Budapest University of Technology and Economics
Faculty of Electrical Engineering and Informatics
Department of Broadband Infocommunications and Electromagnetic Theory
MATLAB Laboratory

# Optimization of FBMC-OQAM Transceiver Architectures

*Ph.D. thesis booklet*

Author:
Husam Al-Amaireh

Supervisor:
Dr. Zsolt Kollár

Budapest
2021

Budapest University of Technology and Economics
Faculty of Electrical Engineering and Informatics
Department of Broadband Infocommunications and Electromagnetic Theory
MATLAB Laboratory
H-1111, Budapest, Egry Jozsef utca 18.
E-mail: husam.al-amaireh@edu.bme.hu

# 1 Background and objectives

Fifth generation cellular networks technology (5G) has addressed many challenges including design structures of the transceivers that can best accommodate future requirements. Being one of the favorite candidates for the physical layer of 5G; Filter Bank Multi-Carrier (FBMC) is the focus of my thesis. FBMC is expected to play an important role in wireless communications for future 5G and beyond. Despite many benefits introduced by FBMC like its spectral efficiency by providing well localized time/frequency signals, it still has a major disadvantage compared to Orthogonal Frequency Division Multiplexing (OFDM) transceivers where the FBMC has a higher complexity due to implementing a Prototype Filter (PF) for each sub-carrier at both transmitter and receiver sides.

The FBMC modulation scheme is capable of transmitting $N$ parallel streams combined into one symbol using Offset Quadrature Amplitude Modulation (OQAM). The complex input stream $S$ is split into real and imaginary parts, and they are transmitted with an offset of a half symbol duration $N/2$. Then, each stream is filtered by a PF $p_0$ and modulated to a separate sub-carrier frequency. The resulting discrete time-domain baseband FBMC signal can be expressed as:

$$x[n]= \sum_{m=-\infty}^{\infty} \sum_{k=0}^{N-1} \left(\Theta^k \Re\{S_k[m]\} p_0[n-mN] + \Theta^{k+1} \Im\{S_k[m]\} p_0[n-mN-N/2]\right) e^{j\frac{2\pi}{N}kn}, \quad (1)$$

where $j = \sqrt{-1}$ is the imaginary unit and $S_k[m]$ is the complex QAM value – taken from the complex modulation alphabet – in the $m^{\text{th}}$ symbol on the $k^{\text{th}}$ sub-carriers with the frequency $f_k = \frac{2\pi}{N}k$. Each sub-carrier is additionally multiplied by a phase rotation factor $\Theta^k = e^{j\frac{\pi}{2}k}$ in order to ensure the orthogonality between the neighboring sub-carriers and the consecutive symbols. The time-domain structure of the FBMC signal is shown in Fig. 1. It can be seen that the $m^{\text{th}}$ symbol is overlapping with the time-domain symbols

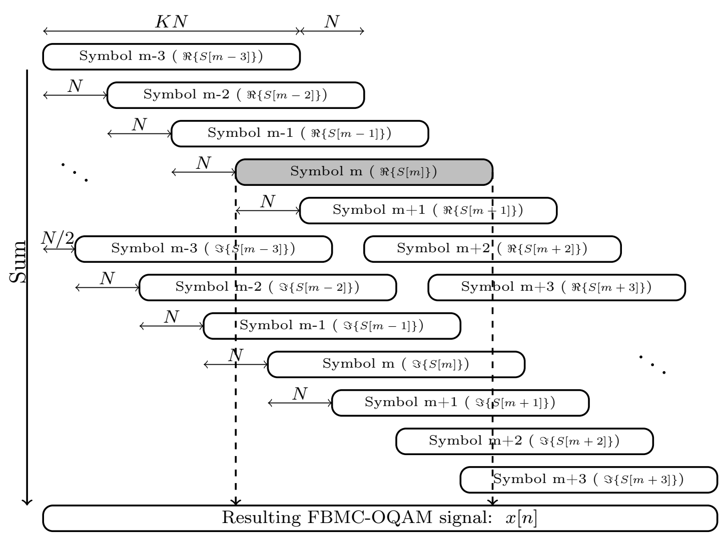


Figure 1: Signal structure of a time-domain FBMC signal with an overlapping factor of $K = 4$.

with indices $m-3, \ldots, m+3$. At a given time instant four symbols overlap in the resulting FBMC signal, which corresponds to the overlapping factor $K$. Considering the OQAM, an offset of $N/2$ can be seen between the symbols generated from $\Re\{S[m]\}$ and $\Im\{S[m]\}$.

In the literature, the FBMC signal can be realized using any of the two structures: Frequency spreading (FS) and Polyphase Network (PPN). These two structures will be explained in details.

1. FS-FBMC transmitter

   FS transmitter implements an IFFT at the modulator of an augmented size equal to $N$ multiplied by overlapping factor $K$, and the filtering process is performed in frequency domain. The basic idea in this transmitter structure is to construct the transmitted symbols in the frequency-domain, and then convert them to the time-domain using enlarged IFFTs as in [1]. The real and imaginary data parts are extracted from the input data symbols $S[m]$ and are treated separately where an IFFT of size $KN$ is applied at each data part. The $k^{\text{th}}$ sub-carriers is multiplied with the phase rotating factor $\Theta^k$ and spread around the discrete frequency with the index $kK$. Each spread value is multiplied by the frequency-domain coefficients of the prototype filter $P_\kappa$ – where $\kappa = 0, \ldots, K-1$ – in a symmetric manner. The block diagram of FS transmitter can be seen in Fig. 2.

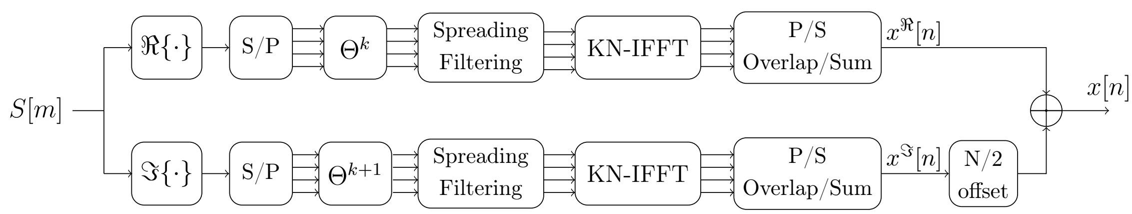


Figure 2: Creating an FBMC signal using FS with two $KN$-IFFT.

2. PPN-FBMC transmitter

   PPN transmitter implements a size $N$ IFFT which plays the role of filter bank modulator, and the filtering process is performed in time domain as shown in [2]. Polyphase filter representation reduces significantly the complexity of filter bank, and it can be represented as the following:

$$\mathbf{P} = \begin{bmatrix} \Theta^0 \\ \Theta^1 \\ \vdots \\ \Theta^{N-1} \end{bmatrix} \odot \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & W_N^1 & \cdots & W_N^{N-1} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & W_N^{N-1} & \cdots & W_N^{(N-1)^2} \end{bmatrix} \begin{bmatrix} P_{0,0}\left(z^N\right) \\ P_{0,1}\left(z^N\right) z^{-1} \\ \vdots \\ P_{0,N-1}\left(z^N\right) z^{-(N-1)} \end{bmatrix}, \tag{2}$$

   where the first vector represents the phase rotation which is multiplied element-wise ($\odot$) with a matrix ($\mathbf{W}$), which is the Inverse Discrete Fourier Transform (IDFT) matrix and the last one is an PPN decomposition with the corresponding delays. The FBMC transmitter using two N-IFFTs and PPN filtering is presented in Fig. 3.

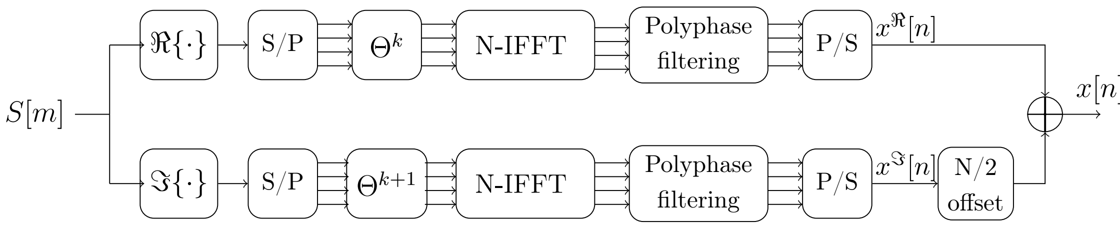


Figure 3: Creating an FBMC signal using two $N$-IFFT and PPN filtering.

Regarding complexity consideration requirements, PPN is more preferred at the transmitter side, for this I have addressed the complexity reduction of PPN transmitters by proposing a new improved PPN transmitter structure. By using MATLAB simulation and mathematically derived equations, I have shown that the new structure provides better complexity compared with standard structures, furthermore the new proposed structure provides better quantization errors performance compared with standard structures.

Considering FBMC receivers, again FS requires more complexity than PPN, however several studies suggested that FS is more preferable at the receiver side for number of reasons mainly because of its equalization performance compared with PPN. To tackle the increased FS complexity disadvantage and to make it more closer to PPN at the receiver side, I have introduced a new structure which benefits from the signal reception process at the receiver side known by sliding window as shown in Fig. 4, by implementing a recently introduced Discrete Fourier Transform (DFT) algorithm which is called Hopping DFT (HDFT). Furthermore, I have derived an improved HDFT structure that can perform much better in terms of complexity and processing delays compared with the original one. Regarding PPN receivers, I have also introduced two different receivers structures, the first one by replacing the two FFTs with one, while the other structure replaces the two full size FFTs with two half sized ones. MATLAB simulation results has proven that the new method has reduced the complexity of FS structure.

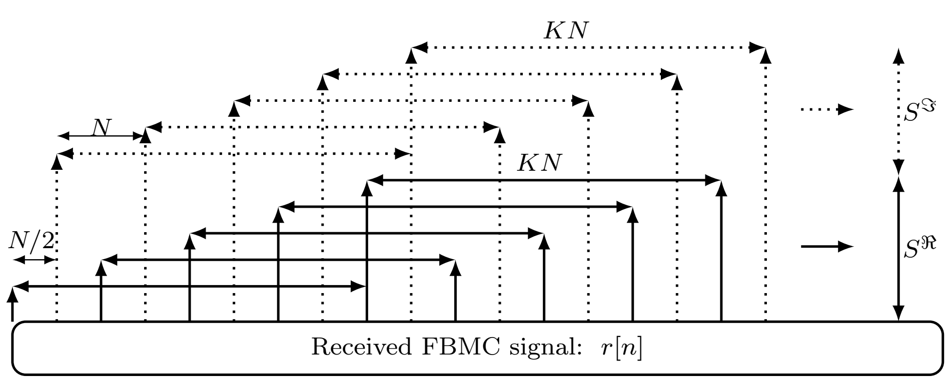


Figure 4: Received FBMC signal using sliding window operation.

# 2 Investigation methods

In order to achieve the previously mentioned goals and to verify the proposed results the following investigation methods were used.

## 2.1 Mathematical derivations and signal processing steps

The modified improvements to the state of the art FBMC transceiver structures were introduced both in terms of block diagrams and detailed signal processing steps. Furthermore, the equivalence of the proposed schemes were also shown. A thorough, step by step, explanation of the complexity requirement were provided, detailing the hardware complexity of each signal processing block. The complexity requirements were expressed in terms of number of required real additions and multiplications in order to give a guide for systems engineers developing and realizing hardware implementation of FBMC physical layers.

## 2.2 Simulation

All of the proposed FBMC transceiver structures were programmed, simulated and verified using MATLAB environment. The simulation results are in line with the expected and theoretical results. Furthermore, a standalone toolbox was also developed which is able to simulate the FBMC transceiver architectures in different scenarios.

# 3 List of publications

This thesis is the results of the work which has been published in the following journals and selected conference contributions. Until now these publications have received 8 independent citations.

## 3.1 Journal papers

J1. Zs. Kollár and H. Al-Amaireh. FBMC transmitters with reduced complexity. *Radioengineering*, 27(4):1147–1154, Dec. 2018. Impact Factor (1.048)

Independently cited by [4], [5], [6], [7].

J2. H. Al-Amaireh and Zs. Kollár. Overview and complexity evaluation of FBMC transmitter architectures. *Infocommunications*, X(4):10–16, 2018

J3. H. Al-amaireh and Zs. Kollár. Optimization of hopping DFT for FS-FBMC receivers. *Signal Processing*, page 107983

## 3.2 Conference papers

C1. H. Al-Amaireh and Zs. Kollár. Complexity comparison of filter bank multicarrier transmitter schemes. In *2018 11th International Symposium on Communication Systems, Networks Digital Signal Processing (CSNDSP)*, pages 1–4, July 2018

Independently cited by [4], [11], [12].

C2. H. Al-Amaireh and Zs. Kollár. Reducing the complexity of FS-FBMC receivers using Hopping DFT. In *2019 29th International Conference Radioelektronika (RADIOELEKTRONIKA)*, pages 1–5. IEEE, 2019

Independently cited by [4].

# 4 New scientific results - Theses

**Thesis group I: Improving the structure of the PPN-FBMC transmitter**

FBMC-OQAM transmitters can be implemented using two different structures that are derived from the direct implementation. These two structures are the Frequency Spreading (FS) based and PolyPhase Network (PPN) based. At the transmitter side, they both generate the same FBMC transmit signal. However, they differ in the applied signal processing steps. FS transmitters apply filtering in the frequency domain. Afterwards, an IFFT of size $KN$ is applied and finally the symbols are overlapped and summed in the time domain. On the other hand, PPN transmitters apply an IFFT of size $N$ and then the filtering is applied in the time domain using a Polyphase filter bank. Due to the augmented IFFT size, the FS based FBMC transmitters have a higher complexity. Hence, PPN based transmitter architecture is preferred.

At the transmitter side, the real and imaginary parts of the complex input symbols are extracted and processed separately before being transmitted with an offset of $N/2$ between them. The method presented by Varga & Kollár, the complexity of the PPN transmitter was reduced by replacing the two IFFTs with a single one. In my work I propose another alternative solution to improve the PPN structure by replacing the two FFTs of size $N$ each with two IFFTs of size $N/2$. This improvement will reduce the complexity requirements of the PPN transmitter to almost the half of the conventional PPN-FBMC transmitter. Furthermore, the quantization error of the proposed schemes is the lowest among existing solutions. My contributions in this thesis group are:

**Thesis I-1:** I have proposed an alternative PPN-FBMC transmitter structure which improves the complexity requirements using $N/2$-IFFTs instead of $N$-IFFTs. The proposed structure can be seen in Fig. 5.

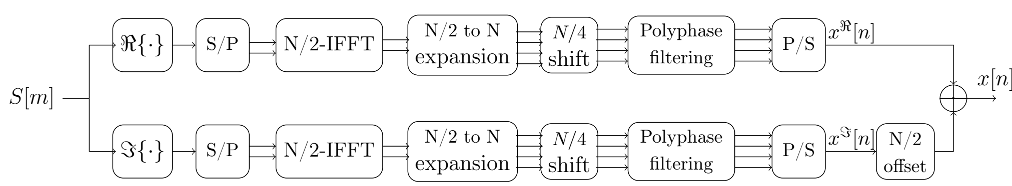


Figure 5: Thesis-I: The proposed alternative structure for creating the FBMC-OQAM signal using two $N/2$-IFFT and PPN filtering.

**Thesis I-2:** I have shown through simulations that in terms of quantization error my proposed structure shows the best performance compared to existing solutions in the literature.

The results presented for this thesis group were published in [J1].

**Thesis group II: Improving the structure of FBMC-OQAM receiver**

Although PPN structure is more preferred at the transmitter side mainly because of its reduced complexity, the decision at the receiver side is more complicated. FS receivers have shown better performance when being implemented in multi-path channels as suggested by several authors. The major complexity of FS receivers arises from FFT implementation. The signal reception at the FS receivers is performed by applying a sliding window of size $KN$ and it keeps shifting by uniform steps of size $N$. By implementing a lately introduced algorithm called Hopping Discrete Fourier Transform (HDFT), I have proposed a new FS structure that only processes the new incoming symbols of size $N$ or $N/2$ rather than processing the whole FBMC of size $KN$. Furthermore, I have also shown that the proposed architecture has a smaller latency as it requires less stages compared with the original one.

On the other hand, PPN receivers have a major advantage over FS in that they have a significantly lower complexity. By benefiting from the received signal characteristics, the receiver structure can be further improved. I have shown that PPN receivers can be improved in either of the following ways: whether by replacing the two FFTs with a single one or by replacing two full size FFTs with half sized ones. These improvements differ from the methods I have proposed for PPN-FBMC transmitter in that they require additional signal processing steps due to the overlapping nature of the FBMC-OQAM signal. My contributions in this thesis group are:

**Thesis II-1:** I have proposed novel FS-FBMC receiver structures by implementing HDFT based on hopping steps of size $N$ as can be seen in Fig. 6.

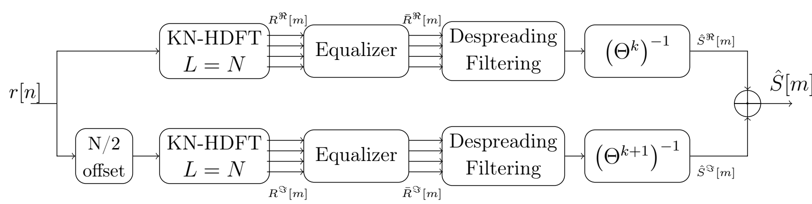


Figure 6: Thesis-II: FS-FBMC using HDFT with $L = N$.

**Thesis II-2:** I have proposed novel FS-FBMC receiver structures by implementing HDFT based on hopping steps of size $N/2$ where the performance differs from the previous one depending on overlapping factor $K$. The novel structure is given in Fig. 7.

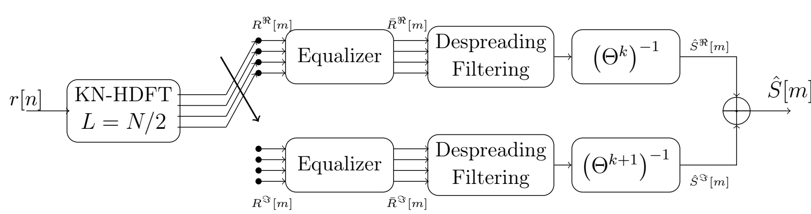


Figure 7: Thesis-II: FS-FBMC using HDFT with $L = N/2$.

**Thesis II-3:** I have proposed a novel PPN-FBMC receiver implementation using a single FFT instead of two as shown in Fig. 8. Also, I have shown that in order to implement the new structures, additional signal processing steps are needed compared to the PPN-FBMC transmitter.

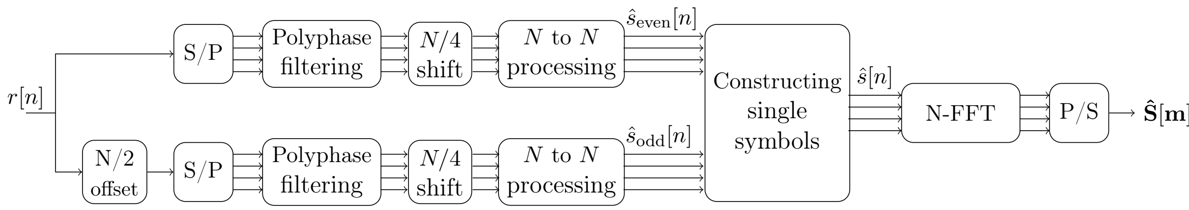


Figure 8: Thesis-II: Recovering the FBMC-OQAM signal using single N-FFT and PPN filtering.

**Thesis II-4:** I have proposed a novel PPN-FBMC receivers by implementing two half FFTs instead of two full size ones as shown in Fig. 9. I have also shown that in order to implement the new structures, additional signal processing steps are needed compared to the PPN-FBMC transmitter.

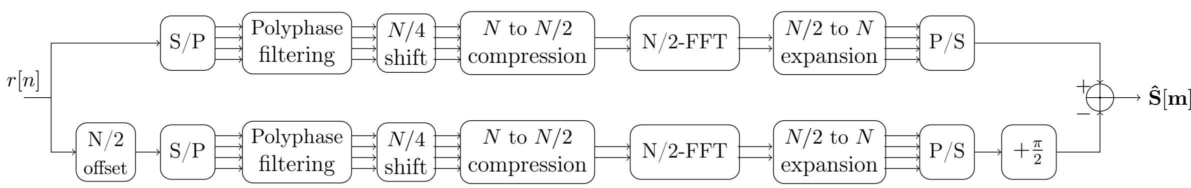


Figure 9: Thesis-II: The proposed alternative structure for recovering the FBMC-OQAM signal using two N/2-FFTs and PPN filtering.

The results presented for this thesis group were published in [C2] and [J3].

**Thesis group III: Derivation of a novel and faster HDFT structure**

The implementation of standard HDFT in FS-FBMC receivers will reduce its complexity as mentioned. In this thesis I go a step further and improve the HDFT itself. HDFT is composed of several terms including one called Updating Vector Transform (UVT). The structure of UVT has some similarities with Discrete Fourier Transform (DFT). I have exploited UVT structure and managed to derive an improved and significantly faster one. My contributions in this thesis group are:

**Thesis III-1:** I have derived three improved HDFT structures through optimizing the UVT block based on a modified split-radix method. The three UVT structures are as follows:

- SR-Odd, which can be expressed as:

$$D_{k'}^{L}[m] = W_V^{-k'} \sum_{p=0}^{L/2-1} d[mL-2p] W_{V/2}^{(p-L/2+2)k'} + W_{V/2}^{-3k'} \sum_{p=0}^{L/8-1} d[mL-8p-1] W_{V/8}^{(p-L/8+1)k'} + W_{V/2}^{-k'} \sum_{p=0}^{L/8-1} d[mL-8p-5] W_{V/8}^{(p-L/8+1)k'} + \sum_{p=0}^{L/4-1} d[mL-4p-3] W_{V/4}^{(p-L/4+1)k'}. \quad (3)$$

- SR-even, which can be represented as:

$$D_{k'}^{L}[m] = W_V^{-3k'} \sum_{p=0}^{L/4-1} d[mL-4p] W_{V/4}^{(p-L/4+1)k'} + W_V^{-k'} \sum_{p=0}^{L/4-1} d[mL-4p-2] W_{V/4}^{(p-L/4+1)k'} + + \sum_{p=0}^{L/2-1} d[mL-2p-1] W_{V/2}^{(p-L/2+1)k'}. \quad (4)$$

- SR-mixed, which can be represented as a combination from SR-odd and SR-even.

Where $D_{k'}^{L}[m]$ is the UVT, in the $m^{th}$ symbol with $L$ is the hopping step size and $k'$ is the sub-carrier index.

**Thesis III-2:** I have computed the complexity requirement for all HDFT structures, compared them, and I have shown that my novel structure outperforms the previously presented solutions. For this, I have shown the results in tables and presented them in figures. As an example, Fig. 10 and Fig. 11 show the required number of multiplications for $L = N$ an $L = N/2$, respectively.

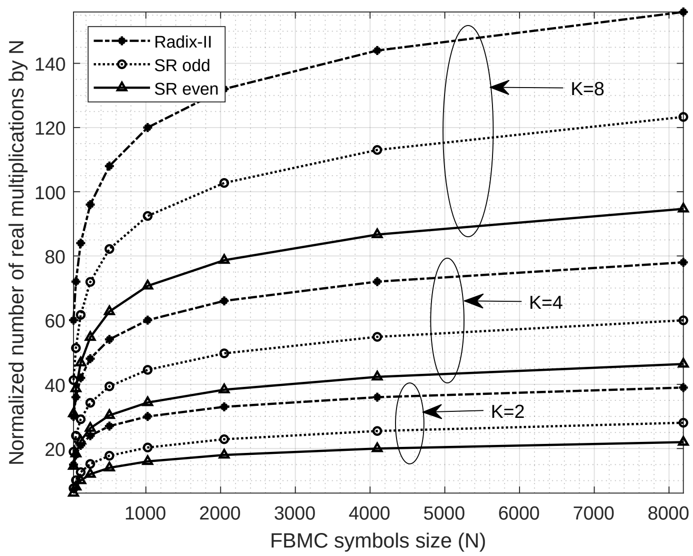


Figure 10: Thesis-III: Comparison of the number of real multiplications for different UVT implementations with $L = N$.

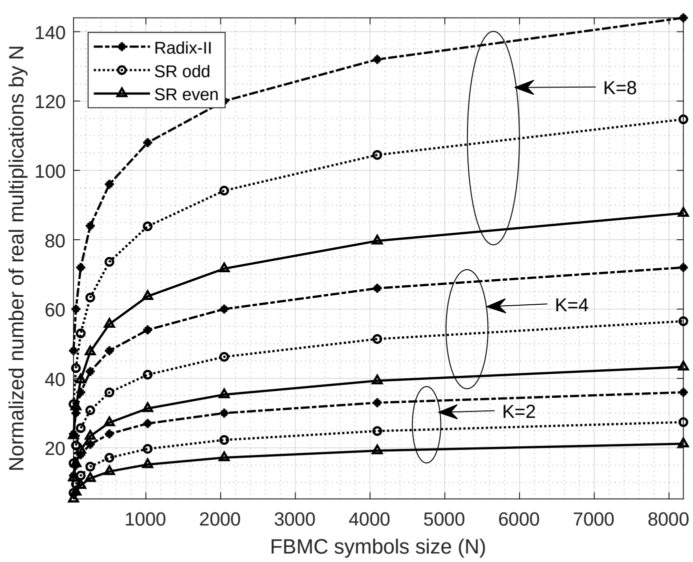


Figure 11: Thesis-III: Comparison of the number of real multiplications for different UVT implementations with $L = N/2$.

**Thesis III-3:** I have designed a new butterfly network for fast computation of UVT which can be realized in the future by FPGA. In Fig. 12, the required network to construct the UVT is built for a symbol size $N = 8$, overlapping factor $K = 4$, and hopping step of size $L = N/2$.

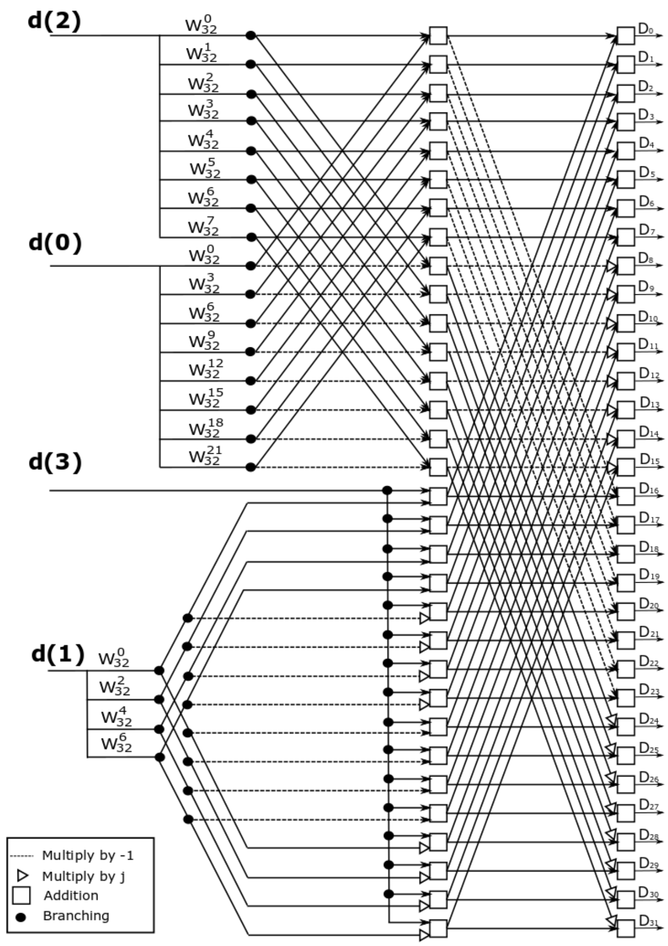


Figure 12: Thesis-III: HDFT-SR Network for $L = \frac{N}{2} = 4$ and $KN = 32$.

**Thesis III-4:** I have designed an improvement to the HDFT structure which can reduce the required multiplication by applying a modified UVT which operates alternatively, in parallel with the normal UVT for the special cases of $(K = 4, L = N/2)$, $(K = 8, L = N)$ and $(K = 8, L = N/2)$.

The results presented for this thesis group were published in [J3].

**Thesis group IV: Creating closed-form expressions for the complexity of FBMC-OQAM transceivers**

The complexity calculations are extremely important to compare and evaluate the performance of different FBMC transceiver structures. In the literature, the complexity description of the standard structures are only partially covered. Furthermore, the introduced novel structures have not been investigated either. These calculations are extremely important when FBMC transceivers are designed, especially for FGPA or VLSI platforms. My contributions in this thesis group are:

**Thesis IV-1:** I have derived the complexity requirements in terms of real multiplications and additions for the investigated FBMC-OQAM transmitters and receivers. Furthermore, the necessary comparison was performed to show which one is more preferable. In this thesis I have built several tables and generated figures accordingly as for example, Fig. 13 shows the number of multiplications for standard structures while Fig. 14 shows the multiplications for improved structures:

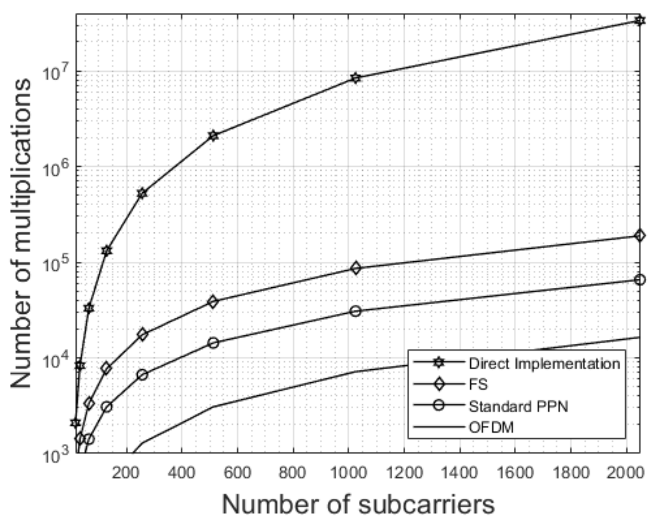


Figure 13: Thesis-IV: Number of multiplications for the standard FBMC-OQAM transmitters as a function of the number of sub-carriers $N$.

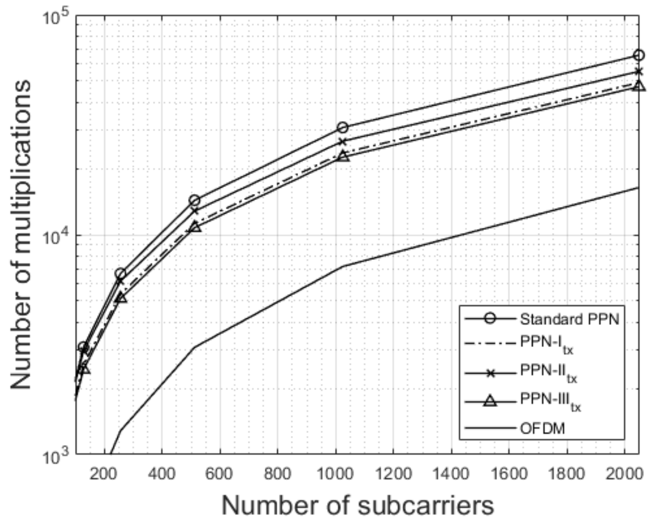


Figure 14: Thesis IV: Number of multiplications for the improved FBMC-OQAM transmitters as a function of the number of sub-carriers $N$.

**Thesis IV-2:** I have derived the complexity requirements in terms of real multiplications and additions for HDFT-FBMC receivers. I have also shown their dependency on overlapping factor $K$. Furthermore, I have given an optimized implementation for the two proposed structures as an example, the results shown in Fig. 15, and Fig. 16 for the overlapping factor $K = 2, 4$ respectively:

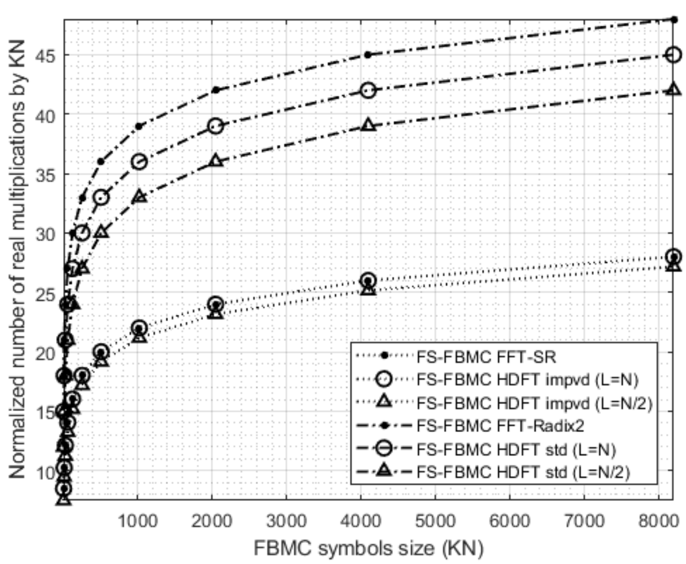


Figure 15: Thesis-IV: Complexity comparison of improved versus unimproved FS-FBMC receivers ($K$=2).

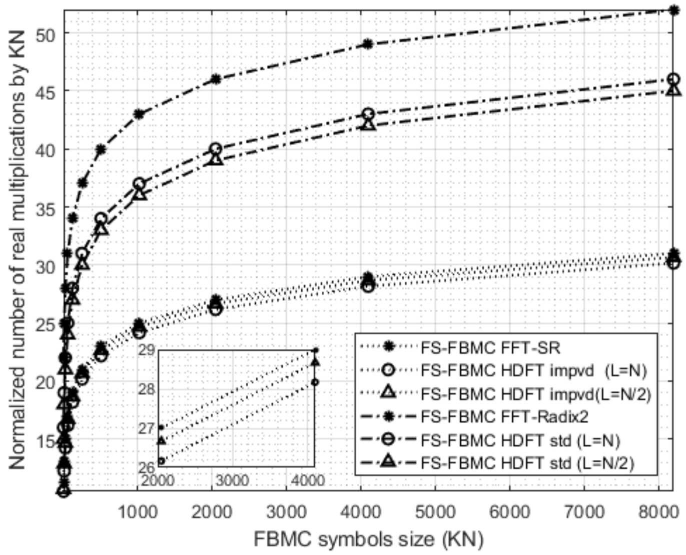


Figure 16: Thesis-IV: Complexity comparison of improved versus unimproved FS-FBMC receivers ($K$=4).

The results presented for this thesis group were published in [J1], [J2], [J3], and [C1].

# 5 Utilization of the results and outlook

FBMC signal has a very attractive signal characteristics as it is well-localized in both time and frequency domain simultaneously. These characteristics make FBMC, and in particular FBMC-OQAM a strong multi-carrier modulation candidate scheme for future wireless access generations especially when considering the forecast of a tremendous increase in data rates requirements which dictates more strict emphasis on the bandwidth efficiency and on the spectral mask.

There are several multi-carrier schemes which can be an a possible alternative to OFDM such as GFDM, UFMC, and FBMC. I have chosen the latter to be the core of my thesis work, I have described its main features and detailed its different variants which are: CWT, FMT, and FBMC-OQAM. I focused my work on improving FBMC-OQAM variant as it is considered the most preferred one mainly because of its bandwidth efficiency compared with CWT and a more relaxed filter transition bandwidth compared with FMT. Furthermore, I have established the background for the design and characteristics of the applied prototype filters that can be implemented in FBMC both at the transmitters and at the receivers.

Throughout my work, I have investigated and detailed the possible FBMC-OQAM transmitters structures known from the literature. At the transmitter, the real and imaginary parts of the complex input symbols are extracted and processed separately before being transmitted with an offset of $N/2$ between them with each FBMC-OQAM symbol overlap with a number of symbols that equals $K$. I have given the description of the two standard structures which are FS-FBMC and PPN-FBMC. Both transmitter structures generates the same signal characteristics. Nevertheless, PPN-FBMC is being preferred over FS-FBMC because of its lower complexity requirements. As a result, I have worked on further improving PPN-FBMC transmitter structure. First, I have demonstrated further improved structures introduced by other authors. Then, I have designed and introduced a novel structure. This new structure modifies the standard PPN-FBMC by replacing the two full symbol size IFFTs by two IFFTs with a half symbol size. This improvement is achieved by benefiting from real data processing of FBMC-OQAM scheme.

Furthermore, The analysis of my proposed transmitter structure was given. I have derived the complexity requirements (number of real multiplications and additions) for all standard structures which are: direct implementation, FS-FBMC and PPN-FBMC. Then, I have derived the complexity requirements for the improved PPN-FBMC structures. I have presented the complexity requirement of the structures and I have compared the results. I have shown that my proposed novel structure reduces the complexity requirements for standard PPN-FBMC almost by half, then I have shown that my proposed structure can achieve the lowest quantization error compared to the other investigated structures.

Moreover, I worked on improving FBMC-OQAM receivers structures as well. As mentioned earlier FS-FBMC requires significantly higher computational complexity compared with PPN-FBMC. The same case applies for the receiver design, however, when considering the choice of the receiver implementation, other factors play important roles as well. Several studies suggested that FS-FBMC receiver has a superior performance in case of multi-path channels and it is considered to be less sensitive to misalignment due to time synchronization errors compared to PPN-FBMC. For these reasons, I proposed improvements for both types of receiver structures. Regarding FS-FBMC structure, I have detailed its general structure then by studying the structure of FBMC-OQAM received signal I proposed novel structures. The signal reception for the FS-FBMC receiver is performed by applying a sliding observation window of size $KN$ and it keeps shifting by uniform steps of size $N$. Based on this sliding property, I proposed a structure that is based on a recently introduced algorithm called HDFT, where instead of recalculating the FFT for the entire $KN$ long symbols, only samples of size $N$ or $N/2$ need to be processed in a recursive manner. Based on HDFT, I have proposed two alternatives for FS-FBMC receivers by applying hopping step size of $N$ or $N/2$. I have also derived a UVT algorithm with a lower complexity which can be applied in HDFT structures. The new algorithm reduces the complexity of the original HDFT to almost half. Considering PPN-FBMC receivers, I have proposed two novel structures: first by replacing the two FFTs with a single one and the second structure by replacing two FFTs with two half sized FFTs. The modifications of PPN-FBMC receivers require extra signal processing compared with the modifications applied at the improved PPN-FBMC transmitters.

In addition to deriving the novel receivers structures, I have also analyzed them and I have also given the complexity for the standard structures known from the literature: direct implementation, FS-FBMC, and PPN-FBMC. Then, I have presented a detailed study of the complexity requirements for the proposed modified structures. I have also shown that the efficiency of each HDFT structure depends on the overlapping factor $K$. I have shown that when $K = 2$, HDFT with $N/2$ hopping step size performs better, on the other hand, when $K = 4, 8$ then HDFT with hopping step size $N$ performs better. Also, I have also given the complexity requirements for the improved PPN-FBMC receivers. I have presented the results in tables and compared them visually through figures as well. It was shown that PPN-FBMC improved structures always require the lowest complexity among other FBMC receivers. It was also shown, that HDFT receiver structure can reduce the complexity of FS-FBMC receivers. Finally, because of extra multiplications with twiddle factor required for HDFT, I have introduced further improvements to HDFT that eliminates or reduces (depending on $L$ and $K$) the multiplications required by the twiddle factor.

As a future work, the hardware implementation of the suggested transmitter and receiver architectures would be beneficial. A deep analysis of the effects of the numerical precision should be studied in details, especially considering fix-point implementations. This will play an important role if FGPA or VLSI realization is considered. It is expected that large volumes of low cost hardware will be implemented in future networks which means that quantization noise will be significant due to the applied low precision hardware. Also, the effects of the numerical precision on the spectral characteristics should be investigated. Furthermore, the possible channel equalization techniques should be taken also into account when analyzing the bit error rate performance of the proposed receiver architectures, and joint design concept which benefits for both low complexity and good bit error rate performance should be developed.

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