On Spectral Shaping of Multicarrier Waveforms Employing FIR-Filtering and Active Interference Cancellation

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Abstract—For next generation wireless communication systems (also referred to as “5G”), many advanced multicarrier waveform techniques have recently been proposed to enhance the system performance beyond today’s most prominent multicarrier technique, namely, orthogonal frequency division multiplexing (OFDM). Despite several advantages of OFDM, its less pronounced frequency localization property and considerable out-of-band (OOB) emissions make it less suited for many applications in 5G such as massive machine communications and Internet of Things. In order to reduce the high OOB emissions, novel multicarrier modulation techniques like universal filtered multicarrier (UFMC) and generalized frequency division multiplexing (GFDM) employing improved pulse shaping are currently being investigated. An important aspect is “spectral shaping”, i.e., generating spectral notches in OFDM signals, as already explored in the past for applications in ultra-wideband (UWB) systems. In this paper, we compare the effectiveness of suppressing OOB emissions employing FIR-filtering and active interference cancellation (AIC), respectively, in the context of 5G scenarios. Moreover, we propose a novel scheme to combine AIC and FIR-filtering into one multicarrier transmission system, i.e., UFMC with AIC. The simulation results show that the proposed AIC algorithm for UFMC reduces OOB emissions more effectively and introduces less spectral overshoot compared to the conventional method while hardly increasing computational complexity.

I. INTRODUCTION

With the rollout of future applications such as Internet of Things (IoT) and tactile Internet, different technical challenges, e.g., higher data rate, spectral efficiency, supported number of devices, relaxed synchronization and lower latency, have to be mastered in the upcoming 5G (5G) wireless communication network [1]. It is believed that 5G will be a major paradigm shift compared to the current Long Term Revolution (LTE) design based on synchronicity and orthogonality [2]. Disruptive technologies in all layers are required to realize the manifold improvements. The information-bearing waveform of the physical channel plays a primary role in communication systems. Orthogonal frequency division multiplexing (OFDM) in conjunction with a cyclic prefix (CP) is the waveform choice of many standards, e.g., LTE and various wireless LAN standards, because of its simplicity and efficiency. One of the main well-known drawbacks of OFDM is the high out-of-band (OOB) emission (“sin (x)/x” spectrum), which makes it sensitive to synchronization errors.

To enhance the system performance of OFDM, and in order to support a wider range of traffic types, other multicarrier waveforms based on filtering approaches have recently been studied in the context of 5G. Filterbank based multicarrier (FBMC) dates back to the 1960s [3] [4]. It applies frequency-well localized pulse shaping per subcarrier, thus generating very low OOB emissions. However, typically long filters spanning the length of several multicarrier symbols are required. Generalized frequency division multiplexing (GFDM) employs circular pulse shaping for each subcarrier within a block consisting of several multicarrier symbols. It allows flexibility in OOB emissions and spectral efficiency. However, a more complex receiver is required compared to OFDM [5]. Universal filtered multicarrier (UFMC) utilizes much shorter filters (comparable to the CP length in OFDM, e.g., 8%-15% of the symbol length) to reduce OOB emissions of a subband, i.e., a group of subcarriers, while a simple FFT-based receiver like in OFDM can be used [6].

Generating spectral notches has already been investigated in the context of ultra-wideband (UWB) technology [7]. In UWB, a secondary device transmits in a wide frequency band (usually larger than 500 MHz) with a very low power level. To protect licensed primary users against interference, the secondary device has to suppress its power in certain frequency bands (regulated by, e.g., the FCC or ITU). Due to the flexibility of OFDM, the so called multi-band OFDM (MB-OFDM) technique has been considered as promising for UWB. To further suppress the side-lobe level in MB-OFDM, “spectrum sculpting” techniques have been proposed in [8][9][10] using cancellation subcarriers in the frequency domain. In contrast to frequency domain spectral shaping, classical time domain pulse-shaping techniques can also be applied, which, though, appear to be less flexible.

One common objective of both 5G and UWB is to suppress OOB emissions, thus generating less interference to other frequency bands. In UWB, active interference cancellation (AIC) has been proposed due to its flexibility. In 5G, pulse-shaping with well frequency-localized time domain FIR-filters is, in contrast, more suitable because of the scarce frequency resource. The contribution of this paper is to build a unified framework for analyzing and comparing the effectiveness of AIC and FIR-filtering techniques in terms of suppression of
OOB emissions in the context of 5G multicarrier waveforms. Additionally, the associated side effects of the two techniques, i.e., rate loss and SNR loss, are addressed and compared. We also combine the AIC technique with the novel multicarrier UFMC-scheme as an option to further enhance the frequency localization of this waveform. Unlike in [11], wherein AIC was applied to an “OFDM signal” before FIR-filtering, our approach also takes into account the subband-wise filtering of UFMC. Furthermore, a method of optimally combining the two approaches subject to a rate loss constraint is presented.

II. COMPARISON OF OFDM-AIC WITH UFMC

In this section, we present a unified approach to describe and analyze the aforementioned two techniques of generating spectral notches for both OFDM and UFMC signals. We consider an uplink multiuser frequency division multiple access (FDMA) scenario. Following the common practice of waveform analysis in [8], [9], [10], [12], the evaluation is conducted in baseband. Any RF frontend nonlinearity can be addressed separately. The total bandwidth is $N$ subcarriers, which is shared by $M$ users. Each user (or subband) is allocated with a bandwidth of $N_b$ consecutive subcarriers for simplicity. We assume that no guard subcarriers are inserted between subbands, except for $N_c$ cancellation subcarriers in each subband.

In Fig. 1, we show the unified system model of OFDM and UFMC applying AIC and FIR-filtering to suppress OOB emissions, considering only one subband. The other subbands perform the same procedure to satisfy a certain OOB emission level. We refer to [13][14] for a more detailed system model of UFMC. Briefly speaking, UFMC is equivalent to OFDM with subsequent subband-wise FIR-filtering (usually with short filter length comparable to the CP in OFDM). Without sacrificing any subcarriers to bear down the side-lobe, i.e., $N_c = 0$, the output signal $y_i$ of the considered subband $i$ can be expressed as

$$y_i[n] = \sum_{k=0}^{L-1} \sum_{l=-\frac{N}{2}}^{\frac{N}{2}-1} f_i(k) s_i (l-k) \cdot e^{j2\pi n \frac{l-k}{N}},$$

where $f_i(k)$ denotes the FIR-filter coefficients with the length of $L$ for subband $i$. Moreover, $x_i$ and $s_i$ is the time domain and frequency domain signal of the subband $i$, respectively. The output signal $y_i$ can be considered as an UFMC signal, if $L > 1$. Otherwise, it boils down to a normal OFDM signal. The FIR-filter coefficients $f_i(k)$ can be designed according to various criteria, e.g., raised-cosine (RC), least-squares (LS) [15] and equiripple (ER) [16], to obtain better spectral properties. For a better illustration and comparison, we define the power of the OOB emission as [5]

$$P_{OOB} = \int_{f \in OOB} |Y_i(f)|^2 \, df,$$

where $Y_i(f)$ denotes the power spectral density of the transmitted signal $y_i$, and OOB is a set containing all frequencies outside the subband. In Fig. 2, the original OFDM-spectrum as well as some UFMC-spectra using different filters are depicted, where the total number of subcarriers is set to $N = 64$, the considered subband occupies $N_0 = 12$ subcarriers and the FIR-filter length is constrained to $L = 14$. The frequency response of the designed FIR filters is also shown by green solid lines. With (2), the total power of OOB emission is calculated to be $-22.3$ dB for OFDM without any suppression mechanism. With FIR-filtering in UFMC, OOB emissions are significantly reduced. $15.9$ dB lower OOB emissions are attainable using the ER filter design, while the RC and LS filter designs yield in $14.7$ and $14.4$ dB lower emissions, respectively. However, an attenuation of the data carrying tones at the borders of the subband is noticeable due to the short filter length. We will deal with this problem later in this section.

In UWB cognitive radio, devices are required to be able to adapt their transmission according to the channel occupation (so called “detect and avoid” approach). Thus, time-domain filtering is considered as less efficient. A more adaptive solution is to generate spectral notches in the frequency domain using cancellation subcarriers (CS) or to simply disable several subcarriers (tone nulling). Denote the data-carrying
and cancellation subcarriers by vector $d_i$ and $\overline{c}_i$, respectively, the resulting transmitted symbol vector of the $i$-th subband is represented by $s_i = d_i + \overline{c}_i$. It is worth noting that $s_i$ contains merely $N_B$ non-zero elements, since only $N_B$ subcarriers are allocated to the subband. For simplicity, all non-zero elements in $\overline{c}_i$ compose the vector $c_i$ which shall be optimized. $c_i$ is as depicted in Fig. 1 and contains $\frac{N_B}{p}$ non-zero elements at each border of the subband. In order to observe the side-lobes and then suppressing them, oversampling is essential for the AIC component in Fig. 1. For this purpose, we introduce a matrix $P$ with the dimension $pN \times N$, where $p$ denotes the oversampling factor. The element in the $i$-th row and $k$-th column of the matrix is given by

$$
[P]_{ik} = \begin{cases} 
1, & k \neq \frac{l}{p} \\
e^{j2\pi \frac{k}{p}} \left(\frac{i}{p} + \frac{N_B}{p}\right), & k = \frac{l}{p},
\end{cases}
$$

where $N_{cp}$ is the length of the inserted CP in OFDM to avoid ISI for transmissions over multipath channels. Hence, the upsampled spectrum is represented by $s_i = Pd_i + P\overline{c}_i$, where $P$ is obtained by deleting all the $k$-th columns of $P$ with $[\overline{c}_i]_{k} = 0$. The target of AIC is to find the optimal values of cancellation subcarriers $c_i$ which suppress the emission of the data vector $d_i$ within certain frequency ranges. In this paper, we consider all the frequencies outside of the subband as optimization range denoted by the set $OOB = \{ |1| \frac{1}{p} + \frac{N_B}{2} \}$. The optimization problem is thus formulated as [8]

$$
c_i, opt = \arg \min _ {c_i} \sum _ {i \in OOB} ||s_i||^2
$$

and this optimization problem can be solved in a closed-form, which is given by

$$
c_i, opt = \frac{\tilde{P}^+P}{C}d_i,
$$

where $P$ and $\tilde{P}$ is composed of all the rows of $P$ and $\tilde{P}$ that belong to the set $OOB$, and $(\cdot)^+$ denotes the Moore-Penrose Pseudoinverse. It should be noted that upsampling is merely required for the calculation of the AIC matrix $C$, which can be computed offline, so that solely a multiplication of respective data symbols $d_i$ with $C$ is required to determine the values of the CSs during transmission.

In Fig. 3, the spectra of OFDM with $N_c = 2$ and $N_c = 4$ AIC CSs are shown. The cancellation signals $PC_{i, opt}$ are also illustrated with red lines, which are obtained by solving (5). The average OOB emission can be reduced by 13.2 dB and 31.9 dB for $N_c = 2$ and $N_c = 4$ respectively. It is obvious that AIC is very effective in reducing OOB emissions. However, one main problem is its spectral overshoot due to the unconstrained power of CSs. The CSs exhibit 3.0 dB and 7.5 dB spectral overshoot, respectively (compare to interactive webdemo illustrating these effects in [17]).

Both frequency domain AIC and time domain FIR-filtering sacrifice time and frequency resources, respectively. This induces a rate loss. For a fair comparison, we keep the net information rate equal for OFDM-AIC and UFMC, which means $\frac{N_B - N_c}{N + N_{cp}} = \frac{N_B}{N + L - 1}$. We obtain

$$
L = \frac{N_c}{N_B - N_c}N + \frac{N_c}{N_B - N_c}N_{cp} + 1.
$$

For the considered scenario, with $N_B$ allocated subcarriers out of $N$ total subcarriers per user, the maximum achievable rate is proportional to $R_{max} = \frac{N_c}{p}$ depending on the modulation and coding scheme (neglected for simplicity). The insertion of CSs in the frequency domain and the FIR-filtering in the time domain lead to a rate loss, which is defined as $\gamma_{loss} = 1 - \frac{R}{R_{max}}$ with $R = \frac{N_B - N_c}{N + L - 1}$ for UFMC-AIC or $R = \frac{N_B - N_c}{N + N_{cp}}$ for OFDM-AIC. Furthermore, we consider and quantify the spectral overshoot problem of the AIC approach in terms of SNR loss. The loss of SNR using AIC is due to the fact that some portion of the total signal power is wasted on AIC CSs instead of data transmission [9], which is given by the ratio between total signal power and power spent on AIC CSs. Spectral overshoot is, on the contrary, hardly an issue for the time domain filtering approach of UFMC. But the filtering, in particular using short filters, brings (inband) frequency selectivity into UFMC, i.e., subcarriers at the borders are usually slightly attenuated, which is also addressed in terms of SNR loss for UFMC.

In Fig. 4, the OOB emissions and the SNR losses are compared between OFDM-AIC and UFMC systems each with the same rate loss. Depending on the number of used CSs as well as the length of the inserted CP in OFDM-AIC, the filter length $L$ for UFMC is determined by (6) to ensure the same net information rate. The SNR loss, induced either by the wasted power on the CSs for OFDM-AIC or by the frequency selectivity of the filters in UFMC systems, is depicted as well on the secondary $y$-axis. Without CP, OFDM-AIC performs significantly better than UFMC in suppressing OOB emissions, whereas the SNR loss of OFDM-AIC is very high compared to UFMC. Due to the effect of spectral overshoot, the SNR loss of OFDM-AIC grows up to 6.7 dB for a large number of CSs. In contrast, the SNR loss of UFMC induced by the filtering is negligible and decreases for longer filters due to the better defined frequency response. Because of multipath propagation, the insertion of a CP is essential for an interference-free OFDM transmission. Thus, $N_{cp} = 9$ CP samples are inserted into the OFDM-AIC scheme. The insertion of CP has two consequences: on the one hand, the AIC algorithm shows an inferior performance compared to OFDM systems without CP;
on the other hand, slightly longer filters can be applied in UFMC, see (6), which improves the performance of UFMC. Consequently, UFMC, especially with the LS filter design, is capable of higher OOB emission reduction while resulting in a lower SNR loss, compared to CP-OFDM-AIC for small rate losses, e.g., $\gamma_{\text{loss}} < 0.56$.

### III. UFMC with AIC

UFMC and OFDM are similar in nature, thus many known signal processing methods, which have been developed for OFDM, can be reused with some modification in UFMC [18]. In [11], AIC was firstly introduced to UFMC in the context of suppressing inter-subband interference. In this section, we introduce the AIC algorithm to UFMC in the context of suppressing OOB emissions and present an extended AIC algorithm for UFMC.

#### A. Separate AIC and FIR-filtering

The novelty of UFMC is to filter a subband composed of several consecutive subcarriers, thus it combines the advantages of OFDM and FBMC while avoiding their main drawbacks. Before the subband filtering, the signals remain “OFDM signals”. Thus, the AIC algorithm can be applied to UFMC without any modification, since the AIC is performed in the “OFDM-domain”. After FIR-filtering, each UFMC symbol $y_i$, see (1), has a length of $N + L - 1$. Stacking all $y_i$’s in a vector and then padding with $N - L + 1$ zeros ($L < N + 1$) to form a vector $\tilde{y}_i$, the spectrum of UFMC $Y_i$ with separate AIC and FIR-filtering is given by

$$ Y_i = Q \tilde{y}_i = F_i P_{d_i} + F_i \tilde{P}_{c_i}, \quad (7) $$

where $Q$ denotes the DFT-Matrix with the dimension of $pN \times 2N$, and $F_i = \text{diag} \left( Q \tilde{f}_i \right)$ is a diagonal matrix which contains the FIR-filter coefficients in the frequency domain, with $\tilde{f}_i$ being a vector composed of the $L$ FIR-filter coefficients and $2N - L$ zeros (it is always assumed that short FIR-filters are applied, i.e., $L < N$). The coefficients for the AIC tones $c_{i,\text{opt}}$ are computed according to (5).

#### B. Combined AIC and FIR-filtering

The effect of subsequent FIR-filtering can be taken into account while computing the AIC coefficients $c_{i,\text{opt}}$. We extend the optimization problem of (4) to UFMC considering also the filtering effect. The optimization problem is expressed as

$$ c_{i,\text{opt},UF} = \arg \min_c \sum_{l \in \text{OOB}} |Y_i[l]|^2 \quad (8) $$

and with (7) its solution can be obtained as

$$ c_{i,\text{opt},UF} = -\bar{P}_{UF} \bar{P}_{UF} \cdot d_i, \quad (9) $$

and, similarly, $P_{UF}$ and $\bar{P}_{UF}$ are composed of all the rows of $F_i P$ and $F_i \tilde{P}$ that belong to the set $\text{OOB}$, respectively.

Fig. 5 shows a comparison between separate AIC and FIR-filtering and the proposed combined approach, where a LS filter of length $L = 14$ is applied and $N_c = 2$ subcarriers are used for AIC. It is observed that the spectral decay at the edges of the subband is steeper for the combined approach, resulting in an average OOB emission of $-56.3$ dB, which is 7.7 dB lower than for the separate approach. The complexity...
of the proposed approach is almost identical to the separate approach since it requires only one more matrix multiplication with merely diagonal nonzero elements so that the complexity of the pseudo inverse operation still dominates.

C. Joint Optimization of AIC tones and FIR-length

Usually, a certain amount of time and frequency resources have to be sacrificed for other purposes, e.g., lower OOB emissions. Next, we consider the question about how to efficiently make use of the two methods in terms of suppressing OOB emissions for a given rate loss. Given a certain percent $\gamma_{\text{loss}}$ of the information rate that can be sacrificed to reduce OOB emissions, we formulate the optimization of FIR-filter length and number of AIC CSs as follows

$$\left(N_c, L\right) = \arg \min_{N_c, L} P_{\text{OOB}}$$

s.t. $$\frac{N_B - N_c}{N + L - 1} \geq (1 - \gamma_{\text{loss}}) \cdot R_{\max}$$

where $P_{\text{OOB}}$ is defined in (2). Since $N_c$ and $L$ are integers and shall be kept comparatively small, there exist only a few possible combinations. Thus, this optimization problem can be easily solved using a brute-force search with low to moderate complexity for practical systems.

IV. SIMULATION RESULTS

For numerical evaluation, we assume a subband with $N_B = 12$ subcarriers and an FFT size of $N = 64$. The upsampling factor for the computation of the AIC matrix is set to $p = 64$. The adopted filters in UFMC have a transition width of one subcarrier, and the power is normalized for a fair comparison.

First of all, we compare the performance of the conventional AIC algorithm for OFDM and UFMC to the proposed combined AIC and FIR-filtering approach for UFMC. In Fig. 6, the total power of OOB emissions $P_{\text{OOB}}$ is shown for UFMC with separate AIC tone calculation (blue) and the proposed combined scheme (red). The used FIR-filter is of length $L = 10$ with LS design. For comparison, OFDM-AIC with CP is also depicted in green. The length of the CP for OFDM is chosen to be $N_{\text{CP}} = L - 1 = 9$ such that both systems have the same rate loss. Because of the additional filtering, UFMC-AIC in general outperforms CP-OFDM-AIC by more than 20 dB.

Furthermore, the proposed combined AIC approach provides additional 8.6 dB gain compared to the separate approach for the case $N_c = 2$, at hardly increased complexity. Another advantage of the combined approach is the lower SNR loss for all number of CS, which indicates that the spectral overshoot is slightly reduced using the proposed approach. A more insightful comparison including other filter designs and the resulting gains of the combined AIC computation approach is given in Table I. It can be concluded that the LS filter design is most appropriate for minimizing OOB emissions and provides the best additional gain for the combined AIC approach. Thus, in the following solely the LS filter design is further examined.

Secondly, we investigate the impact of filter length and number of CS on the performance gain of the combined AIC algorithm according to Sec. III-B. The additional gain of the combined AIC calculation for UFMC, compared to the separate AIC approach, is quantified in terms of OOB emission power difference for filter length $L$ in the range of 1 to 65, and different amount of CSs. Furthermore, the filter length is normalized to $\frac{L}{N}$. The numerical results are shown in Fig. 7.

<table>
<thead>
<tr>
<th>Number of CSs, $N_c$</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFDM-AIC CP</td>
<td>-27.8</td>
<td>-35.8</td>
<td>-53.6</td>
<td>-82.0</td>
<td>-118.0</td>
</tr>
<tr>
<td>UFMC-AIC RC sep.</td>
<td>-50.6</td>
<td>-70.4</td>
<td>-92.8</td>
<td>-121.0</td>
<td>-159.8</td>
</tr>
<tr>
<td>UFMC-AIC RC comb.</td>
<td>-59.0</td>
<td>-78.8</td>
<td>-101.0</td>
<td>-132.0</td>
<td>-168.3</td>
</tr>
<tr>
<td>gain of comb. approach</td>
<td>8.4</td>
<td>8.4</td>
<td>8.3</td>
<td>11.0</td>
<td>8.6</td>
</tr>
<tr>
<td>UFMC-AIC LS sep.</td>
<td>-50.8</td>
<td>-70.6</td>
<td>-92.9</td>
<td>-121.2</td>
<td>-160.0</td>
</tr>
<tr>
<td>UFMC-AIC LS comb.</td>
<td>-59.3</td>
<td>-79.1</td>
<td>-101.4</td>
<td>-132.5</td>
<td>-168.8</td>
</tr>
<tr>
<td>gain of comb. approach</td>
<td>8.6</td>
<td>8.5</td>
<td>8.5</td>
<td>11.3</td>
<td>8.8</td>
</tr>
<tr>
<td>UFMC-AIC ER sep.</td>
<td>-49.2</td>
<td>-69.5</td>
<td>-91.1</td>
<td>-120.2</td>
<td>-158.5</td>
</tr>
<tr>
<td>UFMC-AIC ER comb.</td>
<td>-49.2</td>
<td>-70.3</td>
<td>-91.5</td>
<td>-122.2</td>
<td>-159.9</td>
</tr>
<tr>
<td>gain of comb. approach</td>
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<td>0.8</td>
<td>0.4</td>
<td>2.0</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Figure 6. UFMC-AIC separate versus combined approach with LS filter of length $L = 10$

Figure 7. Gain of combined AIC calculation

Briefly speaking, the gain tends to increase for longer filters, e.g., the curve for $N_c = 8$. However, it does not increase linearly with the normalized filter length and shows some variation. This is due to the fact that the FIR-filter design, e.g., the LS criterion, does not take the effect of AIC into account. It can be concluded that the proposed combined approach is
capable of reducing the OOB emissions by at least 6 dB for most scenarios, where the normalized filter length is longer than 0.1 compared to a separate AIC calculation. Similarly, a larger gain can be achieved if $N_c$ increases, e.g., for the case where the normalized filter length equals 0.9. Also, the curve for $N_c = 10$ behaves differently, because this is a corner case with only OOB emissions of 2 data subcarriers to be compensated.

Lastly, we simulate all possible combinations of $N_c$ and $L$ for a variety of rate losses $\gamma_{\text{loss}}$ for the optimization according to Sec. III-C. The result is shown in Fig. 8 for UFMC-AIC using separate as well as combined AIC. The simulation results show that for the separate AIC and filtering approach as much resources as possible should be allocated to the AIC calculation in most cases, which, in turn, leads to the highest OOB reduction. Exceptions from this guideline are for $\gamma_{\text{loss}} = 0.17$ as well as for very high rate loss scenarios ($\gamma_{\text{loss}} \gtrsim 0.8$). Almost the same trend can be observed for the combined approach. The main reason behind this is the fact that CSs of the AIC consume more power to mitigate OOB emissions, thus it is more effective but causes higher SNR loss. Moreover, these results also allow to obtain the minimum required rate loss for achieving a certain OOB emission level. If $P_{\text{OBB}} \approx -60 \text{ dB}$ shall be achieved, using the separate AIC approach for UFMC, the minimum required rate loss is about 0.36. However, the required rate loss for UFMC with combined AIC calculation equals 0.27. Consequently, 9% time and frequency resources can be saved for data transmission. These results can be directly compared to UFMC without AIC ($N_c = 0$, dark green line), where the required rate loss amounts to 0.54.

V. CONCLUSIONS

In this paper, we reviewed active interference cancellation (AIC) for OFDM, which was originally proposed for the application in ultra wideband scenarios. Then, the AIC approach was combined with a recently proposed multicarrier modulation technique, namely, universal filtered multicarrier (UFMC). Additionally, we proposed a novel combined AIC and filtering approach for UFMC which allows a more effective suppression of out-of-band (OOB) emissions at hardly increased complexity. Numerical results show that the proposed method behaves better than the conventional approach in terms of spectral overshoot. Also, a lower SNR loss can be achieved. Finally, we showed how to optimally combine FIR-filtering and the AIC scheme in a UFMC system under a given rate loss constraint.

REFERENCES