Multi-Mode Filter Bank Solution for Broadband PMR Coexistence with TETRA

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***Abstract*—Fast convolution processing has recently been proposed as an efficient means for implementing filter bank multi-carrier systems with good spectral containment and high flexibility in tuning the subchannel bandwidths and center frequencies. These features make fast convolution filter banks (FC-FBs) a particularly interesting choice for multi-carrier transmission in challenging radio scenarios like dynamic spectrum access, cognitive radio, and fragmented spectrum use. In this contribution, the target is to study the performance of the FC-FB approach in heterogeneous radio environment. The focus is on the use of FC-FB for simultaneous processing of FB multi-carrier waveforms and narrowband TETRA signals.**

I. INTRODUCTION

Multicarrier modulation offers most of the key elements needed in the challenging new spectrum use scenarios, like opportunistic dynamic spectrum access, cognitive radio, and heterogeneous wireless system coexistence. Characteristic to these situations is the need to adjust the spectral characteristics of the transmitted signal, notably bandwidth and center frequency, to the available unused slots of radio spectrum. To support high data rates, it is often desirable to combine multiple non-contiguous spectrum slots in the transmission. In multicarrier systems, this can be achieved by activating only those subcarriers that are within the available frequency slots. One important example case of such fragmented spectrum use is the high data rate services to be developed for the Professional Mobile Radio (PMR). Currently, PMR supports voice and narrowband data services, based on the family of terrestrial trunked radio (TETRA) standards.

Orthogonal frequency-division multiplexing (OFDM) is extensively utilized in modern broadband radio access systems [1]. However, OFDM has major limitations in the mentioned co-existence scenarios, i.e., spectral inefficiency due to the requirement for using the guard intervals, high sensitivity to frequency offsets, and bad spectral containment which leads to high sensitivity to interferences from asynchronous spectral components in fragmented spectrum use. A more sophisticated multi-carrier scheme that has been shown to constitute an attractive alternative to OFDM is offered by the filter bank (FB) based methods of waveform processing and channelization filtering [2], commonly referred to as filter bank-based multi-carrier (FB-MC) [3]. In filter bank based implementations, it is possible to combine both functions such that the waveforms generated for transmission are spectrally well-contained and on the receiver side the filter bank processing is able to suppress the interferences from adjacent spectral components. 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 and nonlinearity of the active stages of the receiver chain, as well as I/Q imbalance effects on both sides [4].

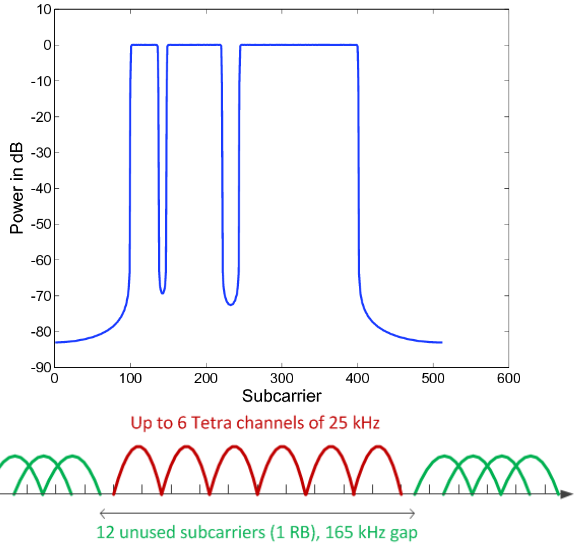

Fig. 1. Heterogeneous spectrum use scenario with narrowband TETRA signals in spectral gaps of a non-contiguous FB-MC waveform.

A relatively widely studied filter bank-based waveform is FBMC/OQAM (filter bank multi-carrier/offset-QAM, more commonly known as OFDM/OQAM) [5], [6]. While reaching high spectral containment, it keeps many of the important features of OFDM. Even though FBMC/OQAM has its limitations in terms of conceptual and implementation complexity and difficulties with certain multiantenna (MIMO) transmission schemes, it has received increasing interest in the mentioned challenging spectrum use scenarios. A particularly flexible and effective scheme for FBMC/OQAM implementation, based on fast-convolution processing, has been recently introduced by the authors in [7]–[9]. In this contribution, the target is to elaborate further fast convolution filter bank (FC-FB) design for the broadband PMR (B-PMR) application in heterogeneous radio environment. The general idea is illustrated in Fig. 1. We focus on the use of FC-FB for simultaneous processing of FB-MC waveforms and narrowband TETRA signals. An important tool for achieving this is provided by a new method for adjusting the center frequencies of FC-FB subcarriers, which is presented in Section III. Then in Section IV, the joint processing scheme for TETRA and B-PMR is presented. In

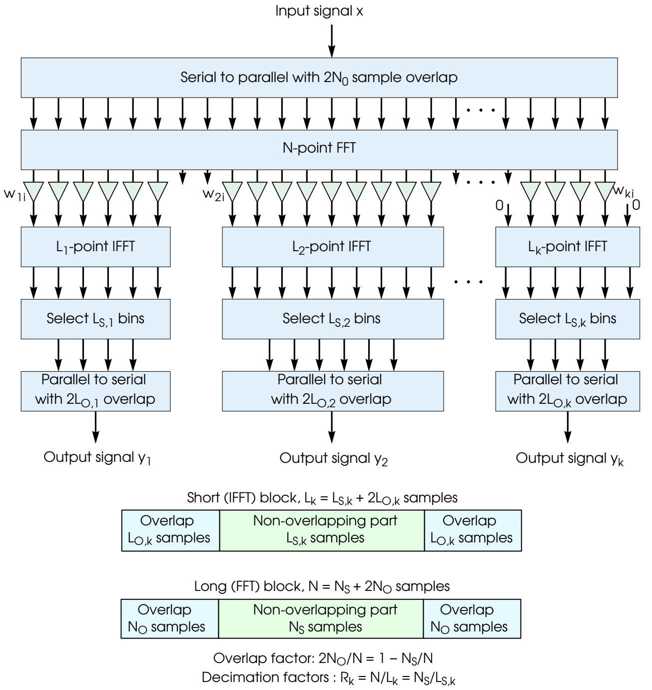

Fig. 2. Fast convolution based flexible analysis filter bank using overlap-save processing. In this structure, the decimation factor of subchannel k is equal to the ratio of the FFT length and IFFT length.

Section V, the spectral leakage effects between TETRA and B-PMR channels is evaluated through simulations.

II. FAST-CONVOLUTION FILTER BANKS

The basic idea of fast convolution 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. Eventually, the time-domain output is obtained by IDFT. Commonly, efficient implementation techniques, like FFT/IFFT, are used for the transforms, and overlap-save processing is adopted for processing long sequences. The application of FC to multirate filters has been presented in [10], and FC implementations of channelization filters have been considered in [11]–[13]. The authors have introduced in [7] the idea of FC-implementation of nearly perfect-reconstruction filter bank systems and detailed analysis and FC-FB optimization methods are developed in [8], [14]. The timing offset compensation in FC processing is demonstrated in [15] whereas FC-FB based transmission scheme of the FBMC/OQAM type with the main parameters of the 5 MHz LTE system is developed in [9]. These papers demonstrate the greatly increased flexibility and efficiency of FC-FB in communication signal processing, in comparison with the commonly used polyphase implementation structure.

The overlap-save processing of fast-convolution analysis filter bank is represented in Fig. 2. We consider a case where the incoming high-rate, wideband signal is to be split into several narrowband signals with adjustable frequency responses and possibly also adjustable sampling rates. We are interested in cases where the output signals are oversampled by a small factor, typically two. We also note that different subbands may be overlapping. The dual structure of Fig. 2 can be used for combining multiple low-rate, narrowband signals into a single wideband signal, following the frequency-division multiplexing principle.

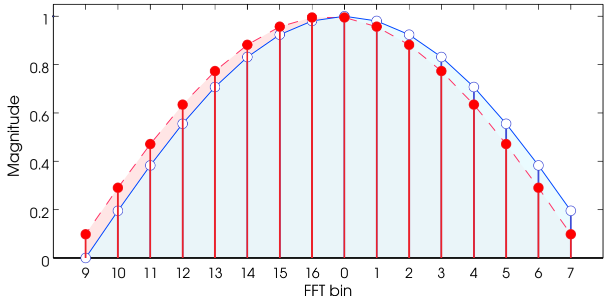

Fig. 3. Subchannel center frequency shifting by FFT-domain weight adjustment. Solid envelope corresponds to original non-shifted weights whereas dashed envelope corresponds to shifted ones obtained using the linear interpolation.

In FC processing, the subchannel bandwidths and center frequencies can be independently tuned, with the resolution of the FFT bin spacing. Different types of multiplexes (FBMC/OQAM, filtered multitone (FMT), or single carrier) can be combined in a single FC-FB structure. It is also possible to use different transition band shapes for different multiplexes, if so desired. The flexibility of the scheme can be used also for coarse frequency offset compensation by shifting the set of frequency bins connected to the subchannel processing functions.

III. PULSE SHAPING AND CHANNELIZATION FOR NARROWBAND TETRA SIGNAL

The basic TETRA waveform uses differential BPSK or QPSK modulation with square root raised cosine (RRC) type pulse shaping with the roll-off of 0.35, symbol rate of 18 kHz and channel bandwidth of 25 kHz. Such pulse shaping filtering can naturally be implemented, both in the transmitter and receiver sides, using multirate fast-convolution filtering, or FC-FB filter bank in cases where multiple signals are to be processed simultaneously. In heterogeneous environment, there might also be a benefit to implement the TETRA pulse shaping and B-PMR processing with the same FC-FB platform. The parameterization of the FC-FB system to accommodate both TETRA and LTE like B-PMR systems is not straightforward. However, these limitations are greatly alleviated by the possibility of fine-tuning the subchannel center frequencies beyond the resolution provided by the FFT bin spacing of the FC-FB. This method is proposed for carrier frequency offset compensation in the EMPhAtiC deliverable D3.2 [16], where it is discussed in some more details. The idea is illustrated in Fig. 3. Linear interpolation based calculation of the new weight coefficients was found to be sufficient for most purposes. But if only a small number for frequency shifts are needed, more optimized designs can be obtained and stored in the memory of the implementation platform.

When considering the FC-FB implementation of the TETRA pulse shaping, it is necessary to consider its compatibility with traditional time-domain implementations, which

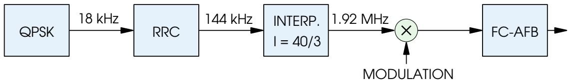

Fig. 4. Simulation model for evaluating the compatibility of the FC-FB approach with the traditional time-domain implementation.

TABLE I. MSE LEVELS BETWEEN TRANSMITTED AND RECEIVED SEQUENCES FOR FC DESIGNS

Overlap factor	Shift	RRC design	Optimized design
0.25	0	−36.2 dB	−39.4 dB
	1/3	−34.9 dB	−37.1 dB
0.5	0	−40.6 dB	−48.8 dB
	1/3	−39.9 dB	−40.8 dB

would be used by most of the devices anyway. Next we evaluate the compatibility, as well as the performance of the center frequency tuning method through numerical results. For time-domain pulse shaping, an RRC filter of order 128 and interpolation factor of 8 is designed using the Matlab function *firrcos*. It is combined with an FIR interpolation filter to reach the needed sample rate for the FC-FB processing. The quality of pulse shaping is characterized by the mean-squared error (MSE) between transmitted and received sequences. QPSK modulation is used in simulations with ideal noise-free channel.

For FC-FB, we consider a design with FFT bin spacing of 1.5 kHz. The IFFT (short transform) length for 2×-oversampled subchannel signals is $L = 24$, and the 25 kHz bandwidth corresponds to about 16 FFT bins. We consider two FC-FB overlap factors (see Fig. 2 for details), $12/24 = 0.5$ and $6/24 = 0.25$. A straightforward way to obtain the FFT-domain weights for TETRA channels is to calculate the FFT weights directly from the RRC function with the roll-off of 0.35. Alternatively, the numerical optimization methods introduced in EMPhAtiC Deliverable D2.1 [17] can be used for maximizing the minimum stopband attenuation.

Figure 5 shows the MSE characteristics of different designs. Table I shows the resulting MSE levels for cases where the FC decimator is used together with the time-domain interpolator. The MSE levels are given for both overlap factors (0.5 and 0.25). In addition, we consider two cases for the subchannel frequency shift. In the first case, the frequency shift is zero, whereas in the second case, the subchannel is shifted by one third of the FFT bin spacing. The MSE level for the corresponding reference time-domain decimator (i.e., cascade of time-domain interpolation and decimation filters) is −51 dB. It can be seen that the optimization gives a clear improvement in the MSE level, but in all the considered cases the interference is small enough and would not have an effect on the link performance in practice.

IV. BROADBAND PMR-TETRA COEXISTENCE SCENARIO

We are considering LTE-like parameterization for the FBMC/OQAM based B-PMR. The subcarrier spacing is 15 kHz and subcarriers are allocated to different users in resource blocks of 12 subcarriers. The TETRA channel spacing is 25 kHz, and there may be an offset of the channel raster, as a multiple of 6.25 kHz. Figure 6 illustrates the situation assuming that the B-PMR and TETRA channel edges coincide at the lower edge of the frequency band. We can see the picture as repetitions of 75 kHz frequency blocks consisting of three TETRA channels or five B-PMR subchannels. However, within the 180 kHz resource blocks (shown using the hatched background in Figs. 6(a) and (c)), the structure is repeated only with 900 kHz spacing. As seen in Fig. 6(c), a single unused resource block between two active ones contains a spectral gap of 165 kHz, which may contain five or six TETRA channels.

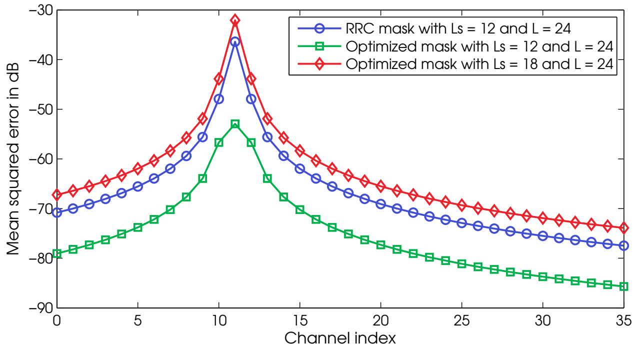

Fig. 5. Comparison of direct RRC and optimized filtering masks for TETRA pulse shaping. Mean-squared error between the transmitted and received sequences in FC-FB transmultiplexer configuration with one active channel in index 11 ($N = 1280$, $L = 24$, and $L_s = 12$ or $L_s = 18$).

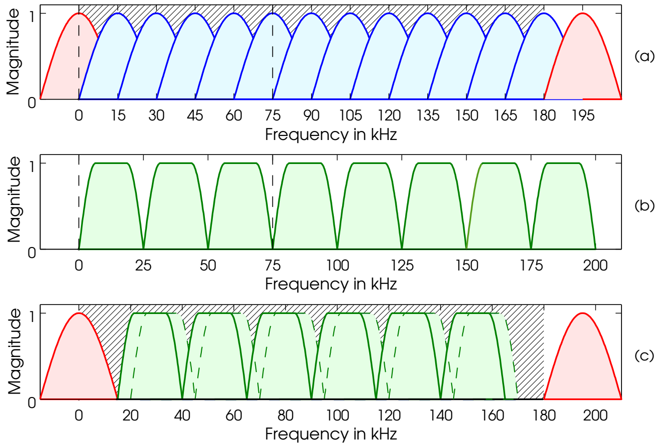

Fig. 6. (a) One resource block containing 12 B-PMR subcarries with 15 kHz subcarrier spacing. (b) TETRA channels with 25 kHz channel spacing. (c) 165 kHz gap between two active B-PMR resource blocks containing six TETRA channels. The additional guardbands next to the active B-PMR resource blocks depend on the location of the resource block.

It is desirable that the B-PMR and TETRA symbol rates, 15 kHz and 18 kHz, are both multiples of the FFT bin spacing. The feasible values for spacing are 1.5 kHz or 1 kHz. The latter one leads to considerably longer transform lengths, so we focus on using the 1.5 kHz FFT bin spacing. The short transform length for B-PMR is 20 and for the TETRA it is 24. The overlapping factor should be the same for both systems, so the possible choices are $10/20 = 12/24 = 0.5$ or $5/20 = 6/24 = 0.25$. The distance of the TETRA channel center frequencies from the lower edge of the frequency band are 12.5 kHz, 37.5 kHz, 62.5 kHz, etc. We can see that the distance from the TETRA channel center frequency to the closest FFT bin is 0 or ±1/3 kHz. Then it would be sufficient to have two sets of optimized weighting coefficients, since the cases with +1/3 kHz and −1/3 kHz shifts use reversed sets of coefficients.

V. NUMERICAL SIMULATIONS

We have tested the spectral leakage effects in both directions between TETRA and B-PMR systems. Figure 7 shows the results for the FC-FB configuration which allows simultaneous processing of both B-PMR and TETRA, i.e., with the long transform length $N = 1280$, short transform length $L = 20$, and overlapping block length $L_s = 10$. There are two TETRA channels in a one resource block wide gap of the B-PMR spectrum. Both TETRA channels are at the minimum distance to the closest active B-PMR subchannels, i.e., the distance of the center frequencies is 7.5 kHz +12.5 kHz. This is a special worst-case test configuration, since with the actual TETRA channel raster, there would be wider guardband on either or both sides of the gap.

The results are shown for the cases where the TETRA channel has the same power level as the B-PMR subcarriers, as well as for the case where the TETRA channels are at a 30 dB higher power level. The simulation is for ideal, noise-free channel. The total interference at each active subcarrier is measured, so it includes the interference due to the FC-FB implementation of the B-PMR transmitter and receiver, as well as the leakage from the TETRA channels. With 0 dB relative TETRA power level, the interference is below −46 dB in all B-PMR subcarriers. With +30 dB relative TETRA power level, the interference is at about −26 dB at the edge subcarriers and clearly below −30 dB in other subcarriers. Thus the performance can be considered to be sufficient even when the TETRA channels are at such a high power level. In practice, the limitations would be mostly due to the imperfections of the analog RF circuitry. Figure 8 show similar results for the overlapping block length of $L_s = 15$. The effect of smaller overlapping factor is clearly visible with lower TETRA power levels, but it might be considered sufficient from this perspective.

Figures 9 and 10 show the spectrum leakage effects in the opposite direction, i.e., from TETRA channels to B-PMR subchannels when the TETRA pulse shaping is implemented using FC-FB. The interference is measured in six simultaneously active TETRA channels in one resource block wide gap of B-PMR. Again, TETRA channels closest to the edges of the gap are at minimum distance from the active B-PMR subcarriers. When the TETRA channels are at the same power level as the B-PMR subcarriers, the signal-to-interference ratio (SIR) of TETRA channels is over 39 dB with the higher overlapping factor and over 34 dB with the smaller overlapping factor. When the TETRA channels are at −20 dB relative power levels, the corresponding SIR values are 27 dB and 21 dB.

VI. CONCLUSIONS

In this contribution, the performance and the feasibility of the FC-FB approach is demonstrated in heterogeneous radio environment. It is shown that this approach can be used for simultaneously processing FB multicarrier waveforms and narrowband TETRA signals with good reachable levels of attenuation. An efficient tool for adjusting the center frequencies of the FC-FB subcarriers is also proposed.

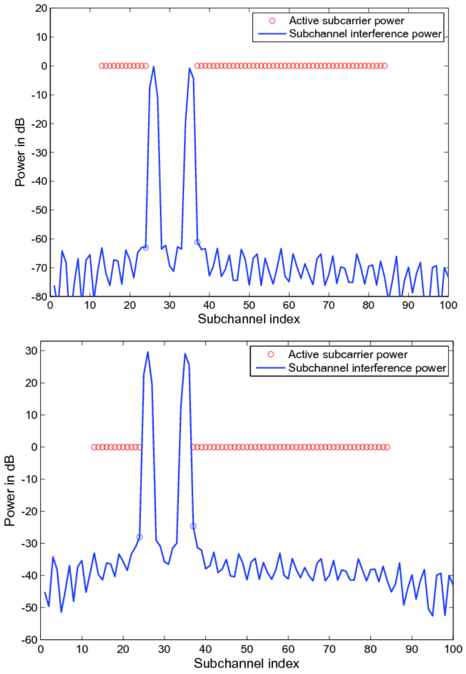

Fig. 7. Interference leakage from two TETRA channels to B-PMR subchannels for new FC-FB receiver configuration ($N = 1280$ and $L = 20$) with $L_s = 10$. The TETRA channels are at the minimum distance to the active B-PMR subchannels and at the power level of (a) 0 dB (b) +30 dB with respect to the B-PMR subcarriers.

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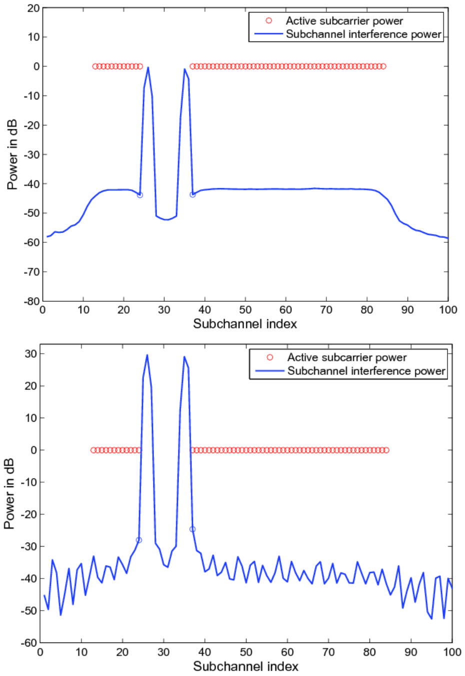

Fig. 8. Interference leakage from two TETRA channels to B-PMR subchannels for new FC-FB receiver configuration ($N = 1280$ and $L = 20$) with $L_s = 15$. The TETRA channels are at the minimum distance to the active B-PMR subchannels and at the power level of (a) 0 dB (b) +30 dB with respect to the B-PMR subcarriers.

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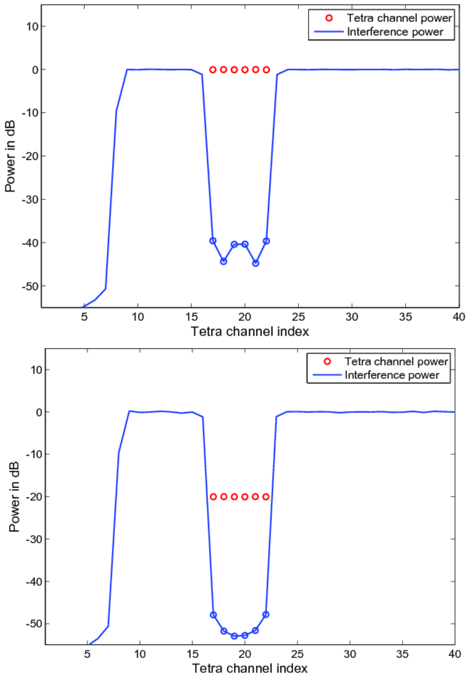

Fig. 9. Interference leakage from active B-PMR subchannels to TETRA channels for the proposed TETRA FC-FB receiver configuration ($N = 1280$, $L = 24$, and $L_s = 12$). The first and last TETRA channels are at the minimum distance to the active B-PMR subchannels. (a) TETRA and B-PMR subchannels at the same power level. (b) TETRA at 20 dB lower power level.

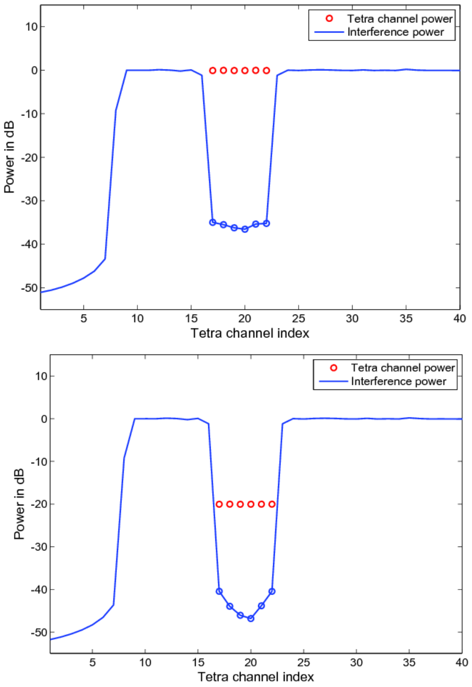

Fig. 10. Interference leakage from active B-PMR subchannels to TETRA channels for the proposed TETRA FC-FB receiver configuration ($N = 1280$, $L = 24$, and $L_s = 18$). The first and last TETRA channels are at the minimum distance to the active B-PMR subchannels. (a) TETRA and B-PMR subchannels at the same power level. (b) TETRA at 20 dB lower power level.