



Sensitivity analysis of offset QAM multicarrier systems to residual carrier frequency and timing offsets

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ARTICLE INFO

Article history:

Received 20 September 2010

Received in revised form

30 November 2010

Accepted 15 December 2010

Available online 8 January 2011

Keywords:

Filter bank multicarrier

Offset quadrature amplitude modulation

Cosine modulated filter bank

Signal-to-interference ratio

Carrier frequency offset

Timing offset

ABSTRACT

This paper presents a sensitivity analysis of filter bank multicarrier (FBMC) systems to carrier frequency offset (CFO) and timing offset. Although the emphasis of the paper is on the class of FBMC systems that are based on offset quadrature amplitude modulation (OQAM), the developed results are found applicable to cosine modulated-based FBMC systems as well. We assume that coarse CFO and timing offset estimations and compensations have already been performed so that the residual CFO and timing offset are small. A simple closed-form approximation to the signal-to-interference ratio (SIR) is derived. This approximation is compared numerically with the exact SIR and confirmed to be accurate for a variety of FBMC systems with different prototype filters. The derived SIR is characterized by a pair of coefficients that are only dependent on the underlying prototype filter, thus, allows the designer to pick from the choices of the prototype filter the one that has minimum sensitivity to CFO and/or timing offset.

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1. Introduction

Filter bank multicarrier (FBMC) communication systems have recently received increasing attention for broadband communications in both wired and wireless communications. The FBMC system uses an effective signaling method that achieves high spectral efficiency over broadband channels. Orthogonal frequency division multiplexing (OFDM), belonging to the family of FBMC with a rectangular prototype filter [1], is widely used in many communication systems, e.g., IEEE 802.11a/g, IEEE 802.16a, DVB-T, and asymmetric digital subcarrier line (ADSL). However, there are a few drawbacks of OFDM systems. Firstly, each OFDM subcarrier exhibits a *sinc*-shaped frequency response across all subcarriers. This

causes large intercarrier interference (ICI) in the presence of any carrier frequency offset (CFO). In addition, if OFDM is used for the uplink of a multiple access network (i.e., in an orthogonal frequency division multiple access (OFDMA) network), any mismatch between the carrier frequencies of the different nodes in the network will result in loss of orthogonality of the subcarrier signals, thus a significant performance loss [2]. The problem is more serious in cognitive radios where primary and secondary users that may operate based on different modulation schemes (being single or multicarrier) should co-exist [3]. Secondly, OFDM avoids intersymbol interference (ISI) by using a cyclic prefix (CP) longer than the maximum delay spread of the channel. The CP does not carry useful information and thus reduces the bandwidth efficiency of the system. These weaknesses have shifted researchers to other FBMC systems [3–18].

The goal of this paper is to study a class of FBMC systems that are fundamentally different from OFDM and

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offer a number of advantages in terms of robustness to CFO and multiple access effects. Interestingly, the class of FBMC systems that are studied in this paper were invented in the 1960s, a few years before the introduction of what is now known as OFDM. In 1966, Chang [4] suggested an orthogonal signaling method for transmission of pulse amplitude modulated (PAM) symbols. Subsequently, Saltzberg [5] extended the Chang's method to transmission of quadrature amplitude modulated (QAM) symbols. Although, Chang's and Saltzberg's methods are usually viewed as two different modulation methods – Chang signaling transmits PAM symbols in a set of vestigial side-band (VSB) subcarrier channels while Saltzberg signaling transmits QAM symbols in a set of double side-band (DSB) subcarrier channels – a closer look at the two methods reveals that one can be obtained from the other through a modulation step. This result which has recently been reported in [18] has a number of interesting implications. Particularly, in the context of this paper, it is found that Chang's and Saltzberg's methods are both equally sensitive to all channel impairments, including CFO and timing offset. Hence, we argue the results derived in this paper are also applicable to the cosine modulated FBMC systems – the name that has been used in the more recent literature, e.g., [19], to refer to the Chang's method.

It is also worth noting that there are some efficient digital implementations of FBMC systems, e.g., [6–15]. Specially, implementation of Saltzberg's multicarrier system through polyphase structures was first introduced by Bellanger [6], later studied by Hirosaki [7], and was further developed by others [8–13] with many interesting ideas.

The pioneering work of Chang [4], on the other hand, has received less attention. However, a vast literature in digital signal processing have studied a class of multicarrier systems that has been referred to as discrete wavelet multitone (DWMT). In the period of 1995–2003 a fair number of contributions from various authors appeared in the literature, e.g., [19–22]. In [19], in particular, a thorough study of DWMT is performed and it is noted that this method operates based on cosine modulated filter banks. The fact that DWMT uses cosine modulated filter banks has also been acknowledged by other authors, e.g., [20]. However, no connection has been made between these works and [4]. Only recently in [18] it has been noted that DWMT has been in fact a re-invention of the Chang's FBMC system, formulated in terms of digital/polyphase filter banks.

A few notes on the various terminologies used in the FBMC literature are in order. In [4,5] no specific names have been given to the multicarrier modulation types that were introduced. In [23], the name staggered QAM was used for the type of modulation suggested in [5]. Later, Hirosaki [7] used the terminology orthogonally multiplexed QAM (OQAM). OQAM was later referred to as OFDM-OQAM by many authors, e.g., [8,9,11–13], with the acronym OQAM standing for *offset QAM*, reflecting the fact that the in-phase and quadrature of each QAM symbol are time offset with respect to each other; see Section 2 for details. The same is true for the Chang's method and its extensions. The name DWMT is used in [22]. The IEEE P1901 working group has called it wavelet-OFDM [24]. On

the other hand, some authors have preferred the name cosine modulated filter bank OFDM (CMFB-OFDM). In [14], where a more thorough study of CMFB-OFDM to very high bit-rate subscriber line (VDSL) has been presented, the shorter name cosine modulated multitone (CMT) has been proposed, following the terminology filtered multitone (FMT) [25]. In this paper, we use CMT, when reference is made to the Chang's method (and its extensions). Also, we follow [18] and use the terminology staggered-modulated multitone (SMT) for the Saltzberg's method (and its extensions).

A principal disadvantage of FBMC systems is their sensitivity to CFO and timing offset [26–32]. CFO is introduced by the Doppler shift in wireless channels, and also by the difference between the transmitter and the receiver local oscillators [26]. A timing offset is introduced when the actual sampling time is different from the optimum sampling time in the receiver. Moreover, a constant phase offset may arise because of the channel delay and the difference between the phase of local oscillators in the receiver and in the transmitter. The effects of these offsets on the SMT system over AWGN channels were investigated [30–32]. It was shown that the interference due to CFO, timing offset, and phase offset in SMT systems consists of both ISI and ICI [30–32]. In [30], signal-to-noise ratio (SNR) degradation of SMT systems due to CFO was studied and it was shown by simulation that SMT is more robust to CFO than OFDM. A general form of received signals was derived and the sensitivity of multiuser FBMC systems to CFO, timing offset, and constant phase offset was investigated in [31]. In [32], the SNR degradation of SMT in the presence of CFO over flat fading channels was investigated by simulations. Here, also, it was found that SMT is more robust to CFO than OFDM. Analyses in [30–32] generally lead to lengthy and complicated equations in which the impact of channel impairments is hard to see. Part of our effort in this paper is to simplify such equations in order to provide clear insight to the impact of CFO and timing offset on the receiver performance. We assume that coarse CFO and timing offset estimation and compensation have already been performed such that the residual CFO and timing offset are small. Through reasonable approximation, we simplify the lengthy ISI and ICI expressions and arrive at very simple equation that show the interference power including both ISI and ICI as quadratic function of CFO and timing offset. This leads to a closed-form approximation of the signal-to-interference ratio (SIR) that contains parameters that are related to the prototype filter based on which the SMT system is constructed. We then extend our results to frequency selective channels and show that as long as the time spread of the channel is small in comparison with the symbol spacing in a SMT system, approximation of the channel over each subcarrier by a flat gain incurs insignificant loss in the accuracy of the equations that were developed for flat fading channels. We compare the closed-form SIR approximation with the exact SIR obtained numerically. The results show that the developed simple SIR expression is an accurate approximation and one can rely on that for any further studies.

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