High spectral resolution for future broadband wireless systems

Maurice Bellanger

CNAM, 292 rue Saint-Martin 75141 Paris cedex 03 France (bellang@cnam.fr)

Abstract

New concepts in wireless communications, particularly cognitive radio, require high resolution spectrum analysis. Additional requirements for future broadband systems are high data rates in large transmission bandwidths and flexible spectrum allocation. It is shown that a multicarrier modulation technique based on filter banks has the potential to meet all these requirements, contrary to the existing OFDM schemes. A key element in the approach is the protype filter and a simple and efficient design is presented. Applications in wireless networks are briefly described, emphasizing the impact of the user spectrum separation provided by the filter bank. The mixing of multicarrier and single carrier modulations, which can be easily implemented, should be an important parameter for the optimization of future wireless and mobile networks.

1. Introduction

Multicarrier techniques are introduced in existing or planned wireless broadband systems to increase the spectral efficiency and provide flexibility in network operation. The most popular implementation is called OFDM (Orthogonal Frequency Division Multiplexing) and it is based on the FFT (Fast Fourier Transform), which is the basic tool for spectrum analysis. However, except for some particular cases, the FFT exhibits poor spectral resolution and, in order to achieve high resolution, it has to be completed by some additional processing. In fact, the FFT is efficient in terms of spectrum resolution only if strict constraints are imposed on the source signals which have to be separated. They must be synchronous and their frequency must be an integer multiple of a fixed frequency interval, which, in multicarrier communication, is the sub-carrier spacing.

The constraints imposed by OFDM schemes are easily met in some situations, for example in the downlink of a mobile system, but not in some other situations, such as the uplink. Moreover, new promising concepts for future systems, such as cognitive radio, will require high resolution spectrum sensing and modulation. The leakage effect of the FFT is a severe drawback in that context [1]. Therefore, for future wireless systems, high spectral resolution is needed and the objective of this paper is to discuss a scheme based on filter banks to that purpose. The rest of the paper is organized as follows. In the next section, some relevant spectral aspects of wireless multicarrier systems are reviewed. In section 3, a prototype filter suitable for filter bank-based multicarrier transmission is presented and its performance is discussed. Section 4 is devoted to applications in various situations of future networks and, to conclude, a list of items for future work is given.

2. Some spectral aspects of multicarrier wireless systems

In existing wireless networks, connections are established between a base station (BS) and user stations, or mobile stations (MS), and the network is fully controlled by the base station. From a spectrum analysis perspective, assuming multicarrier modulation, two different situations have to be distinguished, namely downlink from BS to MS and uplink from MS to BS. In downlink, the spectrum analysis operation is performed at the user end. Since the BS has full control, the signals of the different users can be synchronized and every user performs a synchronous spectrum analysis to identify the transmission channel and extract its own data. The magnitude of the received signal depends on the distance between BS and MS. If the BS has some information about this distance, it can adjust the radiated power in favor of those mobiles which are far from itself. In that context, multicarrier techniques offer optimality and flexibility, since different numbers of sub-bands can be allocated to different users and dynamically adjusted to meet their instantaneous needs. An illustration with three users and different numbers of sub-bands and different powers is shown in Fig.1. However, the multicarrier approach can result in the summation of a large number of independent signals, which leads to a nearly Gaussian distribution of amplitudes and a significant peak factor, typically of the order of 15 dB. At the base station, power is available and the potentially large peak-to-average power ratio (PAPR) can be accomodated.

In the uplink, the situation is different because the users connect to the base station independently. However, synchronism can be maintained at BS if all the MS are synchronized, which requires ranging and time alignment. Adequate protocols have to be employed in the initialization phase and tracking must be implemented during transmission if mobility is assumed. At MS, the multicarrier PAPR is an issue and it is particularly crucial for the users which are far from the BS and have a limited power available. Moreover, the necessary back-off of the transmitter amplifier reduces the reach of the system. A single carrier and low PAPR modulation is desirable for these users. In the future, other modes of operation than BS-MS will be implemented, such as mobile-to-mobile connection. In that context also, single carrier low PAPR modulation is desirable for long distances.

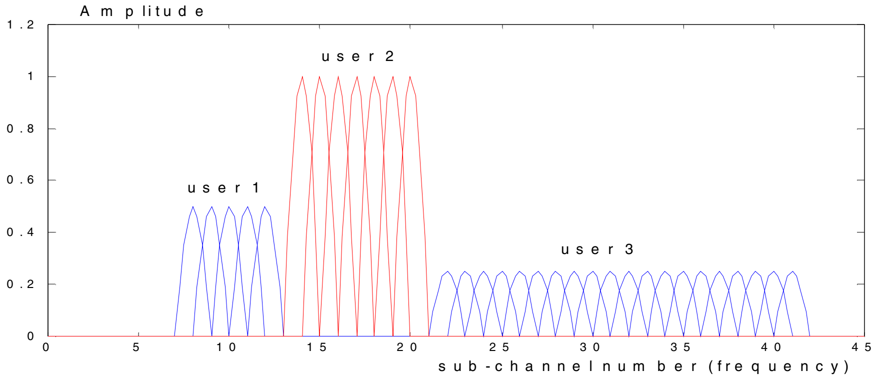

Fig.1. Flexible multi-user multicarrier transmission

Future cognitive radio systems will implement and exploit real time spectrum sensing. In the spectrum sensing context, the analysis is asynchronous because there is no coordination among the sources which produce the received signal. The main parameters are the frequency resolution, the spectral dynamic range (SDR) of the signals to be identified and the accuracy of the noise floor estimations. The frequency resolution is determined by the size of the smallest spectral hole which has to be detected. Then, since this bandwidth is to be used for data transmission, the frequency granularity of the transmission system must be considered. In multicarrier modulation, the smallest bandwidth is the sub-channel spacing. Therefore, spectrum sensing and multicarrier modulation have the same resolution. In such conditions, it is natural to use the same device to perform the two functions. As for the spectral dynamic range, it is a crucial parameter for the usefulness of the cognitive radio concept. If secondary (i.e., unlicensed) users are introduced among primary (i.e., licensed) users, it is necessary to take into account the dynamic range of the primary system itself and maintain a high differential power. To give figures, the system should be able to differentiate signals with a power difference of 50 dB or greater [1]. Next, in an unused frequency band, the estimated noise floor determines the number of bits of the transmitted symbols. It is the sum of two contributions, the thermal noise and the interference from the active neighbouring bands. The thermal noise cannot be controlled but the measured interference level is determined by the rejection performance of the spectrum analyzer. Rejection figures far beyond the 50 dB mentioned above are necessary, if high throughput communication is contemplated..

3. A prototype filter for filter-bank-based multicarrier transmission

The leakage effect of the FFT is illustrated in Fig.2, which shows the frequency response of a sub-channel in an OFDM system. Large sidelobes are present and it is obvious that the requirements of the previous section in terms of spectrum dynamic range and interference rejection cannot be satisfied. In contrast, if a filter bank is used instead of the FFT, the sidelobes are severely attenuated and they are invisible in the figure.

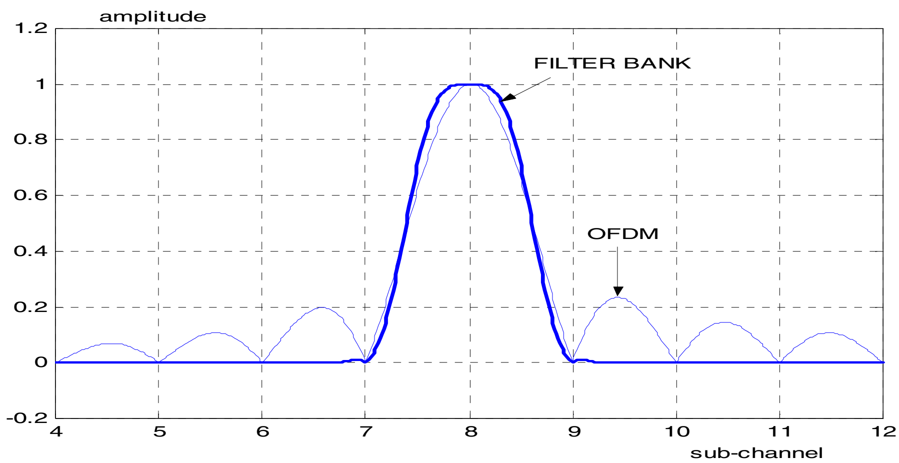

Fig.2. Frequency responses of FFT and filter bank

Filter banks have been known for decades and they are efficiently realized by cascading an FFT and a set of digital filters called a polyphase network (PPN), the PPN being the additional processing that brings high resolution [2]. Application to multicarrier communication has been suggested a number of times in the recent past, as an alternative to OFDM systems [3,4]. However, it is with the new concepts, particularly flexible spectrum allocation and cognitive radio, that they can be fully exploited and show critical benefits.
From a spectrum analysis perspective, the most important item in the filter bank design is the determination of the prototype filter, which controls the frequency responses of the individual sub-channels. In fact, it turns out that a classical design technique, called frequency sampling, yields a good fit to the desired performance [5]. For example, if the number of sub-bands is N=128, if the filter length is L=1024, the ratio L/N=8 leads to the determination of three constants

$$H_1 = 0.971960 \; ; \; H_2 = \sqrt{2}/2 \; ; \; H_3 = \sqrt{1 - H_1^2} = 0.235147 \qquad (1)$$

from which the following set of coefficients is derived

$$h_0 = 0 \qquad (2)$$

$$h_i = 1 - 1.94392 \cos(\pi i / 512) + \sqrt{2} \cos(\pi i / 256) - 0.470294 \cos(\pi 3i / 512) \; ; \; 1 \le i \le 1023$$

The frequency response of this filter is given in Fig.3, where the unit on the frequency axis is the sub-channel spacing. For maximum efficiency, the filter bank is combined with OQAM (Offset Quadrature Amplitude Modulation), and sub-channels i and i±1 overlap, the signal separation being obtained through orthogonality [6].

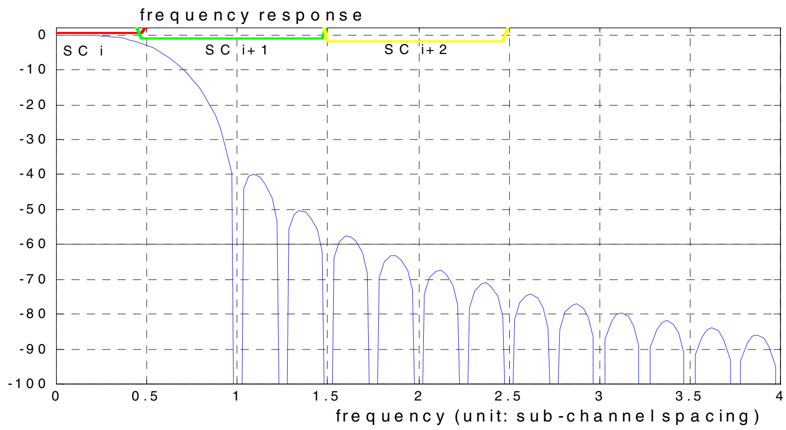

Fig.3 Frequency response of the prototype filter, for a bank of N=128 filters

Beyond the neighbouring sub-channels, that is for frequencies greater than 1.5, the attenuation exceeds 58 dB. In addition, an important feature of this curve is that the magnitudes of the ripples decrease monotonically with the frequency. This is crucial for interference cancellation in spectrum measurement and robustness to high level jammers. Another important property brought by this curve is the sharpness of the edges of the transmitted spectrum, which has to fit into specified masks.

4. Some applications in future wireless networks

The filter bank technique can be applied in the downlink of wireless and mobile systems, in much the same way as OFDM. With this approach, gains in maximum throughput can be expected due to the absence of cyclic prefix, better exploitation of the transmission masks and, whenever appropriate, more accurate and reliable estimations of the noise floor.
However, it is in the uplink of dynamic spectrum access systems that key benefits can be expected, exploiting the spectral separation of the sub-channels. In the allocation of the sub-channels to different users, the bandwidth of at least one sub-channel is left empty between two users, as illustrated in Fig.1. Then, the spectra can be considered as disjoint. In such a situation, there is no need to perform ranging and align the users in time through a complex and lengthy protocol for exchanges between the base station and the mobile stations. A per user equalization procedure, without any feedback from BS to MS can be employed to recover the data. Moreover, fast moving mobile stations can be accomodated, because the corresponding doppler shifts can be compensated on a per user basis. If large differences in signal strengths among users can be anticipated, then the spectrum separation between these users can be increased, to benefit from the monotonicity of the frequency response shown in Fig.3.
The mixing of multicarrier modulation and single carrier modulation is another benefit of the filter bank approach and an additional networking flexibility parameter. At the present time, there are two standardization

groups active in the field of mobile systems. One is the WiMAX forum, working on the standard IEEE 802.16. Mobility features are provided in the amendment 802.16e, dubbed mobile WiMAX, and an advanced air interface for fixed and mobile broadband wireless access systems is under definition under the amendment 802.16m. The modulation technique in mobile WiMAX, which targets metropolitan area networks, is multicarrier for both downlink and uplink [7]. On the contrary, the group called 3GPP-LTE (long term evolution) favors multicarrier modulation for the downlink but single carrier modulation for the uplink, arguing that a low peak-to-average power ratio is critical for the users which are at the border of a cell and must save on their power consumption [8]. With single carrier, constant amplitude modulations can be implemented.
In the filter bank approach, due to the disjoint user spectra, there is no contradiction. Multicarrier modulation can provide high efficiency to the users which are close to the BS and can afford a high PAPR value in their link budget. For those which are too far, they can resort to robust and low power consumption single carrier modulation. An illustration is given in Fig.4. At least one empty sub-channel has to be introduced at the borders of the single carrier spectrum.

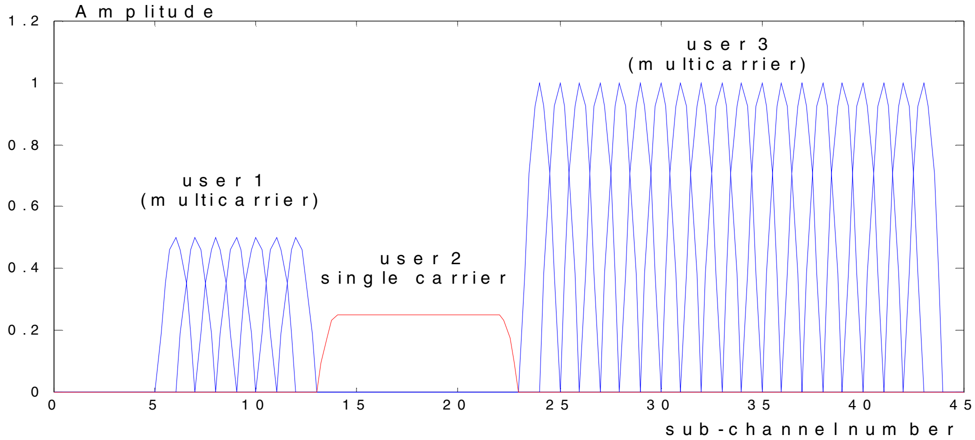

Fig.4. Mixing multicarrier and single carrier modulation with filter banks.

5. Conclusion

The real time high resolution and high accuracy spectrum analysis which is required by future wireless and mobile systems can be achieved with filter banks. In addition, the approach provides the high level of independence of the sub-channels which is necessary for the flexibility in network exploitation. Now, more research work is needed to realize the potential of filter bank based multicarrier schemes and lead to their smooth and successful introduction in the communication environment, particularly on such issues as fast initialization, channel tracking and equalization, combination with multiantenna processing, compatibility with OFDM and existing systems, and impact beyond the physical layer.

Acknowledgement: part of this work is supported by the FP7 european research project PHYDYAS.

References

[1] P.Amini, R.Kempter, R.R.Chen, L.Lin and B.Farhang-Boroujeny, “Filter bank multitone: a physical layer candidate for cognitive radios”, Software Defined Radio conf., SDR’05, Orange County, USA, Nov.14-18, 2005.
[2] M.Bellanger, “Digital processing of signals- theory and practice”, John Wiley, 3rd Ed., Chichester, UK, 2000.
[3] A.N.Akansu, P.Duhamel, X.Lin and M.de Courville, “Orthogonal transmultiplexers in communications: a review”, IEEE Trans. Signal Processing, vol.46, April 1998, pp.979-995.
[4] P. Siohan, C. Siclet and N. Lacaille, "Analysis and design of OFDM/OQAM systems based on filterbank theory", IEEE Trans. on Signal Processing, vol. 50, pp.1170-83, May 2002.
[5] M.Bellanger, “Specification and design of a prototype filter for filter bank based multicarrier transmission”, Proceedings of IEEE-ICASSP’01, Salt Lake City, USA,May 2001.
[6] B. Hirosaki, "An Orthogonally Multiplexed QAM System Using the Discrete Fourier Transform," IEEE Trans. Communications, vol. 29, pp. 982-989, July1981.
[7] IEEE std. 802.16e-2005, “Local and metropolitan area networks, part 16: air interface for fixed and mobile broadband wireless access systems”, December 2005.
[8] H.Ekstrom et al. “Technical solutions for the 3G long-term evolution”, IEEE Communications Magazine, vol.44, n°3, March 2006, pp.38-45.