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RESEARCH ARTICLE

Software Implementation and Cyclic Feature Characterization of Nu-FBMC/OQAM Signals

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ABSTRACT An extended frequency spread (FS) multicarrier system based on the filter bank and offset quadrature amplitude modulation (FS-FBMC/OQAM) approach applied to a critically sampled nonuniform FBMC/OQAM (Nu-FBMC/OQAM) transmission, using subchannel aggregation of uniform filter bank, is analyzed and described. The new adapted structure for this Nu-FBMC/OQAM transmission and corresponding orthogonality conditions are analyzed. Their implementation and verification are performed using MATLAB®. Some novel results related to the cyclic features of this Nu-FBMC/OQAM signal, based on the spectral correlation density (SCD) and estimated by the fast Fourier transform accumulation method (FAM), are presented.

INDEX TERMS Nonuniform filter bank multicarrier, OFDM/OQAM, software implementation, cyclic features.

I. INTRODUCTION

Compared with the classical orthogonal frequency division multiplexing (OFDM), the filter bank (FB) multicarrier based on the offset quadrature amplitude modulation (FBMC/OQAM) can achieve the maximal bit rate, a better spectral efficiency and a greater reduction of the intersymbol interference (ISI) and intercarrier interference (ICI), using time-frequency well-localized transmitter pulse shaping. The FBMC/OQAM is therefore a promising technique for the next-generation of wireless communication. Also, compared to the conventional OFDM, the FBMC/OQAM has a better performance in the presence of nonlinear distortions, although, due to the use of an extended FFT, it increases the peak-to-average power ratio (PAPR). A nonuniform FBMC/OQAM (Nu-FBMC/OQAM) enables flexibility in terms of defining subchannels with arbitrary transmission bandwidths and center frequencies and has the capability to adapt services to different incoming data rates, which is desirable in many applications. Compared to the FBMC/OQAM, the Nu-FBMC/OQAM also offers better reduction of out-of-band emissions in the presence of nonlinear distortions [1].

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Classical approaches to the implementation of nonuniform filter banks (Nu-FB) are based on the combination of (I)FFT and polyphase filters [2], [3], and the application of the tree-structured octave-band digital filter banks [4].

Fast-convolution based multirate filter bank with OQAM (FC-FB/OQAM) using FFT-IFFT pairs and an overlap-save processing, can be used to implement Nu-FBMC/OQAM transmission [5], [6]. The frequency-spreading (FS) filter bank multicarrier (FS-FBMC) approach is based on a combination of spreading the QAM symbols over subcarrier frequency samples, weighting them with prototype filter coefficients, an extended (I)FFT, whose size is equal to the prototype filter length, and an overlap-add/overlap-save processing at the transmitter/receiver, respectively [7]. The FC-FB approach generalizes FS-FBMC by offering a compromise between computational complexity and filtering performance [8].

The work in [1] considers the implementation of Nu-FBMC/OQAM by extending the FS-FBMC procedure to Nu-FBs by aggregating subchannels of even-spaced and odd-spaced uniform FBs to obtain symmetrical and asymmetrical subchannels of Nu-FB.

In this paper, an analytical transformation of the expression for the FBMC/OQAM signal is performed and an expression suitable for the FS-FBMC/OQAM implementation is obtained. Based on the subchannel aggregation of uniform FB, a new adapted structure for the critically sampled Nu-FBMC/OQAM transmission is obtained and described, and its implementation is performed using MATLAB® software. The phase rotation factor and conditions ensuring orthogonality between adjacent subchannels and consecutive data symbols are also analyzed. Extending the FS-FBMC approach to the critically sampled Nu-FBMC/OQAM transmission, whereby the nonuniform subchannel filters have the same symmetric square-root Nyquist transition band shapes, results in a reduction of the Nyquist roll-off factor proportionally to the increase in subchannel bandwidth. By exploiting the results and analysis presented in [9], this paper contains a new contribution regarding the cyclic feature characterization of the Nu-FBMC/OQAM signals, which is based on the spectral correlation density (SCD) estimation using the FFT accumulation method (FAM). It is shown that this signal exhibits strong characteristic conjugate cyclic features at the cycle frequencies associated with the spectral frequencies of the bandpass. It is also observed that the cyclic feature exhibition depends on the transmit power weighting of the nonuniformly spaced subchannels. Second-order cyclostationarity-based signal processing can exploit the results of this cyclic feature analysis to improve the performance of Nu-FBMC/OQAM signal detection, identification, and parameter estimation.

II. FS-FBMC/OQAM TRANSMISSION SYSTEM

The basic concept of the FBMC/OQAM transmission involves sending offset QAM symbols. In this approach, the complex QAM symbols $s_k(n) = s_k^{\Re}(n) + js_k^{\Im}(n)$ are divided into their real $s_k^{\Re}(n)$ and imaginary $s_k^{\Im}(n)$ components (k denotes the subcarrier index and n denotes the time index) and then transmitted with an offset of half the symbol interval and a phase shift that ensures that adjacent symbols with respect to time (n) and frequency (k) position are in quadrature one to the other.

The FBMC/OQAM baseband signal [7], [10], which refers to a uniform FB, can be separated into its real and imaginary parts that are time staggered by half of the symbol interval, and the transmitted FBMC/OQAM signal can be expressed in the following form:

$$\begin{aligned} x(m) &= x^{\Re}(m) + x^{\Im}(m - M/2) \\ &= \sum_n \sum_{k=0}^{M-1} s_k^{\Re}(n) h(m-nM) e^{j\frac{2}{M}k\left(m-\frac{KM}{2}\right)} \theta_k(n) \\ &\quad + \sum_n \sum_{k=0}^{M-1} s_k^{\Im}(n) h\left(m - nM - \frac{M}{2}\right) e^{j\frac{2}{M}k\left(m-\frac{(K+1)M}{2}\right)} \theta_{k+1}(n) \end{aligned} \tag{1}$$

where $h(m)$ is the impulse response of the prototype filter, and $\theta_k(n)$ is the phase rotation factor that should ensure orthogonality between adjacent subchannels and successive data symbols. The prototype filter length can be $L_h = KM+1$ or $L_h = KM$, without loss of generality, and here we take $L_h = KM+1$, where K and M denote the overlapping factor and the maximum number of subcarriers, respectively.

The FS-FBMC/OQAM implementation is based on a convolution of OQAM symbols with the $2K - 1$ nonzero symmetric frequency coefficients H_p, -(K-1) $\leq p \leq K$-1, of the prototype filter, followed by an IFTT application, a parallel-to-serial conversion and an overlap-and-add operation.

The symmetric frequency coefficients H_p ($H_{-p} = H_p$) and the corresponding real-valued impulse response $h(m)$ of the prototype filter are related by the Fourier transform and $h(m)$ can be written as:

$$h(m) = \sum_{p=-K+1}^{K-1} (-1)^p H_p e^{j\frac{2\pi}{KM}pm}, \quad m \in [0, KM] \tag{2}$$

By substituting (2) into (1) and introducing $i = p+kK$, the following expression for the FBMC/OQAM baseband signal, corresponding to the FS-FBMC/OQAM implementation, based on the uniform FB, is obtained:

$$\begin{aligned} x(m) &= \sum_n \sum_{k=0}^{M-1} \theta_k(n) \sum_{i=(k-1)K+1}^{(k+1)K-1} (-1)^i s_k^{\Re}(n) H_{i-kK} e^{j\frac{2}{M}i(m-nM)} \\ &\quad + \sum_n \sum_{k=0}^{M-1} \theta_{k+1}(n) \sum_{i=(k-1)K+1}^{(k+1)K-1} (-1)^i s_k^{\Im}(n) H_{i-kK} e^{j\frac{2}{M}i\left(m-nM-\frac{M}{2}\right)} \end{aligned} \tag{3}$$

From (3), it can be seen that real $s_k^{\Re}(n)$ and imaginary $s_k^{\Im}(n)$ components of the complex QAM symbols, for each k^{th} subcarrier, are spread over $2K$–1 frequency samples (index i) in the range from (k-1)$K+1$ to $(k+1)K$-1 weighted by the frequency response of the prototype filter. In addition, it can be concluded that in the spreading process, the weighted contributions of symbol components on adjacent subchannels k and $k+1$ are overlapped and added at K frequency positions, while there is no overlap at the frequency positions $i = kK$. Therefore, the contributions of the real $s_k^{\Re}(n)$ (also imaginary $s_k^{\Im}(n)$) components with adjacent subchannel indices $k \in \{\lfloor i/k \rfloor, \lceil i/k \rceil\}$, $i \in \{0, 1, \ldots, KM\text{-}1\}$, should be combined due to the overlapping and addition. As a result, (3) can be compactly rewritten as:

$$\begin{aligned} x(m) &= \sum_n \sum_{i=0}^{KM-1} (-1)^i \left(\sum_{k=\lfloor i/K \rfloor}^{\lceil i/K \rceil} \theta_k(n) s_k^{\Re}(n) H_{i-kK} \right) e^{j\frac{2}{KM}i(m-nM)} \\ &\quad + \sum_n \sum_{i=0}^{KM-1} (-1)^i \left(\sum_{k=\lfloor i/K \rfloor}^{\lceil i/K \rceil} \theta_{k+1}(n) s_k^{\Im}(n) H_{i-kK} \right) e^{j\frac{2}{KM}i\left(m-nM-\frac{M}{2}\right)} \end{aligned} \tag{4}$$

where ⌊·⌋ (floor brackets) and ⌈·⌉ (ceiling brackets) denote rounding a number to a lower integer and rounding a number to an upper integer, respectively.

Therefore, FBMC/OQAM signals with an FS implementation can be generated by applying the KM-point IDFT and weighting the symbol components with the prototype filter coefficients, with overlap and addition in the frequency domain.

The FS-FBMC/OQAM receiver performs the matched signal demodulation inversely to the modulator processing.

A. ANALYSIS OF ORTHOGONALITY CONDITIONS

The orthogonality between adjacent subchannels and successive data symbols in FBMC/OQAM transmission systems is ensured by the phase rotation factor $\theta_k(n)$ and prototype filter design. In this case of a FBMC/OQAM transmission system, a square-root Nyquist prototype filter combined with an OQAM processing can ensure orthogonality end cancel the induced interference from neighboring subchannels.

In the FS-FBMC/OQAM implementation, the complex QAM symbol sequence is split into two interleaved sequences of real and imaginary components at even ($2n$) and odd ($2n+1$) time instants and transmitted as in-phase and quadrature sequences, respectively. In the common FBMC/OQAM implementation with an even-spaced uniform FB, the phase rotation factors $\theta_k(n)$ for an in-phase sequence and $\theta_{k+1}(n)$ for a quadrature sequence (k is the subcarrier index and n is time index), which introduce phase shifts of the $(2n)^{\text{th}}$ and $(2n+1)^{\text{th}}$ real symbols, respectively, in the OQAM pre/post-processing phase, are given as [11]:

$$\theta_k(n) = (-1)^n j^k \tag{5}$$

$$\theta_{k+1}(n) = (-1)^n j^{k+1} \tag{6}$$

The phase rotation factor, regardless of the sign of the previous expressions, and the staggering by half of the symbol interval between the in-phase and quadrature components, ensure orthogonality between adjacent subchannels and consecutive data symbols. Therefore, the phase rotation factor has the form $\theta_k(n) = j^k$ [12].

III. NU-FBMC/OQAM SYSTEM MODEL

The Nu-FBMC/OQAM transmission system can support different subchannel bandwidths and different subchannel symbol rates. The symbol rates of the subchannel substreams are determined by the decimation factors.

The incoming complex QAM data symbol stream $s(n)$ with the symbol rate R is split into L (number of the active subchannels) parallel substreams with lower different symbol rates $R_k = R/n_k$, $k = 1, 2, \ldots, L$, where integer decimation factors n_k satisfy the condition of critical sampling, $\sum_{k=1}^{L} (1/n_k) = 1$, which ensures that there is no loss of information [13], [14]. In the critical sampling case of the Nu-FBMC/OQAM system with L subchannels, the decimation factors n_k have the form $n_k = 2^k$ for $k = 1, 2, \ldots, L$-1 and $n_L = 2^{L-1}$. Therefore, a larger value of the decimation factor n_k corresponds to a lower symbol rate R_k of the k^{th} substream and the narrower k^{th} subchannel bandwidth. The splitting and down sampling of the incoming data symbol stream $s(n)$ into parallel nonuniformly partitioned substreams $s_k(n)$, $k = 1, 2, \ldots, L$, for the case of critical sampling and for $L = 4$, is shown in Fig. 1.

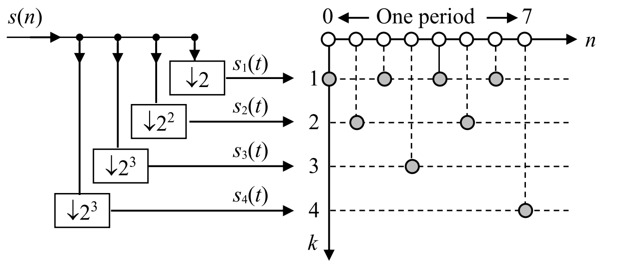

FIGURE 1. Splitting and down sampling of incoming serial data symbol stream into four parallel nonuniformly partitioned substreams.

The real and imaginary data parts of the subchannel complex QAM symbols $s_k^{\Re}(n) = s_k^{\Im}(n) + js_k(n)$ are processed separately. The time staggering by half of the symbol interval between the in-phase $s_k^{\Re}(n)$ and quadrature $s_k^{\Im}(n)$ components in the OQAM subchannel processing is necessary to ensure orthogonality between the overlapping subchannels and requires oversampling by two.

A. SUBCHANNEL AGGREGATION

The basic idea of this Nu-FBMC/OQAM transmitter structure is based on an extension of the FS-FBMC approach. OQAM symbols are filtered in the frequency domain with unequal bandwidth subchannel filters. This nonuniform FBMC is obtained by aggregating subchannels of a uniform filter bank with a symmetric *half*-Nyquist prototype filter of length KM and only $2K-1$ nonzero frequency coefficients, where K is the overlapping factor and $M \geq 2^{L-1}$ is the possible maximum number of uniform subchannels that can be included in the aggregation of nonuniform subchannels. The frequency coefficients of the most popular PHYDYAS *half*-Nyquist prototype filter for $K = 4$ have values $H_0 = 1$, $H_1 = H_{-1} = 0.971960$, $H_2 = H_{-2} = \sqrt{2}/2$, $H_3 = H_{-3} = 0.235147$ [15]. The nonzero sample vector of the frequency response of a nonuniform bandwidth subchannel filter obtained by aggregating two adjacent subchannels of uniform FBMC, can be expressed as $[H_{-3}, H_{-2}, H_{-1}, H_0, \sqrt{H_1^2 + H_{-3}^2}, \sqrt{H_2^2 + H_{-2}^2}, \sqrt{H_{-1}^2 + H_3^2}, H_0, H_1, H_2, H_3]$. Aggregation of four adjacent subchannels is performed similarly.

An example of a nonuniform four-channel FBMC that has the same symmetric transition band shapes, corresponding to the nonuniformly partitioned substreams $s_k(n)$, $k = 1, 2, \ldots, 4$, from Fig. 1, is shown in Fig. 2. In the case presented in Fig. 2, the first nonuniform subchannel filter obtained by aggregating four adjacent subchannels of a uniform FBMC, replicating it along the frequency axis, produces an even-spaced extended uniform FBMC. However, the other

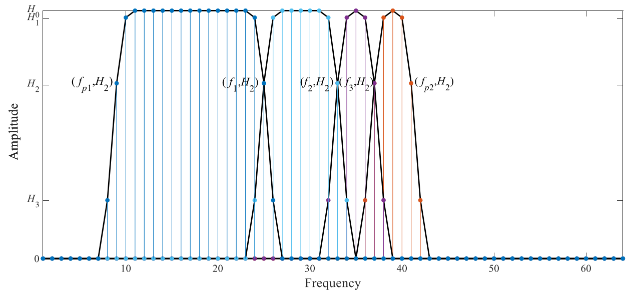

FIGURE 2. Example of nonuniform four-channel FBMC.

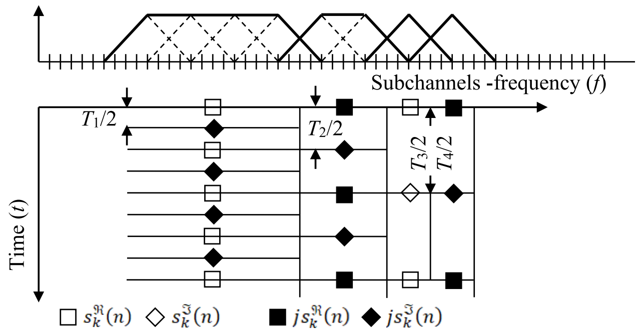

FIGURE 3. Signaling of in-phase and quadrature components in even-spaced Nu-FBMC/OQAM.

(second, third and fourth) nonuniform bandwidth subchannel filters, considered in the same way, belong to an odd-spaced extended uniform FBMC.

Nonuniform subchannel filters with aggregation $J_k = 2^{L-1}/n_k$, $k = 1, 2, \ldots, L$, uniform subchannels are assigned to the data symbol substreams $s_k(n)$, $k = 1, 2, \ldots, L$, where the number of nonzero frequency coefficients of the k^{th} nonuniform filter is:

$$P_k = 2K - 1 + (2^{L-1}/n_k - 1)K, \quad k = 1, 2, \ldots, L. \quad (7)$$

Data symbol substreams $s_k(n)$, $k = 1, 2, \ldots, L$, transmitted on the k^{th} nonuniform subchannel, are "spread" over a number of subcarriers equal to the P_k nonzero frequency coefficients of the k^{th} nonuniform filter.

B. ORTHOGONALITY ANALYSIS IN THE CASE OF NU-FBMC/OQAM

Similarly to [1], the orthogonality conditions in terms of signaling in the in-phase $s_k^{\Re}(n)$ and quadrature $s_k^{\Im}(n)$ components are empirically determined for Nu-FBMC/OQAM signals.

In the case of the FS-FBMC approach, one can observe two cases of positioning nonuniform filters (subchannels) per frequency so that they belong to the corresponding even or odd uniform filter bank (FBMC). Signaling intervals are different in subchannels with nonuniform bandwidths, but it should be ensured that in-phase $s_k^{\Re}(n)$ and quadrature $s_k^{\Im}(n)$ components of the subchannel complex QAM symbols $s_k(n) = s_k^{\Re}(n) + js_k^{\Im}(n)$, that are simultaneously signaled in adjacent (nonuniformly spaced) subchannels, are of different types, i.e. they can be neither real (Re) nor both imaginary (j·Im). It can be shown that the subchannels belonging to the corresponding even uniform FBMC at their input have $s_k^{\Re}(n)/js_k^{\Im}(n)$ or $js_k^{\Re}(n)/s_k^{\Im}(n)$ in-phase/quadrature components, while the subchannels belonging to the corresponding odd uniform FBMC at their input have either $s_k^{\Re}(n)/s_k^{\Im}(n)$ or $js_k^{\Re}(n)/js_k^{\Im}(n)$, for each half of the corresponding symbol interval, depending on the in-phase/quadrature components of complex QAM symbols used in the adjacent subchannels. The generation of a real Nu-FBMC/OQAM signal is considered here, so mirror filters are not used as in the case of the generation of the Nu-FBMC/OQAM complex envelope [1].

Fig. 3 shows the signaling of QAM complex symbols in the case where the first nonuniform bandwidth subchannel filter belonging to an even extended uniform FBMC, and the other nonuniform bandwidth subchannel filters (second, third, and fourth) belonging to an odd extended uniform FBMC.

In the case that the first nonuniform bandwidth subchannel filter belongs to an odd extended uniform FBMC, only the signaling on the first subchannel would change compared to the previous case and would be $s_1^{\Re}(n)/s_1^{\Im}(n)$.

The previously described orthogonality properties are verified by the simulation method.

C. NU-FBMC/OQAM TRANSMISSION BASED ON EXTENDED FS-FBMC/OQAM APPROACH

By extending the FS-FBMC approach, each complex data symbol substream $s_k(n)$, $k = 1, 2, \ldots, L$, transmitted on the nonuniform k^{th} subchannel is spread over P_k subcarriers, given by (7), by filtering with the corresponding nonuniform bandwidth subchannel filter. OQAM preprocessing requires that the real $s_k^{\Re}(n)$ and imaginary $s_k^{\Im}(n)$ symbol components are shifted by half of the symbol interval, processed separately, and the preprocessing should ensure orthogonality between adjacent overlapping nonuniform subchannels by signaling of in-phase $s_k^{\Re}(n)$ and quadrature $s_k^{\Im}(n)$ components of the QAM symbols as described in the previous section. An extending IFFT of size $N = KM$ is applied to each part of the separately filtered real and imaginary components of the OQAM symbols. The generated time-domain data from the N-point IFFT output are converted through a Parallel-to-Serial (P/S) conversion and overlapped and summed with the following N-point IFFT output sequence delayed by $M/(2J_k)$ samples, corresponding to staggering by half of the symbol interval on the k^{th} nonuniform subchannel obtained by aggregation of $J_k = 2^{L-1}/n_k$ uniform subchannels.

Due to the overlap factor K, the IFFT size in FS-FBMC is extended to $N = KM$ compared with M in OFDM. These extended IFFTs (IFFT_{KM}) are applied in Nu-FBMC/OQAM to each of the "spread" outputs of the k^{th} nonuniform bandwidth subchannel filter ($k = 1, 2, \ldots, L$-2). However, the "spread" outputs of the (L-1)$^{\text{th}}$ and L^{th} overlapping subchannel filters with the same bandwidths are summed in the overlapped transition band and a single IFFT_{KM} is applied to them.

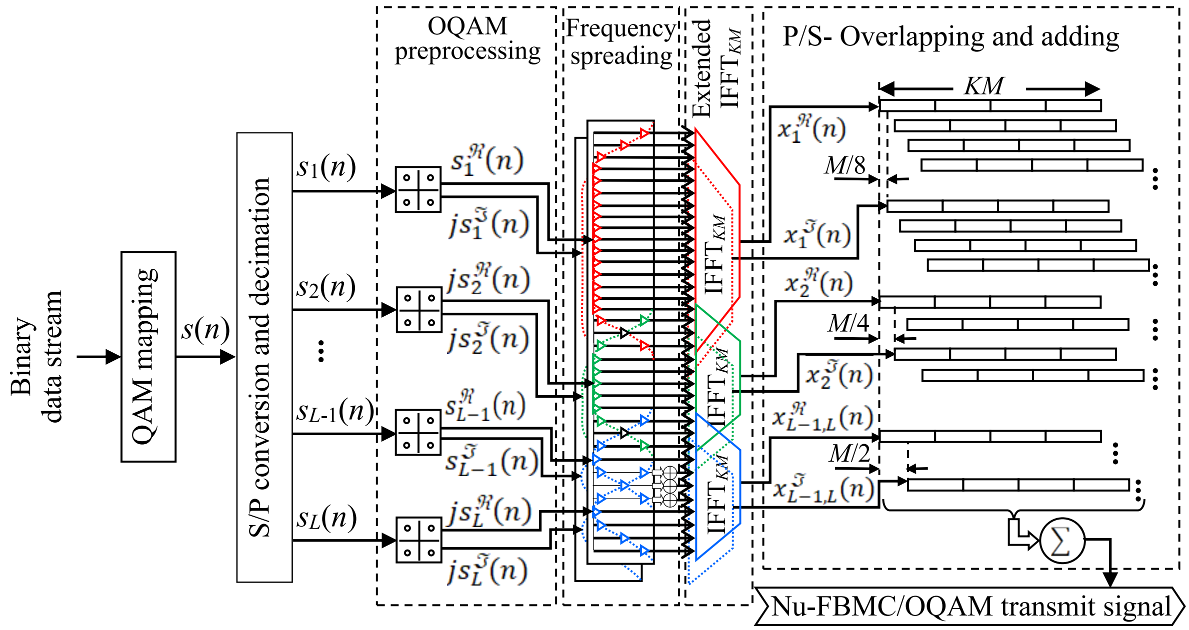

FIGURE 4. An even-spaced four-channel Nu-FBMC/OQAM transmitter system model.

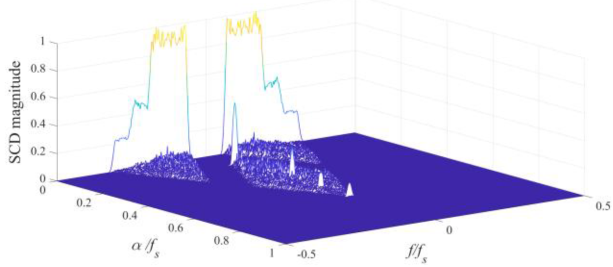

FIGURE 5. The cyclic spectrum magnitude of a Nu-FBMC/OQAM signal.

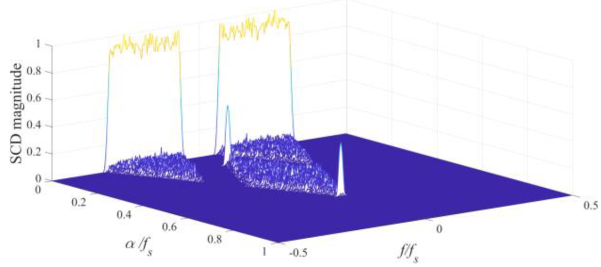

FIGURE 6. The cyclic spectrum magnitude of an equiponderated Nu-FBMC/OQAM signal.

The generic model structure of an even-spaced four-channel Nu-FBMC/OQAM transmitter system is presented in Fig. 4.

The counterpart to the transmitter overlap-and-add operation is an overlapping shifted window on the receiver side where KM samples of Nu-FBMC/OQAM signal are selected every $M/(2J_k)$ samples, which corresponds to staggering by half of the symbol interval on the k^{th} nonuniform subchannel. The extending FFT is then applied to each block of KM selected samples. The FFT output data are weighted with the frequency coefficients of the corresponding nonuniform subchannel filters and merged in a "frequency despreading" operation. An appropriate OQAM postprocessing is also applied to the nonuniform subchannels used, in accordance with the transmitter orthogonality conditions described. The real and imaginary parts for each estimated QAM symbol are restored and demodulated to get the final output.

IV. CYCLIC FEATURE CHARACTERIZATION OF NU-FBMC/OQAM SIGNALS

Cyclostationarity is a property of signals with inherent periodicities that exhibit as a non-zero correlation between separate spectral components whose frequency separation is called the cycle frequency and denoted by α, and the center frequency is called the spectral frequency and denoted by f. The cyclic feature-based signal processing in cyclostationary signal detection, identification and parameter estimation provide significant advantages.

Based on the previous analysis of cyclic features of OFDM/OQAM signals [9], it can be concluded that even in the case of nonuniform shaping filters with strictly limited bandwidths, there is no exhibition of unconjugated cyclic features corresponding to cyclic frequencies in the baseband. However, it can also be concluded that the conjugate cyclic features of the Nu-FBMC/OQAM signals will be completely suppressed in the bandpass except at the cycle frequencies α associated with the edge frequencies of the Nu-FBMC/OQAM signal bandwidth and associated with frequency boundaries between nonuniform different bandwidth subchannel filters when their signal strengths are not equiponderated at their outputs. In the case of critically sampled nonuniform filter banks without additional weighting of the nonuniformly spaced subchannels (this results in different subchannel transmit powers) cyclic features are exhibited at the cyclic frequencies α associated with the edge frequencies of the passband, f_{p1} and f_{p2}, and frequency boundaries, f_k, $k = 1,\ldots, L$-2, between nonuniform filters with different bandwidths.

Fig. 5 shows the cyclic spectrum magnitude (or SCD magnitude) in the bifrequency plane (f, α) for the critically sampled four-channel Nu-FBMC/OQAM signal, estimated by the FFT accumulation method (FAM).

As evident from Fig. 5, the cyclic features of the Nu-FBMC/OQAM signal ($K = 4$, $L = 4$, $f_{p1}/f_s = 1/16$, $f_{p2}/f_s = 5/16$, $f_1/f_s = 3/16$, $f_2/f_s = 4/16$, with f_s being the sampling frequency) are exhibited at the cyclic frequencies α that are equal to the double edge frequencies of the passband, f_{p1} and f_{p2}, and frequency boundaries, f_k, $k = 1,2$, at which the nonuniform different bandwidth subchannel filters merge. Thus, the cyclic features of this non-equiponderated Nu-FBMC/OQAM signal are exhibited at the cyclic frequencies $\alpha = 2f_{p1}, 2f_{p2}, 2f_1, 2f_2$. Conjugate cyclic features at cycle frequencies corresponding to the frequency boundaries between nonuniform subchannel filters of different bandwidths are not suppressed due to differences in their partial amplitude contribution to the generation of the overall Nu-FBMC/OQAM signal.

However, when the different subchannel transmit powers are equiponderated, only the cyclic features associated with the frequency boundaries of the overall Nu-FBMC/OQAM signal are exhibited. In the considered case, these are the cyclic frequencies $\alpha = 2f_{p1}$, $2f_{p2}$, as shown in Fig. 6. In this case, the subchannel frequency responses obtained without aggregation and with the aggregation of two uniform adjacent channels are weighted by a factor of 2 and $\sqrt{2}$, respectively, in relation to the subchannel with aggregation of four uniform adjacent subchannels.

V. CONCLUSION

It is shown, based on the proposed extended FS-FBMC approach, which uses subchannel aggregation of even-spaced and odd-spaced uniform filter banks, that a Nu-FBMC/OQAM signal can be generated. Orthogonality conditions of this signal are empirically determined and confirmed by simulations in MATLAB®. The performed analysis and simulation results show that Nu-FBMC/OQAM signals exhibit the characteristic conjugate cyclic features at the cycle frequencies associated with the edge frequencies of the Nu-FBMC/OQAM signal bandpass. However, in the case when the subchannel transmit powers are not equiponderated, additional conjugate cyclic features associated with the frequency boundaries between nonuniform subchannel filters with different bandwidths are exhibited.

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