FILTER BANK BASED MULTI-MODE MULTIPLE ACCESS SCHEME FOR WIRELESS UPLINK

Tero Ihalainen[†], *Ari Viholainen*[†], *Tobias Hidalgo Stitz*[†], *Markku Renfors*[†], *and Maurice Bellanger*[⋆]

[†]Department of Communications Engineering, Tampere University of Technology
P.O. Box 553, FI-33101, Tampere, Finland, Email: tero.j.ihalainen@tut.fi
[⋆]CNAM, 292 rue Saint-Martin, 75141 Paris cedex 03, France, Email: bellang@cnam.fr

ABSTRACT

This paper investigates the potential of filter bank (FB) processing in the context of uplink multi-user access. First, a FB based scheme, conceptually similar to the single carrier frequency division multiple access (SC-FDMA) developed by 3GPP for uplink in the Long Term Evolution of UMTS, is analyzed. Specifically, a method for synthesizing spectrally well-localized uplink waveforms with low peak-to-average power ratio, using FB based multicarrier (FBMC) modulation in combination with FB spreading, is introduced. Secondly, the superior frequency selectivity of the FB approach, when combined with frequency sampling -designed subchannel/subband processing, is found to enable flexible and bandwidth efficient multi-mode uplink transmission with relaxed constraints on inter-user timing synchronization. The proposed concept allows different mobile terminals to operate in the reverse link simultaneously in multicarrier, SC-FDMA, or conventional single carrier mode according to attributes such as the required transmission power.

1. INTRODUCTION

Future wireless communications are faced with high expectations ranging from ever higher peak data rates and improved spectral efficiency to support for different mobility scenarios. These demands set great challenges for wireless system design. One of the biggest obstacles originates from broadband high data rate transmission over time dispersive mobile radio channel, which imposes major difficulties for channel equalization. With the conventional single carrier transmission based on adaptive time domain equalization, the computational complexity easily becomes overwhelming, making such an approach impractical. On the other hand, the most prominent multicarrier modulation technique, OFDM (orthogonal frequency division multiplexing), has been successfully deployed over fading multipath channels making use of a suitable cyclic prefix. In fact, OFDM has become the modulation technique of choice and the basis of the air interface in a number of standards covering wide range of applications from digital audio and video broadcasting to wireless local and metropolitan area networks. More recently, OFDM has also been adopted to cellular networks by combining it with elements of time division multiple access to obtain a technique called OFDMA (orthogonal frequency division multiple access). Both WiMAX (Worldwide Interoperability for Microwave Access) [1] and UMTS LTE (Universal Mobile Telecommunications System's Long Term Evolution) [2] use OFDMA as the multiple access technology in the forward link from a basestation to mobile terminals (downlink). While WiMAX relies on OFDMA also in the reverse link, the 3GPP (Third Generation Partnership Project) standardization group has chosen to implement the LTE uplink based on the single carrier FDMA (SC-FDMA) [3].

SC-FDMA is a new access technology for high data rate cellular uplink communications that accommodates multi-user access to single carrier transmission with frequency domain equalization (SC-FDE) [4, 5]. SC-FDMA inherits many of the attractive features of the SC-FDE concept, specifically, the low peak-to-average power ratio (PAPR) transmission, robustness to carrier frequency offsets, and low complexity frequency domain equalization. As for the implementation, SC-FDMA can be seen as a variant of OFDMA, where the OFDM processing core is complemented with DFT spreading / IDFT de-spreading and frequency domain multi-user multiplexing / de-multiplexing in the transmitter / receiver side of the link, respectively. The resulting technique is referred hereafter to as DFT-s-OFDMA.

As a counterbalance of its ability to elegantly cope with frequency selective fading channels, OFDM suffers from a number of drawbacks. These include a loss in spectral efficiency due to cyclic prefix -induced redundancy, sensitivity to narrowband interference and high level of out-of-band radiation, both imposed by a trivial (rectangular) subcarrier pulse shaping. As an alternative, filter bank based multicarrier (FBMC) technique, in combination with OQAM (offset quadrature amplitude modulation) [6, 7, 8], has recently drawn increasing attention as it shows strong potential to overcome the limitations of OFDM at a cost of somewhat increased processing complexity. In this paper, we propose a multi-mode multi-user uplink scheme for future wireless cellular systems that is based on FBMC/OQAM.

The remainder of this paper is organized as follows: In Section 2, a short overview of FBMC/OQAM principles is given. Section 3 discusses the fundamentals of DFT-s-OFDMA. Section 4 defines and analyzes a FB -spread FBMC concept. Section 5 introduces a multi-mode multiple access scheme for uplink that builds on frequency selective FB processing. The transmit and receive processing, specific to different transmission modes, are explained. In Section 6, advantages and implications of mixed single carrier and multicarrier transmissions are discussed. Finally, conclusions and perspectives are drawn in Section 7.

2. FBMC/OQAM TRANSMISSION

When applied to multicarrier communications, the filter banks are used in the transmultiplexer configuration with

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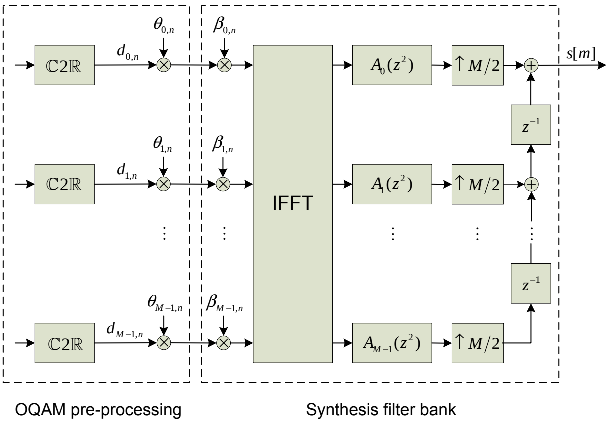

Figure 1: An efficient implementation structure of the FBMC/OQAM synthesis filter bank.

the synthesis (SFB) and analysis (AFB) bank implementing the modulator and demodulator, respectively. Here, we focus on uniform complex modulated filter banks where frequency shifted subchannel filters of equal bandwidths are obtained from a single linear-phase lowpass prototype filter $p[m]$ through exponential modulation. The complex I/Q baseband signal at the output of a SFB, a block diagram of which is shown in Figure 1, can be expressed as[1]

$$s[m]=\sum_{k=0}^{M-1}\sum_{n=-\infty}^{\infty} d_{k,n}\theta_{k,n}\beta_{k,n}p[m-n\frac{M}{2}]e^{j\frac{2\pi}{M}km}, \qquad (1)$$

where

$$\theta_{k,n}=e^{j\frac{\pi}{2}(k+n)}=j^{k+n} \qquad (2)$$

and

$$\beta_{k,n}=e^{-j\frac{2\pi k}{M}(\frac{L_p-1}{2})}. \qquad (3)$$

Here, m, M, $d_{k,n}$, and $\theta_{k,n}$ denote the sample index at high-rate (at the output of the SFB), the overall number of subchannels, the real-valued symbol modulated (at rate $2/T$) on the kth subcarrier during the nth OQAM sub-symbol interval, and the phase mapping between the real-valued symbol sequence and the complex-valued input samples of the synthesis bank, respectively. The signalling interval T is defined as the inverse of the subcarrier spacing, i.e., $T = 1/\Delta f$. The $\mathbb{C}2\mathbb{R}$-blocks indicate the conversion from the real and imaginary parts of a complex valued symbol from a QAM alphabet into real-valued data. Symbols $d_{k,n}$ and $d_{k,n+1}$ can be interpreted to carry the in-phase and quadrature components, in an interleaved manner, with a relative time offset of $T/2$. The length of the prototype filter[2], $L_p = KM-1$, depends on the size of the filter bank and the overlapping factor K. Fig. 1 shows an efficient implementation structure where the exponential modulation of the prototype filter is constructed by complementing a filtering section, comprising the polyphase decomposition of the prototype filter, with the IFFT (inverse fast Fourier transform). At the receiver, the inverse operations (of those performed in the transmitter) are carried out in the reversed order to recover the transmitted data.

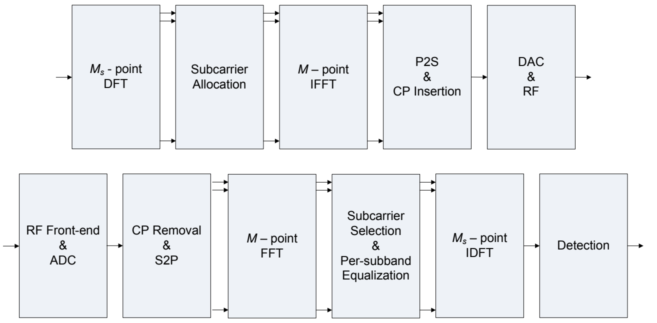

Figure 2: The block diagrams of DFT-s-OFDMA transmit (top) and receive (bottom) processing.

In modulated filter banks the spectral properties of the subchannel filters, and therefore also the obtainable stopband frequency rejection, are defined by the design of the prototype filter. A straightforward and efficient design method, which has been shown to be well suited for multicarrier communications and is currently also being considered in the context of cognitive radio [10], is the frequency sampling technique [11]. With this design, ideally, a single unused subchannel is sufficient for creating a necessary guard band between asynchronous adjacent multiplexes.

3. DFT-SPREAD OFDMA

Figure 2 shows block diagrams of the DFT-s-OFDMA transmit and receive processing. In the transmitter, an M_s-length sequence of complex symbols is first converted to frequency domain by means of an M_s-point DFT. Here, $M_s < M$, where M denotes the total number of subcarriers on the operated frequency band. Next, a subcarrier allocation is performed, which maps the resulting frequency domain representation (a set of DFT -spread complex numbers) into an M-point IFFT according to the scheduled frequency resources. Multi-user access is incorporated through frequency multiplexing by assigning each user with a unique set of active subcarrier indexes (zero data are allocated for the unoccupied subcarriers). Different strategies for subcarrier allocation are possible. They can coarsely be categorized as localized or distributed mapping rules. The localized mode assigns a set of consecutive subcarriers to a user, resulting in a continuous spectrum which occupies a fraction of the overall band. In the distributed mode, the DFT output samples are allocated (e.g., evenly-spaced) over the whole band, giving rise to a non-continuous comb-shaped spectrum. Moreover, in [3] different subcarrier mappings are shown to provide different tradeoffs in terms of PAPR and throughput performance. After the IFFT, the transformed block is extended by a cyclic prefix to enable simple frequency domain equalization and to provide inter-user orthogonality.

At the receiver, after radio frequency (RF) front-end and analog-to-digital conversion (ADC), removal of cyclic prefixes effectively eliminates the inter-block interference due to multipath propagation. The received signal is then converted to frequency domain using an M-point FFT. Due to circular convolution (imposed by the cyclic prefix insertion) between the transmitted signal and the multipath impulse response, the channel effect appears multiplicative and frequency-flat for each subband. Therefore, frequency domain equalization by a single complex coefficient per subband is sufficient to

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[1] A more detailed description of the signal model can be found in [9].

[2] Also other choices for L_p are possible. Implications of L_p on the trans-multiplexer model are addressed in [9].

compensate for the channel distortion. Finally, an M_s-point IDFT converts the equalized samples to time domain, canceling the spreading operation performed in the transmitter side, and outputs the complex symbol estimates. As for the equalization and detection, the processing in DFT-s-OFDMA receiver differs essentially from that performed in OFDMA [4, 5]. While in OFDMA, both equalization and detection are carried out individually on each subcarrier symbol in frequency domain, the DFT-s-OFDMA receiver executes detection only after frequency domain equalized data have been converted back to time domain using IDFT de-spreading. Consequently, DFT-s-OFDMA inherently provides robustness against nulls of the channel transfer function in the signal band, whereas OFDMA requires channel coding and interleaving to overcome the deteriorating impact of deep fading notches of the channel.

4. FB-SPREAD FBMC

Next, we investigate a scheme, conceptually similar to DFT-s-OFDMA where, however, cyclic prefixes are absent and synthesis and analysis FBs substitute IFFT and FFT transforms, respectively. Such a system model can be derived by complementing a FBMC core with a data spreading (as pre-processing) and a de-spreading (as post-processing) operator in the transmitter and receiver, respectively.

Filter bank transform is characterized by the impulse response of the prototype filter, length of which typically extends over multiple consecutive symbol periods. Therefore, rather than considering a single M_s-length symbol block at a time, as in DFT-s-OFDMA, it is necessary to process data segments of $G = N \times M_s$ symbols (N being some integer) at once instead. The data spreading is carried out by passing a data segment through an M_s-subchannel AFB, in contrast to a DFT block transform performed in DFT-s-OFDMA. The transformed data is then mapped into an M-subchannel synthesis FB according to the scheduled frequency resources (again zero data are allocated to unoccupied subchannels). The SFB converts the spread data to time domain synthesizing a burst for transmission.

A low PAPR is of great importance for battery powered mobile terminals. The lower PAPR allows decreasing the power amplifier back-off, which in turn extends the operation time of a mobile terminal, at a certain transmission rate, compared to modulation schemes with a higher PAPR. Moreover, it enables to increase the coverage at cell edge.

We have evaluated the PAPR in a number of different system configurations including FBMC, OFDM, DFT-s-FBMC, FB-s-FBMC, DFT-s-OFDM, and SC. By simulating a transmission of 10^6 blocks of data, an empirical CCDF (Complementary Cumulative Distribution Function) was obtained for each configuration. The CCDF is defined as the probability that the PAPR of a block of M samples exceeds a given threshold. In the simulations, $M = 1024$ subcarriers (subchannels) were considered for FBMC, OFDM, DFT-s-FBMC, FB-s-FBMC, and DFT-s-OFDM. The overlapping factor $K = 4$ was used in the FBMC core. Moreover, a localized mode band allocation of $M_s = 160$ subcarries was assumed. For SC transmission, pulse shaping with a square root raised cosine filter of different rolloff factors $\alpha = \{0.1, 0.3, 0.5\}$ and oversampling rate of four were tested. All the simulations were carried out using QPSK modulation. Figure 3 shows the CCDFs of PAPR for the different multiplexing configurations. In line with the prior analysis in [12], it can be observed that the PAPR distributions are practically identical for FBMC and OFDM. While DFT -spreading combined with OFDM clearly improves the PAPR distribution, it turns out to be insufficient when combined with FBMC. FB-s-FBMC provides improved performance due to the fact that the AFB as a pre-processor provides a closer approximation of the analysis-synthesis cascade, compared to the adhoc DFT block transform. It is possible to apply filter bank design with smaller overlapping factor (K_s) for the spreading operation compared to that (K) used in the FBMC processing core. The value $K_s = 3$ gives a good trade-off between processing complexity and PAPR reduction. It is obvious that FB-s-FBMC is computationally more demanding compared to DFT-s-FBMC. Also there is some overhead in data transmission capacity due to the 'tails' of the spreading transform. However, the resulting PAPR performance is clearly better than with DFT-s-FBMC. Regarding the traditional single carrier waveforms, it is well-known, that significant PAPR reduction can be obtained at the cost of increasing excess bandwidth.

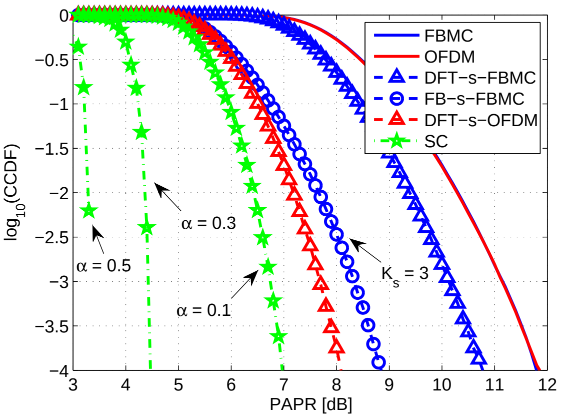

Figure 3: The CCDFs of PAPR for FBMC, OFDM, DFT-s-FBMC, FB-s-FBMC, DFT-s-OFDM and SC waveforms with $M = 1024$, $K = 4$, $M_s = 160$, $K_s = 3$, and $\alpha = \{0.1, 0.3, 0.5\}$.

5. MULTI-MODE UPLINK TRANSMISSION BASED ON FILTER BANK PROCESSING

In this section, we introduce a FB processing -based uplink multiple access scheme which enables different mobile terminals to simultaneously transmit in the reverse link at different operation modes; including FBMC, FB-s-FBMC, and conventional SC modulation. This concept is fundamentally grounded on the possibility to construct independent subchannels or groups of subchannels with continuous flow of data, permitted by the FBMC technique. The spectral isolation among these 'data pipes' enables the received data, originating from different mobiles, to be processed at a basestation receiver independently and adaptively. Moreover, the proposed multi-mode scheme permits mobile terminals to communicate with a basestation in a flexible manner and in accordance with the respective link conditions and/or targeted service types (voice, data, multimedia, etc.) Therefore, it provides means to adaptively trade off higher level of scheduling flexibility and improved link efficiency of FBMC mode for the improved power efficiency of FB-s-FBMC and

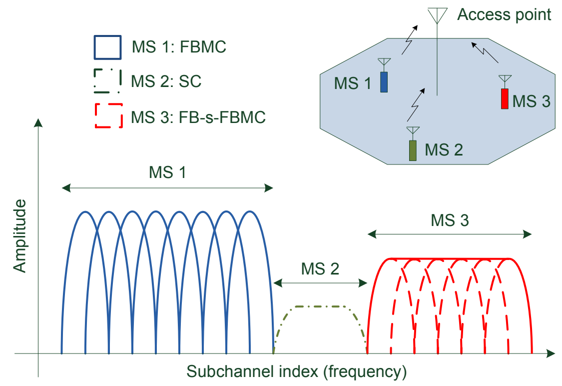

Figure 4: An exemplary multi-mode uplink access scenario with three mobile terminals and different multiplexing modes.

SC modes and vice versa. Figure 4 illustrates the concept through an example where three mobile terminals (MS) with different link attenuations are scheduled using different multiplexing modes by a serving basestation. While the MS 1 with a low link attenuation transmits in FBMC multicarrier mode, the other two mobile terminals, suffering from more severe path losses, are assigned FB-s-FBMC and SC modes to make use of the lower PAPR. Furthermore, as will be illustrated in the following sections both transmit and receive processing, required to support different operation modes, share several common processing elements. This is crucial to keep the overall implementation complexity reasonable.

5.1 Transmitter Processing

Figure 5 shows a block diagram of a transmitter structure capable of supporting the proposed multi-mode uplink transmission. The FB-s-FBMC multiplexing mode can be established by including a FB -spreading operator (the block with dashed line) as a pre-processing stage complementing the FBMC core (the blocks with solid lines). In case a mobile would be scheduled to operate in FBMC mode instead, this pre-processing block would be bypassed and the complex valued symbols would be directly processed in accordance with the FBMC scheme. Also a conventional SC transmission can be envisioned, e.g., for low-rate MSs and/or MSs temporarily located close to the edge of a serving cell. In this case, the baseband signal can be synthesized with a separate SC modem (the block with dash-dot line), prior to passing it to the digital-to-analog converter (DAC) and the RF circuitry that can be considered to be common for all the modes.

5.2 Receiver Processing

The access point receiver observes a composite signal that consists of multiple signals originating from different mobile terminals and corrupted by the respective multipath channels. It is the task of the receiver to demodulate, equalize and detect each uplink signal in accordance with the assigned multiplexing scheme. The necessary processing can be carried out using a receiver structure shown in Figure 6. After the RF front-end and ADC, an AFB is used to convert the wideband time domain signal to frequency domain. It should be noted here that the AFB can implement a major part of the channelization filtering efficiently and in a highly flexible manner. Next, frequency domain equalization is carried out. For the parts of the overall frequency band that were assigned for mobile terminals transmitting in FBMC mode, subcarrier-wise equalization and detection can be performed according to principles detailed in [13]. Specifically, a subcarrier-wise channel compensation can be devised using low-complexity linear equalizers, with coefficients that can straightforwardly be set using the frequency sampling design principle. This equalizer structure is able to perform frequency selective per-subchannel equalization, necessary due to absence of cyclic prefixes. Moreover, the same equalizer can be adapted to simultaneously execute per-subband timing compensation without additional implementation complexity [13, 14]. As for the mobile terminals that were scheduled to transmit in low PAPR FB-s-FBMC mode, an M_s-subchannel synthesis bank is used to post-process (de-spread) the equalized samples. It moreover converts the signal to time domain where the symbol detection is finally carried out. In case of SC multiplexing mode, filter bank based frequency domain fractionally-spaced equalization (FB-FDE) [15] can be utilized. In that case, the receive filter can be implemented efficiently in the frequency domain by incorporating it with the subband equalization. This means that pulse shaping filtering can be introduced without additional computational effort, even if it has very sharp transition bands. Finally, a SFB is used to transform the subband processed samples to time domain where symbol detections are carried out. In summary, the same subband-wise low-complexity equalizer structure can be used in all transmission modes, with some minor differences in the way equalizer coefficients are derived.

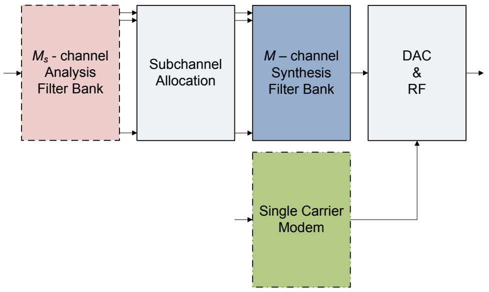

Figure 5: A block diagram of a multi-mode transmitter based on filter bank processing.

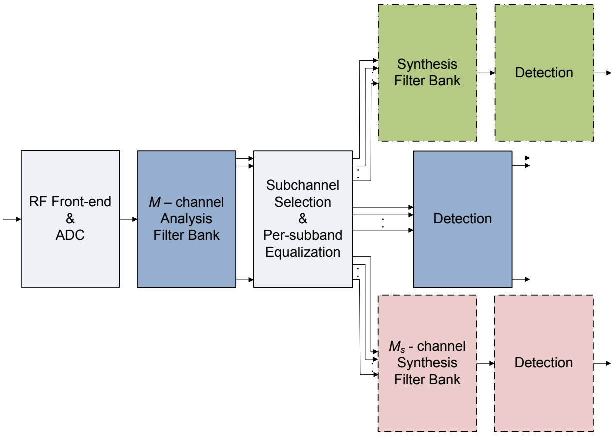

Figure 6: A block diagram of a multi-mode receiver based on filter bank processing.

6. IMPLICATIONS OF MIXING SINGLE CARRIER AND MULTICARRIER WAVEFORMS

While it is possible to envisage multi-mode transmission based on both DFT and FB based processing, there are some fundamental differences between these two approaches as far as practicality is concerned. Cyclic prefixes in OFDM and DFT-s-OFDMA are dimensioned to accommodate both the maximum delay spread of the multipath channel and the possible timing inaccuracies among different uplink signals. As long as different uplink signals can be time synchronized within this cyclic prefix, the orthogonality between different frequency multiplexed uplink users is maintained. This is a necessary condition to avoid severe intercarrier interference imposed by the heavily overlapping subcarrier responses. With FBMC and FB-s-FBMC the timing synchronization between different frequency multiplexed uplink signals can be relaxed by relying on the spectral isolation introduced by the frequency selectivity of the subcarrier pulse shaping. As for the general time synchronization process, similar cell search and random access procedures as those proposed for the LTE can be visioned. The timing adjustment (compensation for the fractional time delay) within each of the frequency multiplexed asynchronous uplink bands can be carried out using frequency domain subband equalizers. Orthogonality among different time multiplexed bursts within a specific band requires timing-advance control signalling.

The flexibility benefits of the FB approach are especially emphasized when data transmission in cognitive radio (CR) context is considered. In fact, the possibility to construct independent signal multiplexes can be considered as a vital constraint in CR scenarios, where spectral opportunities (spectrum holes) appear stochastically, making it quite difficult to construct synchronized multi-user access in a coordinated manner. While in the DFT based approach, guard bands of several subcarriers must be established around the multiplexed signal to limit the out-of-band radiation, a single unoccupied subchannel is in principle sufficient to fulfill the task when FBs with proper prototype design are used.

The PAPR analysis in Section 4 shows that, although a pre-processing of data by a spreading operator improves the power efficiency of both DFT and FB -based approaches, the PAPR of the resulting DFT-s-OFDMA and FB-s-FBMC waveforms still fall significantly behind that obtained with SC transmission. Therefore, it is compelling to envisage a multi-mode uplink concept where SC operation mode could be executed when the highest level of power efficiency is required. However, it is very demanding, if not impossible, to simultaneously frequency multiplex SC and DFT-s-OFDMA / OFDM -based uplink signals in a spectrally efficient manner due to high level of out-of-band radiation imposed by DFT-s-OFDMA and OFDM. Channel selection filtering necessary to properly separate the SC signal in the receiver side would also suffer from the poor selectivity of the DFT. On the other hand, both FB-s-FBMC and FBMC provide spectrally well-localized signals due to superior control of the out-of-band behavior. When combined with the FB-FDE receive processing of [15], power efficient SC transmission can be blended with FB-s-FBMC and FBMC operation modes.

7. CONCLUSIONS

This paper introduced a flexible multi-mode multiple access scheme for wireless uplink that builds on filter bank processing. The concept can provide independent uplink signal multiplexes in bandwidth efficient manner and with relaxed constraints on inter-user timing synchronization. A reverse link, supporting simultaneously both multicarrier and single carrier modes, can be established, making use of the superior selectivity of the frequency sampling designed prototype filter and a low-complexity linear equalizer structure, capable of frequency-selective per-subband processing facilitating both efficient channel and timing compensation.

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