Optimized Burst Truncation in Fast-Convolution Filter Bank Based Waveform Generation

Juha Yli-Kaakinen, Markku Renfors
Dept. of Electronics and Communications Engineering, Tampere University of Technology, Finland
{juha.yli-kaakinen, markku.renfors}@tut.fi

***Abstract*—In this paper we investigate the time-frequency localization tradeoffs in practical implementation of filter bank multicarrier (FBMC) waveforms in short burst transmission. Frequency localization is considered as an important characteristic for future wireless communication systems, including 5G, but it comes with the cost of not-so-good time localization. This appears in the form of relatively long 'tails' of the generated transmission burst. Truncation of the burst tails is an obvious choice for reducing the time-overheads in short burst based multiple access or duplexing schemes, but it introduces transients in the inband interference and out-of-band radiation characteristics. We study the burst truncation effects while utilizing a flexible FBMC waveform generation scheme based on fast-convolution processing. Also a novel method to optimize the used symbol waveform taking into account the truncation effects is developed.**

I. Introduction

Orthogonal frequency-division multiplexing (OFDM) is the most important multicarrier technique and it is extensively utilized in modern broadband radio access systems. This is due to the simple and robust way of channel equalization, high flexibility and efficiency in allocating spectral resources to different users, as well as simplicity of combining multiantenna schemes with the core functionality [1]. However, OFDM has one major limitation in challenging new spectrum use scenarios, like opportunistic dynamic spectrum access, heterogeneous wireless system coexistence, and asynchronous multiple access in general: limitations in spectral containment, which lead to high sensitivity to interferences from asynchronous spectral components.

An alternative scheme is offered by the filter bank based methods of waveform processing and channelization filtering [2]–[4]. The transmitted waveforms generated by these methods are spectrally well-contained and the unused portions of the spectrum allocated for dynamic/fragmented use are inherently clean. The filter bank processing on the receiver side is able to suppress the interferences from the unused parts of the allocated spectrum. Naturally, there are limitations in the reachable levels of attenuation, mostly determined by the analog RF imperfections, notably power amplifier nonlinearity on the transmitter side. A relatively widely studied filter bank based waveform is FBMC/OQAM (filter bank multicarrier/offset-QAM, also known as OFDM/OQAM) [3] [4]. While reaching high spectral containment, it keeps many of the important features of OFDM.

In this paper, we consider FBMC/OQAM waveform generation utilizing fast-convolution filter bank (FC-FB) structure. FC-FB has recently been introduced in the waveform processing context as an efficient implementation architecture for different FBMC schemes with greatly increased flexibility and improved support for asynchronous multi-user operation [5].

Good frequency localization of a communication waveform comes with the cost of not-so-good time localization. The subcarrier level Nyquist pulse shaping utilized in FBMC has impulse response length exceeding the symbol interval. Therefore, relatively long 'tails' are generated around each transmission burst. Truncation of the burst tails reduces the time-overheads in short burst based multiple access or duplexing schemes, but it degrades the spectral characteristics of the waveform and introduces transients in the inband (IB) interference and out-of-band (OoB) radiation characteristics. In this paper, we investigate the burst truncation effects while utilizing the flexible FBMC waveform generation scheme based on fast-convolution (FC) processing.

In traditional polyphase implementation, the overall FBMC symbol length depends on the overlap factor of the prototype filter design, K. In well-frequency-localized cases, $K = 4$ is commonly used, in which case the transmission burst is extended on both sides by 'tails' which have a length of almost two symbol intervals. In [6], the burst truncation effects for FBMC were investigated, and it was found that the burst tails can be truncated to the length of half of the symbol interval without severe impact on the IB and OoB effects.

In FC-FB implementation, the burst truncation effects are combined with the cyclic distortion effects, which cannot be avoided in computationally efficient implementation of FC processing. In [5] a precise linear periodically time-variant (LPTV) model was developed for overlap-save type FC processing. This model can be used for evaluating the IB and OoB interference effects. Also the burst truncation effects can be modeled as a LPTV system and, in case of FC-FB based waveform generation, this effect can be combined with the cyclic distortion model. Our approach to FC-FB design is based on optimizing directly the FFT-domain weight mask, utilizing the LPTV model. In this paper, we include the burst truncation model in the optimization. Generally, we explore the burst truncation effects in short burst transmission based time division multiple access (TDMA), highlighting the required guard-times between the bursts in order to control the time- and frequency-domain interference leakage effects.

In Section II, the FC-FB processing structure and the LPTV system model are briefly reviewed. In Section III, the used TDMA system model is explained, assuming asynchronous burst transmission, leading to uncertainty in the arrival times of different transmission bursts at the receiver. Then the combined LPTV model, including the burst truncation effect together with the cyclic distortion effect, is explained. In Section IV, numerical results and comparison of the power leakage characteristics of different FC-FB designs are provided. Finally, conclusions are drawn in Section V.

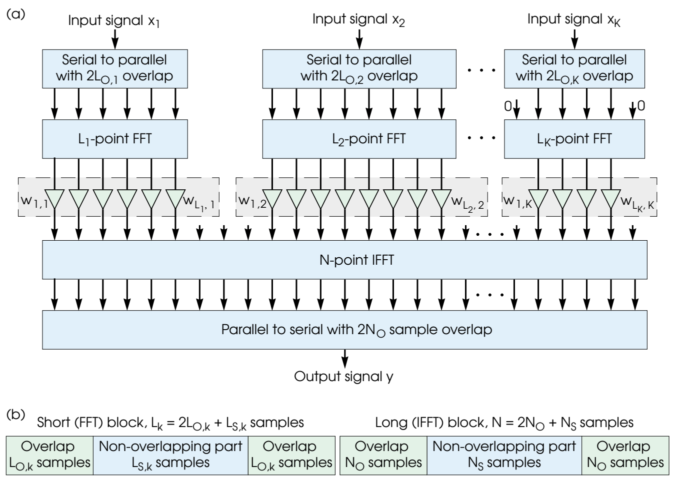

Fig. 1. (a) FC-based synthesis filter bank using overlap-save processing. (b) Notations used for the number of samples in overlap-save blocks.

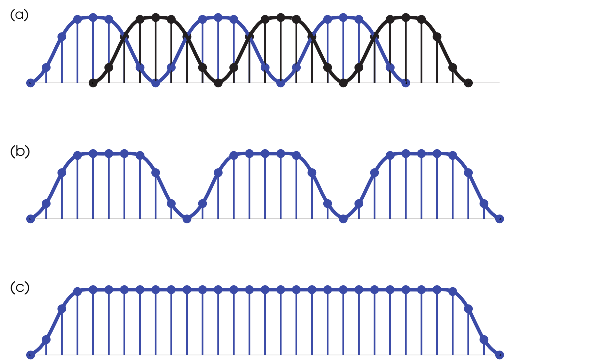

Fig. 2. Examples of FFT-domain weight masks for different waveforms which can be implemented using the FC-FB structure. (a) FBMC/OQAM type multiplex of six subchannels, (b) FMT type multiplex of three subchannels, and (c) single-carrier transmission channel.

II. Fast-Convolution Filter Banks

The main idea of the FC-based multirate filter banks is that a high-order filter can be implemented effectively through multiplication in frequency domain, after taking DFT's of the input sequence and the filter impulse response. The time-domain output signal is obtained by IDFT. In practice, efficient implementation techniques, like FFT/IFFT, are used for the transforms, and overlap-save processing is applied for processing long sequences. The application of FC to multirate filters has been presented in [7], and FC implementations of channelization filters have been considered in [8]–[10]. The authors have introduced the idea of FC implementation of nearly perfect-reconstruction filter bank systems and detailed analysis and FC-FB optimization methods are developed in [5]. These papers demonstrate the flexibility and efficiency of FC-FB in communication signal processing.

Figure 1 shows the structure of FC-based flexible synthesis filter bank, for a case where several narrowband signals with adjustable frequency responses and adjustable sampling rates are to be combined into high rate, wideband signal. It is assumed that the input signals are oversampled by the factor of two. We also note that different subbands may be overlapping. The dual structure of Fig. 1 can be used on the receiver side as an analysis bank for splitting wideband signal into multiple low-rate, narrowband signals. Figure 1 includes sampling rate increase by factors

$$R_k = N/L_k = N_S/L_{S,k} \tag{1}$$

where k is the subband index. In other words, the sampling rate conversion factor is determined by the FFT size, and can be configured for each subband individually. The FFT size determines the maximum number of frequency bins, i.e., the bandwidth of the subband. Based on (1), the input and output block lengths are related through the interpolation factor. The input and output block lengths have to exactly match, taking into account the sampling rate conversion factor. Consequently, it is required that $L_k/N = L_{S,k}/N_S$. We can see that the configurability of the input sampling rate depends greatly on the choice of N and N_S. Later discussions focus on uniform filter banks, and the subband index k is dropped for clarity.

There are two key parameters which have an effect on the spectral characteristics of the FC-FB scheme:

- The FFT (short transform) length L defines how well the filter frequency response can be optimized. Increasing the value of L helps to improve the stopband attenuation, because a higher number of frequency domain weights are used for shaping the transition bands.
- The overlap factor $1 - L_S/L$: In FC based multirate signal processing, there is a cyclic distortion effect. This effect can be reduced by increasing the overlap factor. But increased overlap means also higher computational complexity. The cyclic distortion disappears only with the maximum overlapping factor of $(L-1)/L$, which usually leads to quite high complexity.

In [5] these effects were analyzed using a periodically time-variant model for FC and effective tools for frequency response analysis and FC filter optimization were developed. It is also shown that the complexity of the FC-based filter banks is reduced when compared with the traditional polyphase implementations of FBMC [5].

Figure 2(a) shows an FBMC/OQAM type multiplex of six subchannels. The subchannel filters are defined by weight masks. The FFT length corresponds to the subchannel bandwidth whereas the subchannel spacing is half of the subchannel bandwidth (cf. Fig. 2(a)). Therefore, the subchannels are oversampled by two, which is also necessary for staggered, OQAM type subchannel processing. OQAM subcarrier signal model, in turn, is necessary for reaching (near) orthogonality of overlapping subcarriers in FB systems. The transition band shape should be of the square-root Nyquist filter type. The root-raised-cosine model can be used straightforwardly for constructing such transition bands. However, depending on the FC parameters, optimization of the weights may give significant improvement in the spectral characteristics [5]. Figures 2(b)–(c) highlight the flexibility of the FC-FB scheme by also showing weight masks for filtered multitone (FMT) and FB based single-carrier waveform generation. In all these cases, the same transition band weight values are utilized.

A. LPTV Model for FC-FB

Next we briefly review the LPTV model for FC-FB. The process applied to a single FC block can be modeled as a linear time-variant system that is described by a set of impulse responses $\tilde{h}_n[\eta]$, $n = 1, 2, \ldots, \Lambda$. Assume that the input signal is a complex exponential (tone) $x[n] = Ce^{j\omega n}$. Now the nth output sample can be obtained using convolution as follows

$$y[n] = \sum_{\eta} \tilde{h}_n[\eta]x[n-\eta] \tag{2a}$$

$$= Ce^{j\omega n} \sum_{\eta} \tilde{h}_n[\eta]e^{-j\omega\eta} = Ce^{j\omega n}\tilde{H}_n(e^{j\omega}) \tag{2b}$$

where $\tilde{H}_n(e^{j\omega})$ is the discrete-time Fourier transform of $\tilde{h}_n[\eta]$.

We can see that each output sample of a data block is multiplied by a complex coefficient which corresponds to the Fourier transform of corresponding equivalent impulse response at the frequency of the input tone. In general, these complex coefficients are different for different samples n within the output data block. Thus, for a single input tone, the cyclic distortion can be modeled as a modulation by a periodic sequence $\tilde{H}_n(e^{j\omega})$ which depends on target impulse response and the parameters of FC processing [5], [8], [11].

B. Frequency Response Calculation

Our FC filter bank design process is based on the FFT-domain model of the lowpass prototype filter, in terms of the weight coefficients. This model leads to the minimum number of free parameters in the optimization. The definition of frequency response is based on the total interference at a subband output due to a tone at the analysis filter bank input. Based on the multirate FC processing model presented above, the process for evaluating the frequency response can then be summarized as follows [5]:

1) Assume that N, L, and L_S are given, together with L frequency-domain weight values.
2) Calculate the ideal linear time-invariant filter impulse response $h[\eta]$ using IFFT.
3) Construct $\tilde{h}_n[\eta]$ for the selected set of L_S resampling phases $n \in \Lambda$.
4) Calculate $\tilde{H}_n(e^{j\omega_i})$ using FFT for $n \in \Lambda$ and for the set of frequencies $\omega_i \in \Omega$ used in the analysis or design.
5) Calculate the total interference values for the used set of frequencies. For stopband tones (Ω_s), we calculate the total interference, containing both the regular aliased signal power and modulated tones:

$$I_s(\omega_i) = \frac{1}{L_S} \sum_{n\in\Lambda} |\tilde{H}_n(e^{j\omega_i})|^2 \quad \text{for } \omega_i \in \Omega_s. \tag{3}$$

For passband tones (Ω_p), the gain experienced by the tone is given by

$$g(\omega_i) = \frac{1}{L_S} \sum_{n\in\Lambda} \tilde{H}_n(e^{j\omega_i}) \quad \text{for } \omega_i \in \Omega_p \tag{4}$$

and the interference due to modulated tones is given by

$$I_p(\omega_i) = \frac{1}{L_S} \sum_{n\in\Lambda} |\tilde{H}_n(e^{j\omega_i}) - g(\omega_i)|^2 \quad \text{for } \omega_i \in \Omega_p. \tag{5}$$

In the basic FC-FB design process, at Step 3, the impulse responses $\tilde{h}_n[\eta]$ are derived from the cyclic convolution model. The effect of burst truncation can be included in these impulse responses, together with cyclic distortion effects, as described below. It can also be noted that the LPTV model can be used also for analyzing the effects of burst truncation in traditional polyphase implementations of FBMC.

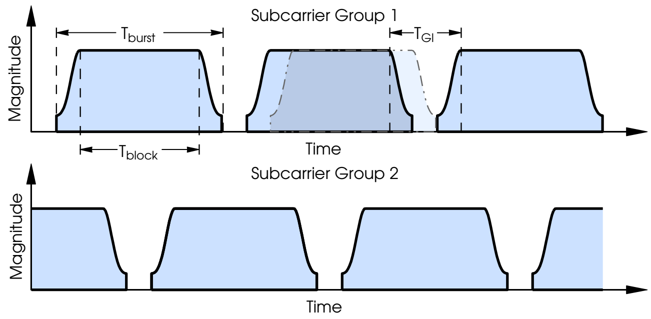

Fig. 3. Illustration of asynchronous TDMA transmission bursts in different groups of subcarriers.

III. FBMC Burst Truncation

In traditional polyphase implementation, the overlap factor of the prototype filter design, K, determines the impulse response length as $L_{\text{proto}} = KL_{\text{symb}}$, where L_{symb} is the multicarrier symbol interval in samples. Due to the OQAM signal model, the overall FBMC symbol length becomes $L_{\text{tot}} = KL_{\text{symb}} + L_{\text{symb}}/2$. In well-frequency-localized cases, $K = 4$ is commonly used [6], in which case the transmission burst is extended on both sides by 'tails' which have the length of $L_{\text{tail}} = (L_{\text{tot}} - L_{\text{symb}})/2 = (2K-1)L_{\text{symb}}/4 = 1.75L_{\text{symb}}$.

In [6], the burst truncation effects for FBMC/OQAM with the traditional polyphase implementation structure were investigated, and it was found that the burst tails can be truncated to the length of $0.5L_{\text{symb}}$, while the inband (IB) interference remains below 40 dBc and out-of-band (OoB) spectral leakage remains below 50 dBc, measured at the second subcarrier from the edge of an active group of subcarriers.

In this section we will evaluate the burst truncation effects in FC-FB implementation of FBMC/OQAM, considering alternative FC-FB designs, including novel optimized designs based on combining the cyclic distortion and burst truncation effects in the LPTV model. This combination can be expressed in a simple way, using the following LPTV impulse response model:

$$\hat{h}_n[\eta] = w_{\text{trunc}}[n] \cdot \tilde{h}_n[\eta], \tag{6}$$

where $w_{\text{trunc}}[n]$ is the used truncation window. In the numerical results, a rectangular window corresponding to the truncated tail length is used, but the model applies for arbitrary transmission block level windowing.

We examine the burst truncation effects in case of asynchronous system with both TDMA and FDMA elements, and having in mind an LTE uplink -like parametrization and frame structure. It is assumed that different users are transmitting blocks of FBMC/OQAM type multicarrier symbols in different groups of subcarriers without precise time alignment, as illustrated in Figure 3. We consider also the possibility that the turn-over periods are not aligned in adjacent groups of subcarriers. Therefore it is important to control the power leakage to adjacent subcarriers also during the turn-over period. In FC-FB based receiver processing, it is possible to effectively compensate the timing offsets of the received data blocks [12]. It is also possible to effectively compensate the possible carrier frequency offsets of different users [13], but this element is not included in the following discussions.

In this transmission scenario, three different kinds of interference effects will be considered:

- Inband interference, which is due to (i) non-perfect reconstruction nature of the filter bank, (ii) cyclic distortion due to FC implementation, and (iii) burst truncation.
- Out-of-band power leakage due to (i) imperfect frequency localization of the ideal linear filter bank, (ii) cyclic distortion, and (iii) burst truncation.
- Time-domain power leakage between consecutive transmission bursts due to the impulse response tails, and depending on the FC-FB design and burst truncation effects.

It can be mentioned that in the considered uplink transmission case, overlap of the burst tails with the data blocks is possible and tolerable, if the interference level is small enough. However, burst truncation may help to reduce the interference and also reduce the complexity because generating the burst tails fully may require higher number of FC processing blocks per transmission burst.

The main parameters affecting the three types of interference leakage are: (i) Initial FC-FB design, (ii) truncation length of the burst tails, and (iii) guard interval between transmission bursts. Experiments with smooth, raised-cosine -shaped truncation confirmed the conclusions of [6] that hard truncation with rectangular window gives the best results in the considered cases.

IV. Numerical Results

In our case study, we use parameters similar to the 5 MHz 3GPP LTE system [1]: 512 subcarriers, out of which 300 are active, and 15 kHz subcarrier spacing is used. For the FC-FB based FBMC/OQAM solution, we choose $L = 16$ and $L_S = 10$, which has been found to provide a good tradeoff between implementation complexity and performance. The long transform length becomes $N = 4096$. The transmission block length is 15 symbols, i.e., 30 subcarrier samples. The results are shown by averaging the interference power over 100 isolated transmission blocks, i.e., the time-domain leakage effect is not directly included in the figures.

Figures 4(a)–(b) show the results when the tail is truncated to the length of 768 samples, which corresponds to 1.5 symbol intervals. These results are shown for the case where the FFT-domain weights are calculated directly from the square root raised cosine (RRC) function and for the case where the weights are optimized without burst truncation effects. These figures show mean-squared error (MSE) in the transmitted symbols, characterizing the inband interference. Also the active subcarrier power level is shown. Outside the transmission block of 30 samples, this curve represents the worst-case time-domain power leakage between time-adjacent transmission blocks. If the consecutive transmission blocks are perfectly synchronized (i.e., the time difference is a multiple of half-symbol interval), the time-domain power leakage becomes very small.

The OoB power leakage is shown in the same figures for 2nd, 4th, and 10th subcarrier from the group of active subcarriers. In uplink transmission, one-subcarrier guardband is assumed between different users' active subcarrier carrier groups. Consequently, the 2nd subcarrier in Figs. 4(a)–(b) represents the case where the frequency-domain power leakage is strongest. From these figures we can see that no transients in the interference effects are seen at the beginning and end of the transmission block. However, the cyclic distortion effect is increased towards the ends of each FC processing block of $L_S = 10$ samples, which is the cause of the periodicity of the interference patterns. We can also notice that optimized design has significantly lower IB and OoB interference levels than the direct RRC design. With higher time differences, the time-domain power leakage is also significantly lower in the optimized design.

Figures 5(a)–(c) show the corresponding results when the burst tails are truncated to 256 samples, i.e., half of the symbol interval. Here also the optimized FC-FB design taking into account the burst truncation effect is included. Again, both optimized designs have significantly reduced inband interference compared to the direct RRC case. Burst truncation in the RRC case increases the OoB interference over the whole transmission block, while in the optimized cases, OoB interference transients are introduced around the burst truncation instances. When the burst truncation effect is included in the optimization, the transients are reduced by about 4 dB, 7 dB, and 9 dB in the 2nd, 4th, and 10th subcarrier, respectively. Also the time-domain power leakage is reduced in the 2nd and 3rd subcarrier sample outside the transmission block by about 2.5 dB and 5 dB, respectively.

Concerning the guard-time between consecutive transmission blocks we can conclude the following:

- When the guard-time is equal to the half-symbol interval, the time-domain power leakage corresponds to the second subcarrier sample outside the transmission block, and the power leakage is $-20\ldots-24$ dBc depending on the design.
- When the guard-time is equal to the symbol interval, the time-domain power leakage corresponds to the third subcarrier sample outside the transmission block, and the power leakage is $-25\ldots-35$ dBc depending on the design.
- When the guard-time is equal to 1.5 times the symbol interval, the time-domain power leakage corresponds to the fourth subcarrier sample outside the transmission block, and the power leakage is $-35\ldots-45$ dBc depending on the design.

In asynchronous uplink transmission, the unpredictability of the arrival times of the transmission bursts should be taken into consideration. As an example, if the time delay variation is $\pm 0.25 T_{\text{symb}}$, where T_{symb} is the symbol duration, then the frame structure could be designed for the target guard interval of $1.5 T_{\text{symb}}$, in which case the shortest actual guard interval would be T_{symb} and the time-domain power leakage would be below -35 dBc with proper FC-FB design.

V. Concluding Remarks

Truncation of the bursts in short burst based multiple access or duplexing schemes utilizing FBMC/OQAM waveform introduces transients in the inband interference and out-of-band radiation characteristics. In fast convolution (FC) based implementation of FBMC/OQAM, these effect can be reduced by utilizing the proposed optimization method combining the cyclic distortion and burst truncation effect in the linear periodically time-variant model of overlap-save FC processing. Significant gains are obtained in terms of interference level reduction through the proposed optimization method. The cost function used in the optimization was the total interference power in the second OoB subcarrier during the first (or last) FC block. In our future work, the goal is to modify the

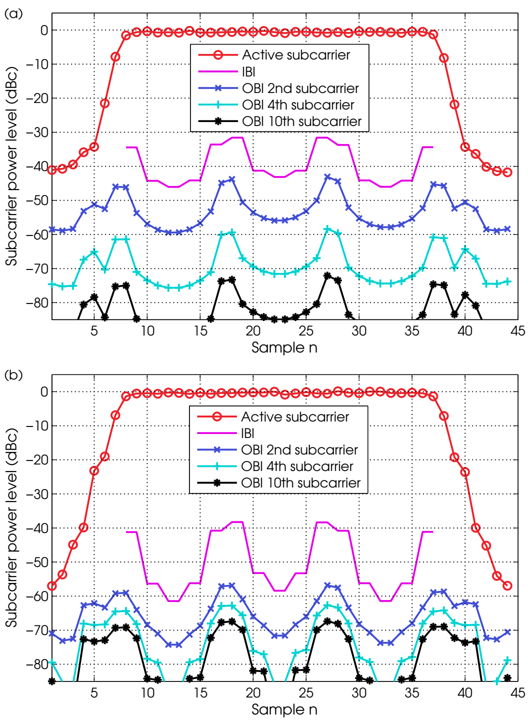

Fig. 4. Interference effects in FC-FB implementation of FBMC/OQAM when the burst tails are truncated to 1.5 times the multicarrier symbol interval. The active subcarrier samples are in the index range $[8 \ldots 37]$. (a) Direct RRC design. (b) Optimized design.

optimization process for more generic cost functions, in order to make a balanced tradeoff between different interference effects, depending also on the application scenario. Another topic is the application of LTPV model for optimized burst truncation in case of polyphase FB based FBMC waveforms.

Acknowledgment

The authors acknowledge the financial support by the European Union FP7-ICT project EMPhAtiC (http://www.ict-emphatic.eu) under grant agreement no. 318362.

References

[1] A. Toskala and H. Holma, Eds., *LTE for UMTS - OFDMA and SC-FDMA Based Radio Access*. Wiley, 2009.

[2] FP7-ICT Project PHYDYAS – Physical Layer for Dynamic Spectrum Access and Cognitive Radio. http://www.ict-phydyas.org.

[3] P. Siohan, C. Siclet, and N. Lacaille, "Analysis and design of OFDM-OQAM systems based on filterbank theory," *IEEE Trans. Signal Processing*, vol. 50, no. 5, pp. 1170–1183, May 2002.

[4] B. Farhang-Boroujeny and R. Kempter, "Multicarrier communication techniques for spectrum sensing and communication in cognitive radios," *IEEE Commun. Mag., Special Issue on Cognitive Radios for Dynamic Spectrum Access*, vol. 46, no. 4, pp. 80–85, Apr. 2008.

[5] M. Renfors, J. Yli-Kaakinen, and F. Harris, "Analysis and design of efficient and flexible fast-convolution based multirate filter banks," *IEEE Trans. Signal Processing*, vol. 62, no. 15, pp. 3768–3783, Aug. 1 2014.

[6] M. Bellanger, M. Renfors, T. Ihalainen, and C. A. F. da Rocha, "OFDM and FBMC transmission techniques: A compatible high performance proposal for broadband power line communications," in *IEEE Int. Symp. Power Line Communications and Its Applications (ISPLC)*, Rio de Janeiro, Brazil, Mar. 2010, pp. 154–159.

[7] M. Borgerding, "Turning overlap-save into a multiband mixing, downsampling filter bank," *IEEE Signal Processing Mag.*, pp. 158–162, Mar. 2006.

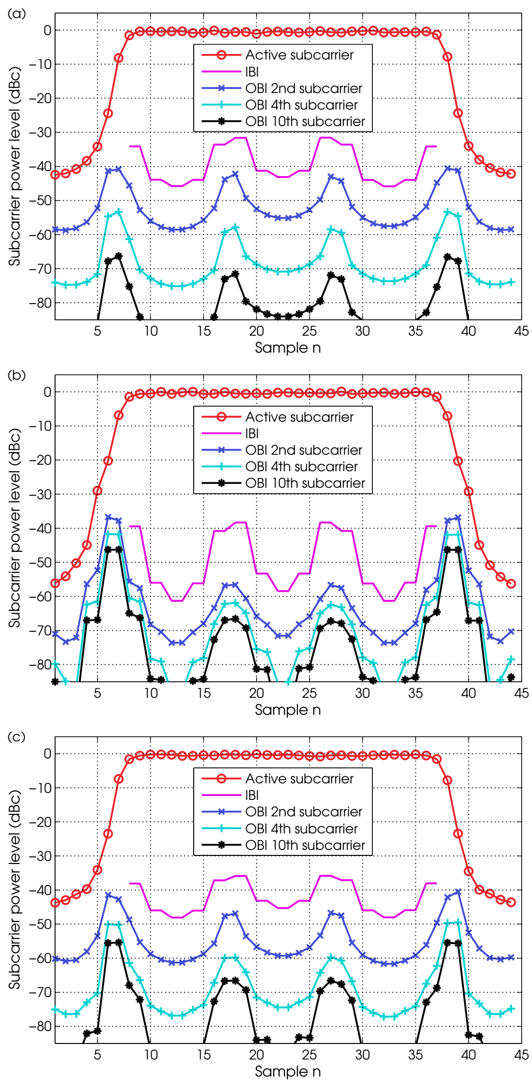

Fig. 5. Interference effects in FC-FB implementation of FBMC/OQAM when the burst tails are truncated to half of the multicarrier symbol interval. (a) Direct RRC design. (b) Optimized design without including burst truncation in the LPTV model. (c) Optimized design including burst truncation in the LPTV model.

[8] M.-L. Boucheret, I. Mortensen, and H. Favaro, "Fast convolution filter banks for satellite payloads with on-board processing," *IEEE J. Select. Areas Commun.*, vol. 17, no. 2, pp. 238–248, Feb. 1999.

[9] C. Zhang and Z. Wang, "A fast frequency domain filter bank realization algorithm," in *Proc. Int. Conf. Signal Processing*, vol. 1, Beijing, China, Aug. 21–25 2000, pp. 130–132.

[10] L. Pucker, "Channelization techniques for software defined radio," in *Proc. Software Defined Radio Technical Conference (SDR'03)*, Orlando, FL, USA, Nov. 18–19 2003.

[11] G. Tohumoğlu, "Analysis of periodically time-varying discrete-time systems in spectral domain," *Applied Mathematics and Computation*, vol. 162, no. 3, pp. 1151–1165, Mar. 2005.

[12] M. Renfors and J. Yli-Kaakinen, "Timing offset compensation in fast-convolution filter bank based waveform processing," in *Proc. Int. Symp. Wireless Communication Systems (ISWCS 2013)*, Ilmenau, Germany, Aug. 2013.

[13] J. Yli-Kaakinen and M. Renfors, "Multi-mode filter bank solution for broadband PMR coexistence with TETRA," in *Proc. European Conf. on Networks and Communications*, Bologna, Italy, Jun. 2014.