A Novel FBMC/OQAM Scheme Facilitating MIMO FDMA without the Need for Guard Bands

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***Abstract*—In filterbank multicarrier systems with offset QAM signaling (FBMC/OQAM), real-field orthogonality is usually not sufficient to yield a frequency isolation of two resource blocks with different MIMO precoding for spatial multiplexing or beamforming. In this paper, we propose a novel scheme to avoid inter-block interference by adopting single band (SSB) filtering on the edge subcarriers of each block. Such filtering is able to maintain the real-field orthogonality condition for the subcarriers within a block while attaining the complex-field orthogonality at the block edges. To support the proposed bi-uniform filterbank structure, a novel resource mapping scheme is devised. Through simulation results it is shown that the proposed scheme can efficiently support pre-coded MIMO transmission in FBMC, achieving the same BLER performance as in OFDM.**

***Keywords*—FBMC/OQAM, complex-field orthogonality, pre-coded MIMO**

I. INTRODUCTION

Filterbank Multicarrier with Offset QAM (FBMC/OQAM) [1], [2] is currently one of the waveform candidates for the 5G mobile system, owing to its excellent waveform localization and high spectral efficiency [3], [4]. Most favourable property of the waveform localization is its potential to substantially relax the synchronization requirement, thus enabling massive machine connections for the Internet of Things with a simplified uplink access. Some recent works [5], [6] have revealed that FBMC transceiver is highly robust against time-synchronization misalignment and can correct carrier frequency offset (CFO) with very low complexity.

OQAM signaling relaxes the orthogonality to the real-field only, which requires some redesign of signal processing algorithms designed for orthogonal frequency-division multiplexing (OFDM) systems. This holds in particular for multiple-input multiple-output (MIMO) algorithms, which have therefore been in the focus of recent FBMC research. For point-to-point transmission using linear minimum mean square error (MMSE) receivers, it has been shown in [7], [8] that FBMC-MIMO can achieve the same link performance as OFDM based systems. However, in frequency division multiple access (FDMA) systems, where multiple users are allocated to different frequency resource blocks, the real-field orthogonality is not sufficient for a proper isolation of the resource blocks assigned to different users. As a consequence, strong inter-block interference (IBI) may occur if blocks are individually pre-coded based on the users' channel state (as in the downlink) or if the resource blocks of different users have experienced individual channel distortion (as in the uplink). To allow for the desired isolation in FBMC, the simple solution is to insert one empty subcarrier between the resource blocks. For a synchronous system, this solution results in a spectral efficiency loss, which has been considered a severe drawback for MIMO-FBMC. In order to reduce such loss, state-of-the-art solutions suggest to estimate such interference at the receiver and cancel this term [7], [9]. Nevertheless, this enhanced estimation and detection introduces high complexity overhead to the receiver. In [8], a joint precoding and decoding design has been introduced to enable MIMO FBMC/OQAM transmission in channels with severe frequency selectivity. The proposed approaches are, however, subject to substantial increase of computational complexity, and they are sensitive to the accuracy of channel state information.

In this paper, a novel scheme for FBMC transmission is proposed, where the edge subcarriers between the resource blocks are filtered with a single side band (SSB) prototype filter to establish the complex-field orthogonality between them, thus avoiding the need for any guard carriers. The proposed scheme relaxes the original uniform filterbank structure of FBMC to a bi-uniform one, enabling to increase the flexibility of resource usage in the system at the cost of a marginal complexity increase.

Throughout this paper, the following mathematical notations are used: $\Re(c)$ returns the real part of complex number c, $< a, b >$ denotes inner product of a and b, $(\cdot)^*$ denotes complex conjugation, $j = \sqrt{-1}$, and $\delta_{m,n}$ is the discrete Dirac function.

II. SYSTEM MODEL

For FBMC/OQAM modulation, each subcarrier $c \in \{1, ..., M\}$), with M being the number of subcarriers, is modulated according to

$$s_c[m] = \sum_{n=-\infty}^{+\infty} d_{c,n} \underbrace{p[m - n\frac{M}{2}] e^{j\frac{2\pi c}{M}(M - \frac{D}{2})} e^{\phi_{c,n}}}_{\triangleq p_{c,n}[m]} \quad (1)$$

where $d_{c,n}$ is a real-valued PAM symbol, $p[m]$ is the prototype filter with filter length $L = KM$, K is the overlapping factor, the causal delay factor is given by $D = (L - 1)/2$, and the phase term is $\phi_{c,n} = j^{(\pi/2)(c+n)}$. We denote the equivalent transmit filter bank applied on subcarrier c at time symbol index n as $p_{c,n}[m]$. Throughout the paper, we assume perfect frequency synchronization, namely, no carrier frequency offset.

Signal orthogonality in OQAM is in the real-field only. If the prototype filter $p[m]$ has perfect reconstruction (PR) or near-perfect reconstruction (NPR) properties, real-field orthogonality is attained after matched filtering operation at the receiver. Using mathematical notations, this relation can be expressed by the inner product of the transmit filter banks on subcarriers c_1 and c_2, with $c_1, c_2 \in \{1, ..., M\}$, yielding zero only for $c_1 = c_2$ after applying the real operator $\Re\{\cdot\}$:

$$\Re < p_{c_1,n}, p_{c_2,n} >= \Re(\delta_{c_1,c_2} + ja_{c_1,c_2}) = \delta_{c_1,c_2} \quad (2)$$

ja_{c_1,c_2} is a pure imaginary term representing the intrinsic interference from the neighboring subcarriers. If the signal is transmitted over a channel with complex coefficients, the channel needs to be equalized by linear operations first to re-establish the real-field orthogonality before the real operator $\Re\{\cdot\}$ should be applied.

In practice, the prototype filters are usually Nyquist and real valued linear phase finite impulse response (FIR) filters, such as PHYDYAS [9], IOTA [10], root raised cosine (RRC) etc. The PHYDYAS filter is frequently used in the existing literature for OQAM, which has steep roll-off in frequency domain. With this filter, the spectra of subcarrier signals overlap for adjacent subcarriers only, while subcarriers spaced more than one subcarrier apart experience effectively no interference.

A. Precoded MIMO case

Assuming c_1 and c_2 are two adjacent subcarriers located at the edge of two resource blocks, the real-field orthogonality cannot be attained for the case that c_1 and c_2 are individually precoded with two different complex coefficients. Taking codebook based precoding in a multi-user scenario as an example, the precoder is usually selected per resource block. As illustrated in Fig. 1, two adjacent resource blocks assigend to different users are individually precoded with coefficients W_1, W_2, which are chosen dependent on the users' channels h_1 and h_2, respectively. The inner product of the effective transmit filter banks on subcarriers c_1 and c_2 can then no longer support the real-field orthogonality:

$$\begin{aligned}\Re < W_1 p_{c_1,n}, W_2 p_{c_2,n} > &= \Re\left(W_1 W_2^* (\delta_{c_1,c_2} + ja_{c1,c2})\right) \\ &\neq \Re\left(W_1 W_2^*\right) \delta_{c_1,c_2} \quad (3)\end{aligned}$$

As a consequence, IBI is created at the edge of two adjacent resource blocks in this case. To avoid such problem, one solution is to leave one subcarrier vacant (sc0 in Fig. 1) so that two adjacent blocks will not interfere with each other [7]; however, this comes at the price of a spectral efficiency loss, which increases with the number of resource blocks with individual precoding.

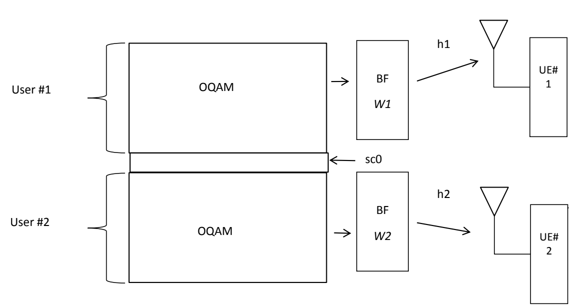

Fig. 1. Precoded MIMO case between two different users.

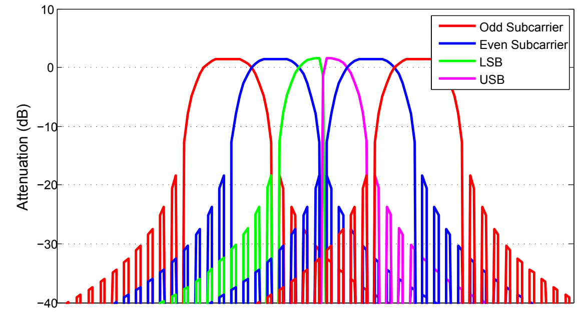

Fig. 2. Proposed bi-uniform filterbank scheme in frequency domain.

III. Proposed Scheme

The idea of the proposed scheme is to establish a complex-field orthogonality between adjacent subcarriers located at the edge of resource blocks, yielding a complete isolation of those blocks in frequency domain.

We assume that $sc0$ is the edge subcarrier between two resource blocks. The complex orthogonality at this block boundary can be established if, instead of a linear phase prototype filter $p[m]$, a pair of SSB filters is used for the edge carrier $sc0$, namely the lower side band (LSB) $p_l[m]$ and upper side band (USB) $p_u[m]$ prototype filter. The LSB and USB filters are given by

$$p_l[m] = \frac{\sqrt{2}}{2}(p[m] + j\mathcal{H}_p[m]) \quad (4)$$

$$p_u[m] = \frac{\sqrt{2}}{2}(p[m] - j\mathcal{H}_p[m]) \quad (5)$$

which are derived from the original real-valued prototype filter $p[m]$ and its Hilbert transform $\mathcal{H}_p[m]$. Note that all filter gains are normalized to unity.

Recalling the property of the Hilbert transform that $< p[m], \mathcal{H}_p[m] >= 0$, both LSB and USB filters are orthogonal to each other in the complex-field. This allows for a novel resource block division between two adjacent blocks on $sc0$, as depicted in Fig. 3. Specifically, instead of the conventional resource mapping principle, where one subcarrier is either allocated to the first or to the second resource block in frequency domain, the novel mapping scheme allocates the SSB filtered edge carrier $sc0$ to the two resource blocks in an alternating manner. The filter used for $sc0$ is switched between USB and LSB for each of these alternating allocations accordingly. For the case of pre-coded MIMO transmission, this mapping implies that the beamforming weights applied on $sc0$ are required to be switched for odd and even symbols accordingly.

Following this mapping, consecutive time domain symbols carry complementary SSB filters on $sc0$, which guarantee complex orthogonality between those signals:

$$< p_{l,sc0,n}[m], p_{u,sc0,n+1}[m] >= 0 \quad (6)$$

with $p_{l,sc0,n}[m]$ and $p_{u,sc0,n}[m]$ being defined similar to $p_{sc0,n}[m]$ in (1), except that the original prototype filter $p[m]$ is replaced by $p_l[m]$ and $p_u[m]$, respectively. An illustration of the two SSB filters applied to the edge carrier $sc0$ is given in Fig. 2.

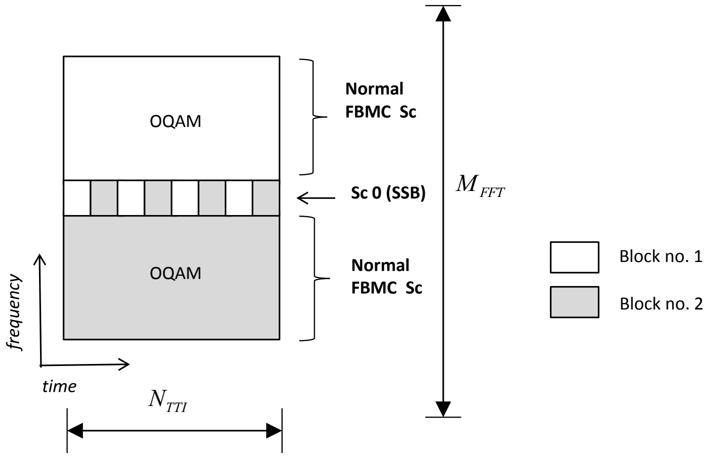

Fig. 3. Proposed resource mapping scheme.

Meanwhile, the real-field orthogonality within each resource block is maintained for filters $p_l[m]$ and $p_u[m]$. Taking $p_l[m]$ as example, it holds that

$$\Re < p_{l,sc0,n}, p_{sc0+q,n} >= 0 \tag{7}$$

for any $q \in \mathbb{Z}$, $q \neq 0$.

IV. Practical Implementation

A. Filter Length and Distortion

The proposed scheme in Section III is ideally fulfilling the requirements of the complex-field orthogonality at the block boarder and real-field orthogonality within each block. However, for a finite-length real valued FIR filter $p[m]$, its Hilbert transform $\mathcal{H}_p[m]$ is of infinite length. In practical implementation, the filter length needs to be limited to a reasonable value, yielding an approximation of the Hilbert transform, denoted as $\tilde{\mathcal{H}}_p[m]$. Using this approximation results in a loss of the Nyquist property as given in (6) and (7). As a consequence, inter-symbol interference (ISI) of several succeeding symbols is introduced for the signal transmitted on the edge carrier $sc0$. However, since the distortion is a-priori known to the system, a Viterbi receiver or a multi-tap equalizer [11], [12] can be applied to the edge subcarrier signal to mitigate the ISI at the receiver. An illustration of the approximated LSB prototype filter is shown in Fig. 4.

B. PPN Implementation

For the proposed SSB scheme, it turns out that the system is now a bi-uniform filter bank, where the original prototype filter $p[m]$ is used to modulate the subcarriers inside the resource blocks, and its complex variant $p[m] + j\tilde{\mathcal{H}}_p[m]$ is used to modulate the edge carrier at the block border. For the implementation using Polyphase Network (PPN) structure, one straightforward way to synthesize and analyze the signal is to have two parallel filterbank structures, where one is dedicated to the conventional FIR filtering with $p[m]$ and the other one dedicated to the filtering with $j\tilde{\mathcal{H}}_p[m]$. At the transmitter, one can combine the signal of the two PPNs at a later stage by simple signal addition. For signal analysis at the receiver, the signal can then be fed to two different PPNs performing the matched filtering with the corresponding prototype filter.

C. FS-FBMC Implementation

Implemention can also be based on frequency sampled (FS) FBMC [5], where the signals are synthesized and analyzed based on a FFT with KM stages. The filters are realized in the frequency domain by modulating each subcarrier with $2K-1$ filter coefficients. We assume here the use of PHYDYAS prototype filter $p[m]$, where $K=4$ and its frequency response being constituted of four distinct filter coefficients $H_i, i \in \{0, \ldots, 3\}$. The edge subcarrier $sc0$ for the odd symbol is modulated by the frequency response of the LSB prototype filter, given by the coefficients

$$\sqrt{2}([H_3, H_2, H_1, H_0/2, 0, 0, 0]) \tag{8}$$

For the even symbol, the frequency response of the USB prototype filter is used, given by the coefficients

$$\sqrt{2}([0, 0, 0, H_0/2, H_1, H_2, H_3]) \tag{9}$$

The scaling parameter is used for normalization purpose. Fig. 5 illustrates modulation of $sc0$ with this USB filter. All other subcarriers in the resource block are filtered with the conventional prototype $p[m]$, given by the coefficients

$$[H_3, H_2, H_1, H_0, H_1, H_2, H_3] \tag{10}$$

as illustrated in Fig. 5 for subcarrier $sc1$. Transforming the above filter coefficients to time domain yields the frequency-sampled PHYDYAS prototype filter

$$p[m] = H_0 + 2\sum_{k=1}^{K-1} H_k \cos\left(2\pi \frac{km}{KM}\right), \tag{11}$$

whereas the proposed LSB prototype filter based on $p[m]$ yields

$$\tilde{p}_l[m] = \sqrt{2}\left(\frac{H_0}{2} + \sum_{k=1}^{K-1} H_k \left(\cos(2\pi\frac{km}{KM}) + j\sin(2\pi\frac{km}{KM})\right)\right) \tag{12}$$

which contains the Hilbert approximation as

$$\tilde{\mathcal{H}}_p[m] = 2\sum_{k=1}^{K-1} H_k \sin(2\pi\frac{km}{KM}) \tag{13}$$

The USB prototype filter $\tilde{p}_u[m]$ can be calculated accordingly. By using the proposed prototype filter $\tilde{p}_l[m]$, the Hilbert

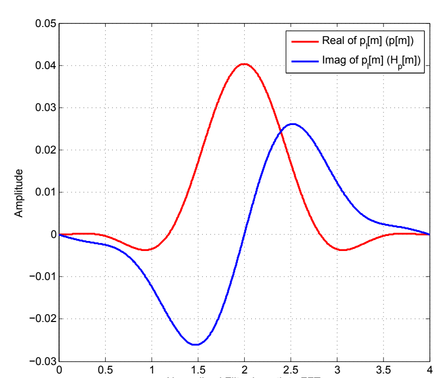

Fig. 4. Approximated LSB $\tilde{p}_l[m]$of PHYDYAS prototype filter.

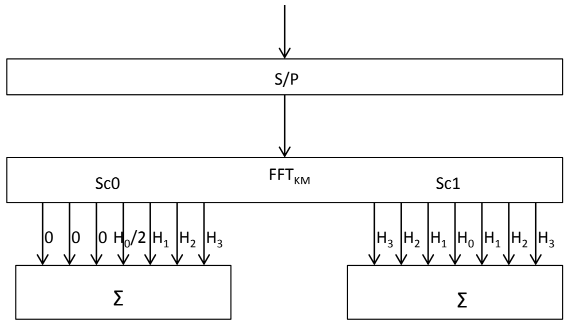

Fig. 5. Proposed FS implementation for synthesis filterbank.

approximation yields a loss of the Nyquist property, which causes an error vector magnitude (EVM) loss of -34 dB for the subcarrier signals within the same resource block, while the residual IBI imposed on the subcarrier at the edge of the adjacent block amounts to less than -11.4 dB. We remark that better orthogonalization can be achieved with longer filter in the time domain. Longer filters clearly impact the overall system design, though, e.g. affecting the dimensioning of guard periods required to isolate transmission frames. Hence, going for longer filters is not always a viable option.

D. Complexity Analysis

For the resource allocation process, the proposed scheme suggests that the edge carrier is alternatingly assigned to one or the other resource block, thus implying that the precoding weights will be switched accordingly as well. This procedure only causes a minor increase of the system complexity and imposes minor changes on the corresponding transmission protocols.

For the signal processing part, if PPN implementation is adopted, a maximum two-fold complexity increase is expected for the filtering, if the edge subcarrier $sc0$ is separately synthesized and analyzed with the pure imaginary part of either of the SSB filters. Nevertheless, there exist many approaches to further reduce the complexity by exploiting the sparsity of edge subcarriers compared to the ordinary ones.

For FS-FBMC implementation using the proposed pulse shape $\tilde{p}_l[m]$ and $\tilde{p}_u[m]$ at the edge carriers, the complexity overhead compared to an implementation based a uniform filter applied to each subcarrier is negligible, as only the filter coefficients for the edge carriers need to be substituted.

To compensate for the loss of Nyquist property, a multi-tap equalizer with pre-known coefficients can be implemented for the edge carrier at the receiver, which leads to a further but small overhead in complexity.

V. Performance Evaluation

In this section, we evaluate the block error rate (BLER) performance of the proposed FBMC/OQAM scheme in LTE-like downlink system with all the basic parameters similar to LTE setting. The evaluated system is supporting multi-user access in downlink with each user being assigned to three resource blocks in total. The parameters used for the simulation of OFDM and FBMC schemes are listed in Table I.

TABLE I. Simulation Parameters

Sampling frequency	7.68 MHz
Bandwidth	5MHz
Carrier frequency	2.59 GHz
Number of subcarriers	$M = 512$
Symbol per TTI	14 (OFDM) 14.5 (FBMC)
Available RBs for system	25 (OFDM) 27 (FBMC)
SC allocation per User	36
CP length of OFDM system	36
Prototype filter	PHYDYAS $K = 4$ [9] and $\tilde{p}_l[m]$ and $\tilde{p}_u[m]$ for edge carrier
Channel coding	Turbo Coding
Modulation and coding scheme (MCS)	LTE MCS 9, 16, 25
Channel model	3GPP Spatial channel model (SCM)
Channel estimation	Ideal
Equalization	MIMO: One tap error (MMSE); Alamouti: MRC +SIC

For a fair comparison between OFDM and FBMC, we use the same basic setting, antenna set-up, and coding block size. It should be noted that, due to the deprivation of cyclic prefix (CP) and using smaller spectral guard band, the FBMC scheme is generally more efficient in frame design, yielding an overall higher spectral efficiency of 12% compared to its LTE-OFDM counterpart.

In Fig. 6, we simulated the downlink beamforming for a multi-user system with 2×1 MIMO configuration, based on full channel state information available at the transmitter. For FBMC, three schemes have been considered:

1) FBMC-NoIBI: conventional FBMC/OQAM scheme with one vacant subcarrier between different blocks
2) FBMC-proposed: the proposed FBMC/OQAM scheme with SSB modulated subcarrier between blocks assigned to different users
3) FBMC-IBI: conventional FBMC/OQAM scheme without any vacant subcarrier between different blocks, resulting in severe IBI

From the simulation results, we observe that the IBI due to different beamforming weights between the users can be avoided completely by using the proposed scheme. For the IBI case, however, there is a performance error floor for FBMC at high SNR. With the novel scheme, each individual FBMC precoding block can now perform the corresponding beamforming transmission with its full degrees of freedom while attaining the same performance as LTE-OFDM.

Fig. 7 shows the BLER performance of LTE compliant codebook based pre-coding for a multi-user system with 4×4 MIMO configuration, applying 4-stream spatial multiplexing per user with MMSE equalizer. We observe here the same performance trend for the codebook based MIMO spatial multiplexing: FBMC applying the novel scheme is achieving the same BLER performance as OFDM while maintaining its favourable waveform properties and spectral efficiency advantage.

VI. Conclusion

In this paper, a novel FBMC/OQAM scheme is introduced based on the idea of bi-uniform filterbank structure, where complex-field orthogonality between resource blocks is established by adopting SSB filters on the edge subcarriers. The proposed scheme reveals that, with only small modification to

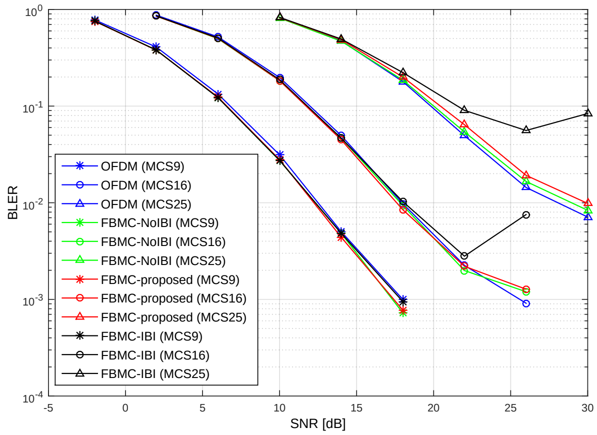

Fig. 6. BLER of 2×1 Beamforming based MISO for SCME Urban Macro channels with a user speed 3km/h.

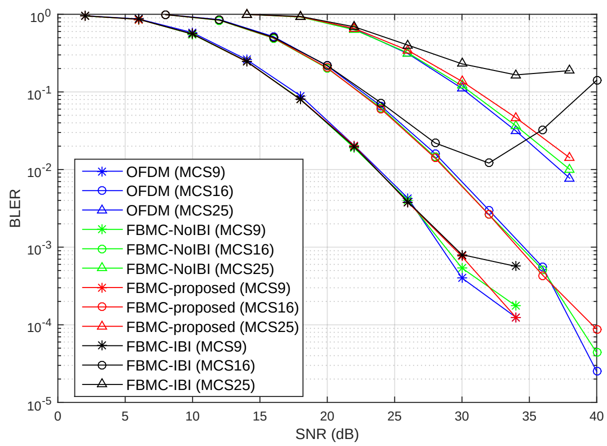

Fig. 7. BLER of 4×4 codebook based precoded MIMO for SCME Urban Micro channels with a user speed 4km/h.

the filtering and resource mapping procedures, the conventional inter-block interference can be fully avoided. FBMC/OQAM is thus able to maintain the full degrees of freedom in the system for utilizing the resource blocks for frequency division multiple access (FDMA). Therefore, block-based complex-field operation, including closed-loop MIMO and beamforming, can be seamlessly supported by FBMC with no performance degradation while being based on efficient implementations.

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REFERENCES

[1] B. Farhang-Boroujeny, "OFDM versus Filter Bank Multicarrier," *IEEE Signal Processing Magazine*, vol. 28, no. 3, pp. 92–112, May 2011.

[2] P. Siohan, C. Siclet, and N. Lacaille, "Analysis and Design of OFDM/OQAM Systems based on Filterbank Theory," *IEEE Transactions on Signal Processing*, vol. 50, no. 5, pp. 1170–1183, May 2002.

[3] METIS, "Proposed solutions for new radio access," in *FP7 ICT project METIS, Deliverable D2.4*, Feb. 2015.

[4] 5GNOW, "5G waveform candidate selection," in *FP7 ICT project 5GNOW, Deliverable D3.1*, 2013.

[5] M. Bellanger, "FS-FBMC: An Alternative Scheme for Filter Bank Based Multicarrier Transmission," in *2012 5th International Symposium on Communications Control and Signal Processing (ISCCSP),*, May 2012, pp. 1–4.

[6] J.-B. Dore, V. Berg, N. Cassiau, and D. Ktenas, "FBMC receiver for multi-user asynchronous transmission on fragmented spectrum," *EURASIP Journal on Advances in Signal Processing*, vol. 2014, no. 1, p. 41, 2014.

[7] M. Najar and et al., "MIMO techniques and beamforming," *FP7 ICT project PHYDYAS, Deliverable D4.2*, 2010.

[8] M. Caus and A. Perez-Neira, "Multi-stream transmission for highly frequency selective channels in MIMO-FBMC/OQAM systems," *IEEE Transactions on Signal Processing*, vol. 62, no. 4, pp. 786–796, Feb 2014.

[9] M. Bellanger et al., "FBMC physical layer : a primer," *ICT-PHYDYAS Project*, pp. 1–31, 2010. [Online]. Available: www.ict-phydyas.org

[10] B. Le Floch, M. Alard, and C. Berrou, "Coded orthogonal frequency division multiplex [TV broadcasting]," *Proceedings of the IEEE*, vol. 83, no. 6, pp. 982–996, Jun. 1995.

[11] D. S. Waldhauser, L. G. Baltar, and J. A. Nossek, "MMSE subcarrier equalization for filter bank based multicarrier systems," in *2008 IEEE 9th Workshop on Signal Processing Advances in Wireless Communications*. IEEE, Jul. 2008, pp. 525–529.

[12] A. Ikhlef and J. Louveaux, "An enhanced MMSE per subchannel equalizer for highly frequency selective channels," in *2009 IEEE 10th Workshop on Signal Processing Advances in Wireless Communications*. IEEE, Jun. 2009, pp. 186–190.