stream is carried by several sub-channels and it performs frequency division multiplexing if each sub-channel carries a different data stream. The objective of the present paper is to explore the spread spectrum operation and analyse the impact of the specificities of the OQAM technique in that context.

II- OQAM SPREAD SPECTRUM TRANSMISSION

The principle of OQAM transmission using the spread spectrum method is shown in figure 1, for a single user.

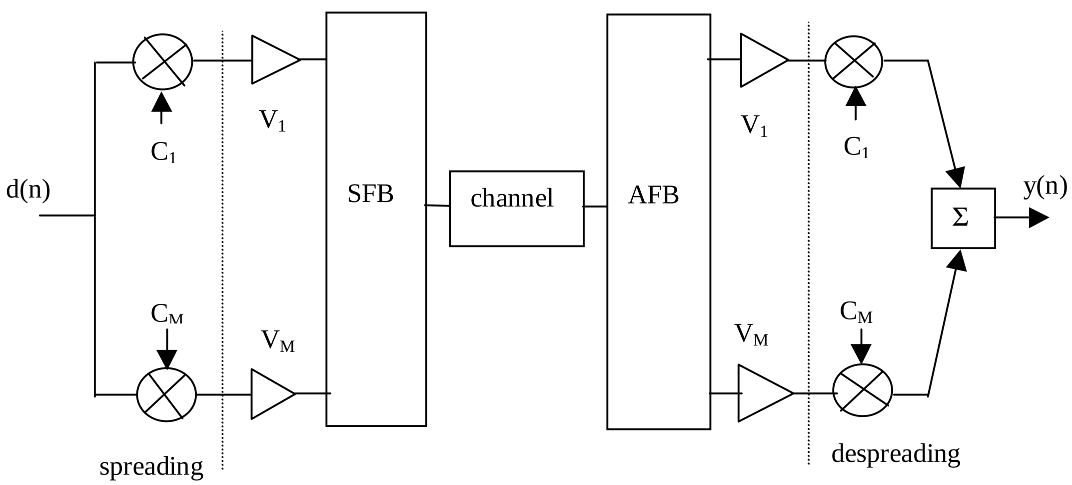

Fig.1. Principle of filter bank based spread spectrum

In the transmitter, the input data symbols *d(n)* are multiplied by the M elements C_m $(1 \le m \le M)$ of the spreading code and fed to M inputs of a synthesis filter bank (SFB), after an input conversion stage, consisting of a multiplication by the elements v_m of a complex vector. In the receiver, the corresponding M outputs of the associated analysis filter bank (AFB) are multiplied by the same elements v_m and C_m and accumulated to produce a sequence *y(n),* which, after detection gives the received data $\hat{d}(n-K)$, with *K* the total delay of the system. The output sequence is expressed in terms of the amplitude A_m and phase φ_m of the sub-channels by

$$y(n) = \frac{1}{M}\sum_{m=1}^{M} A_m\, e^{j\varphi_m}\, d(n-K) + b(n) \qquad (1)$$

where b(n) is the noise component.
At this stage, the importance of the sub-channel phase components is worth emphasizing. For example, if the transmission channel is a pure delay τ , expression (1) becomes

$$y(n) = \frac{1}{M}\sum_{m=m_0}^{m_0+M-1} e^{-j\frac{2\pi}{2N}m\tau} = \frac{1}{M} e^{-j\frac{2\pi}{2N}m_0\tau}\, \frac{1-e^{-j\frac{2\pi}{2N}M\tau}}{1-e^{-j\frac{2\pi}{2N}\tau}} \qquad (2)$$

where N is the number of filters in the SFB and AFB filter banks (N>M) and m_0 is the index of the first sub-band used. Clearly, the phases of the subchannels have a critical impact on the summation. In particular, if $\tau = 2N/M$ in (2), then, y(n) = 0 and there is no transmission. In fact, in the block diagram of figure 1, sub-channel equalizers are introduced in each branch, before global summation, to compensate for the amplitude and phase distortions .
The AFB and SFB filter banks have a number of inputs and outputs, N, that is greater than the size of the code M. They are both generated through uniform frequency shifts of a single prototype filter H(Z), that must satisfy the classical Nyquist criterion, to prevent intersymbol interference in the transmission. A number of approaches have been proposed to design the prototype filter and calculate its coefficients, like the window method [3] and the frequency sampling metod [4].
A specificity of OQAM is that the data are transmitted as real numbers at twice the conventionnal Nyquist rate associated with the prototype filter. In addition, two neighbouring sub-channels overlap, in order to fully exploit the available frequency spectrum. The consequence is an interference pattern between the sub-channels, a simplified version of which is given in table 1, for a typical prototype filter.

		Time		
		n-1	n	n+1
	m-1	- 0.25 j	0.32	0.25 j
Sub-channels	m	0.50	1.00	0.50
	m+1	0.25 j	0.32	-0.25 j

Table 1. Interference pattern of OQAM for real input and odd sub-channel index
(For even index change signs in left and right columns. For imaginary input multiply by –j)

In order to escape intersymbol interference in such conditions, the real input data are applied alternatively to the real and imaginary sub-channel inputs and in opposite manner for two successive sub-channels. Actually, as is shown below, it is advantageous to define the operation as follows

$$v_m = e^{j(m-1)\pi/2} \quad ; \text{ even time index} \qquad (3)$$

$$v_m = e^{j(m-2)\pi/2} \quad ; \text{ odd time index}$$

As concerns the prototype filter, its effect is that a given sub-channel overlaps in the frequency domain with its neighbours only and the separation with the other sub-channels can be considered as nearly perfect. Therefore, the orthogonality constraint is limited to neighbouring sub-channels and no guard time is needed to cope with the transmission channel impulse response, as in OFDM systems. It is sufficient to introduce subchannel equalizers at the output of the AFB [5]. As a consequence, the scheme is known for its efficiency and robustness.
Concerning the sub-channel interference resulting from the pattern of table 1, due to the input conversion of the data and the alternative application to real and imaginary inputs, it occurs in quadrature with the useful signal in

the receiver and, therefore, it does not impact the data recovering process. However, in the spread spectrum case and with the particular selection of the input conversion factors (3), it can be cancelled altogether.
To show this effect, let us consider the case when the first of the M input signals is applied to sub-channel 2 ($m_0 = 1$) of the SFB and let us denote by $y_{m,5}$ the interference signal at the output of the AFB at time n = 5.
According to the interference pattern of table 1, we get

$$y_{2,5}=[0.25\, j\, C_1 - 0.50\, j\, C_2 + 0.25\, j\, C_3]d(4) + [0.32\, j\, C_1 - 0.32\, j\, C_3]d(5)+[-0.25\, j\, C_1 - 0.50\, j\, C_2 - 0.25\, j\, C_3]d(6) \quad (4)$$

$$y_{3,5}=[-0.25\, C_2 + 0.50\, C_3 - 0.25\, C_4]d(4) + [0.32\, C_2 - 0.32\, C_4]\, d(5) + [0.25\, C_2 + 0.50\, C_3 + 0.25\, C_4]\, d(6) \quad (5)$$

In the receiver, the following summation is carried out, which yields, after simplification

$$y_{2,5}\, C_2 + y_{3,5}\, j\, C_3 = [0.25\, j\, C_1 C_2 - 0.25\, j\, C_3 C_4]d(4) + [0.32\, j\, C_1 C_2 - 0.25\, j\, C_3 C_4]d(5) + [-0.25\, j\, C_1 C_2 + 0.25\, j\, C_3 C_4]\, d(6) \quad (6)$$

The product $C_2 C_3$ has disappeared from this partial sum and, in the complete sum, with the M sub-bands, only the border terms may subsist.
Interference cancellation is important because it implies that the received signal is purely real, in the absence of channel distortion and assuming perfect synchronization. Therefore, the imaginary part of the received signal can be exploited in an adaptive procedure to achieve equalization and synchronization blindly, i.e. without a reference sequence or the help of a pilot sub-channel.
As an illustration, a bank of N = 64 filters is considered and M = 32 sub-channels are used. With $m_0 = 1$, the center frequencies are : [1/128, ..., 32/128]. With an ideal channel and perfect synchronization, 32 real signals are summed in the receiver and the maximum value of the imaginary component for a sequence of 100 data is found to be $y_{i,max} = 7.9\ 10^{-5}$. With respect to the channel noise, the spreading gain is G = M = 32.

III- MULTIUSER TRANSMISSION

In a CDMA cellular system, users share the same transmission channel and they are identified by their individual codes. For optimal operation, the codes have to be orthogonal. A classical family of orthogonal codes is the Hadamard set which is generated recursively by the following matrix operation

$$H_N = H_{N/2} \otimes H_2 \qquad ; \qquad H_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \qquad (7)$$

where $\otimes$ is the Kronecker product of matrices.
In wireless systems, there are two different situations concerning multiuser transmission, namely downlink and uplink. In the downlink case, the signal issued from the base station towards scattered users contains the encoded data of all the users and they are synchronous. A particular user has to extract its data from the global signal and the orthogonality of the codes ensures the absence of interference. Once equalization and synchronization are achieved, the signal of interest is real and the interference is concentrated in the imaginary part of the received signal. Again, it is important, for blind channel equalization and synchronization purposes, to cancel that interference.
In fact, the cancellation procedure shown for the single user case does not strictly apply to the multiuser case, because the codes in the transmitter and receiver are different. For example, if two codes C and C' do not match, the summation (6) is : $y_{2,5}\, C_2' + y_{3,5}\, j\, C_3'$ and the cancellation process described in the previous section occurs only if $C_2' C_3 = C_2\, C_3'$.
A systematic search has been carried out for the Hadamard code of length M = 32 and it has been found that interference cancellation occurs entirely or partly for most of the pairs of codes. For example, considering code number 7 (index of the row of the Hadamard matrix), cancellation is nearly perfect for the following code numbers : 1, 4, 6, 10, 11, 13, 16, 18, 19, 21, 24, 25, 28, 30, 31. An interference grid is given in Table 2. The power P_y of the imaginary component has been calculated and two categories are distinguished corresponding to those code pairs for which $P_y > 0.1$ and $0.1 > P_y > 0.01$ respectively .

Spreading code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Despreading code with $P_y > 0.1$	2	1	4	3	6	5	8	7	10	9	12	11	14	13	16	15	18	17	20	19	22	21	24	23	26	25	28	27	30	29	32	31
					7	8	5	6													23			22					31		29	
Despreading code with $P_y > 0.01$									11	12	9	10	9	10	10	9						24	21		27	28	25	26	25	26	26	25
									13	14	14	13	12	11	11	12									29	30	30	29	28	27	27	28
									16	15	15	16	15	16	13	14									32	31	31	32		32		30

Table 2. Interference grid between sub-channel pairs

When allocating the codes to the users, some rules can be applied in order to have no interference or a limited amount of interference in the imaginary part of the signal coming out of the receiver. Then, this imaginary part can be used for adaptive blind sub-channel equalization and synchronization.

In downlink transmission, the signal that reaches a user comes from the base station through a specific radio transmission channel and all the codes follow the same path and are synchronized with the code of the user of interest. Then, equalization of that channel produces interference cancellation in the real part of the received signal and also in the imaginary part, if the codes are properly selected. The context of uplink transmission is more challenging, because signals from scattered users reach the base station through different radio channels and, if no specific individual timing operation is carried out, they are not aligned in time and interference occurs. The channel can be equalized for each user and the other users produce interference signals whose levels depend on the magnitudes and generally increase with the delays. An illustration of the dependence on the delays is given if code number 20 is used for spreading and code 17 is used for despreading and the channel is a pure delay, varying from 0 to 29 sampling periods. It can be observed that, for the particular code pair, the variance of the interference signal is smaller than 0.01, as long as the delay is smaller than 21 sampling periods. Similar behaviour is observed for a number of other code pairs. If this set of codes is allocated to the users in the uplink transmission, a coarse time alignment is sufficient for the individual users and blind channel equalization and synchronization can be envisaged separately for each user at the base station.
Another important impact is the power control requirement. In multi-user spread spectrum systems, uplink transmission requires that the powers radiated by the mobile terminals be adjusted, so that the signals received at the base station have nearly the same power and the separation by the codes is properly obtained. With the filter bank based OQAM approach, since the interference levels are small for small delays, significant power deviations can be tolerated, which increases the radius of the radio cell and the reach of the system.

IV- CONCLUSION

The main results of the analysis presented above can be summarized as follows :

1) the OQAM technique can be used for spread spectrum, while keeping the advantages of the filter bank approach for multicarrier transmission, namely robustness and efficiency, since no guard time is needed .
2) in the downlink case of the cellular multiuser communication, the codes can be allocated to users in such a way that blind equalization should be possible for each mobile user. If confirmed, this is a crucial simplification for the mobile receiver and it further increases the system efficiency, since no pilot symbols or extra subchannel pilot signals might be needed.
3) in the uplink case, only a coarse initial timing alignment should be required for each user entering the system. Then, blind channel equalization could be employed in the base station receiving process, for each user, to recover the data. Again, a significant increase in efficiency can be potentially achieved, due to the absence of pilot symbols during payload transmission. For mobile users, it is sufficient to check the time alignment at regular time intervals.

Flexibility of operation is a crucial requirement and it is worth emphasizing in that respect that, in both downlink and uplink transmission, a combination of techniques is possible : spread spectrum for some groups of subchannels and users, and frequency division multiplexing (FDM) for high bit rate transmission to one or a few users. The corresponding frequency bands have to be separated by the width of only one sub-channel.
Clearly, the filter bank based OQAM technique combines efficiency, robustness and flexibility and it has a great potential for making a better use of the spectrum in wireless communications.

References

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