Digital filtering based on fast theoretical and numerical transformations for 5G systems

I A Kalmykov¹², V Sh Mukhametshin², K T Tyncherov² and M V Selivanova²

¹ North-Caucasus Federal University, 1, Pushkin St., Stavropol, 355017, Russian Federation
² Ufa State Petroleum Technological University, Branch of the University in the City of Oktyabrsky, 54a, Devonskaya St., Oktyabrsky, Republic of Bashkortostan, 452607, Russian Federation

E-mail: kia762@yandex.ru, info@of.ugntu.ru

Abstract. Currently, a trend to increase the performance of wireless data transmission systems can be observed. This requires a new protocol for mobile communications. The draft IMT-2020 standard involves the use of promising 5G mobile networks. These systems must have characteristics that will exceed 4G standards. New technologies will provide a higher data rate and minimal network delays, which should not exceed 1 ms. To achieve these goals, the 5G standard involves the broadband transmission using FBMC (Filter Bank MultiCarrier) or UFMC (Universal Filtered MultiCarrier). Studies have shown that the UFMC method allows for better subcarrier filtration compared to FBMC comb filtration. However, the use of this method requires high computational costs, which negatively affects the speed of information transfer and network delays. Therefore, the aim of the article is to reduce network delays when using the technology of filtering UFMC signals by using a fast algorithm for performing theoretical and numerical transformations (TNT). Therefore, the development of a fast algorithm for performing theoretical and numerical signal transformations for OFDM systems that support the 5G standard is an urgent task

1. Introduction
The growing number of Wi-Fi creates a situation when the existing standards of wireless communication systems do not fully meet the growing needs (e.g., in the oil and gas industry, with the transfer of large amounts of diagnostic information and well monitoring) [1-3]. This requires a new protocol for mobile communications, in particular 5G. The draft IMT-2020 standard is being developed, according to which promising 5G mobile networks must have characteristics that exceed 4G standards. New technologies can increase the transfer rate up to 10 Gbps. The network delays should not exceed 1 ms. The requirements of the promising 5G protocol set in the draft IMT-2020 standard will allow the efficient maintenance of up to one million devices per square kilometer [1-3].

The development of 5G wireless networks is based on two technologies. The first one is broadband transmission using FBMC (Filter Bank MultiCarrier) comb filtration [4]. The second one is based on the use of UFMC (Universal Filtered MultiCarrier) [5]. This approach improves the quality of service that has been achieved in LTE / LTE-Advanced wireless communication systems and the IEEE 802.11a / g / n / ac standard. In particular, the use of filters helps to abandon the cyclic prefix, improving the spectral efficiency of the OFDM signal. However, this increases the computational cost
of digital filtering procedures, which increases the network latency. Therefore, the aim of the article is to reduce network delays when using the technology of filtering UFMC signals by using a fast algorithm for theoretical and numerical transformations (TNT).

2. Materials and methods

The desire to improve the efficiency of 5G mobile networks has intensified studies on modification of OFDM technologies. To improve the spectral efficiency of a signal with frequency orthogonal multiplexing, additional digital signal processing can be implemented. There are two main approaches to implementing digital filtering techniques in OFDM technology. In [2-5], it was shown that the basis of the first approach is broadband transmission methods based on FBMC filtering. The second approach is based on the use of universal UFMC filtering (Filter Bank MultiCarrier).

The first one includes broadband transmission methods using FBMC (Filter Bank MultiCarrier) comb filtration. The second one is based on the use of UFMC (Universal Filtered MultiCarrier). Applying this approach improves the quality of services that has been provided in LTE / LTE-Advanced wireless communication systems and the IEEE 802.11a / g / n / ac standard. In particular, the use of filters helps to abandon the cyclic prefix, improving the spectral efficiency of the OFDM signal. In [6-8], the approaches increasing the speed of digital filtering are presented. One of the promising approaches is the use of fast theoretical and numerical transformations [9].

Figure 1 shows a functional diagram of the transmitting device using UFMC filtering technology without taking into account the units performing digital-to-analog conversion and frequency transfer for transmission over the communication channel.

When implementing UFMC technology, a serial stream consisting of N binary characters must be divided into B parallel blocks. Each such unit is fed to the inputs of QAM modulators. In the serial stream of symbols \( x_{1,k} \), \( i \in 1 \ldots B \), \( k \in 1 \ldots N/B \) are fed to the inputs of the converters of serial samples to parallel (S / P) from the outputs of QAM modulators, and then to the inputs of 2N-pt IFFT units implementing point inverse fast Fourier transformations (OBPF). The size of the OBPF is determined by the need to obtain real time components. Complex-conjugate QAM symbols are added to each block. The result is a frequency range consisting of B sequentially arranged subbands, which contain information subcarriers, as shown in Figure 1.

From the outputs of the 2N-pt IFFT units implementing the point OBPF, the real time components \( X_{1,k} \), where \( i \in 1 \ldots B \), \( k \in 1 \ldots 2N \), are converted into a serial stream by means of P / S converters. The time components of the signal are fed to the inputs of the FIR filters, which are designated as Band Filter Fi, length L in Figure 1. These digital filters have a finite pulse response, which is determined by the information subcarriers of the respective subbands.

![Figure 1. The diagram of a transmitting device that implements UFMC filtering](image-url)
It is known that the length of the FIR filter has a primary impact on the spectral characteristics of communication systems using UFMC filtering. To reduce the value of the spectral components outside the bandwidth, it is necessary to increase the order of the filter. This also helps to increase the resistance of the FIR filter to distortions in the multipath channel and synchronization errors [6]. Therefore, in the 5G systems using UFMC filtering, the filter order equal to 7% of the value of the OBPF block should be chosen.

However, by improving the spectral components of the 5G signal, additional UFMC filtering has a negative effect on the signal processing time. Additional filtering increases the calculations required to generate symbols. Thus, to obtain real time samples of the OFDM signal, it is required to perform complex multiplication operations, as well as complex addition operations. Then the time cost for the UFMC symbol formation will be many times greater than the cost of implementing OBPF. This is due to the fact that 2N time frames taken after the OBPF are subjected to digital filtering, which is based on the linear convolution

\[
Y_{i,n} = \sum_{j=1}^{2N+L-1} h_{i,j} X_{i,n-j}, \quad n \in 1,\ldots,2N + L - 1,
\]  

where \( Y_{i,n} \) – filter response; \( X_{i,k} \) – input sequence of samples; \( h_{i,j} \) – filter weights; \( n \in 1,\ldots,2N + L - 1; \quad i \in 1,\ldots,B; \quad k \in 1,\ldots,2N; \quad L \) – the order of the FIR filter.

Using this filter for digital filtering, \((2N + L - 1)L\) multiplication operations will be required [6]. It is obvious that increasing the order of the filter \( L \) will lead to significant time delays, which are associated with the need to obtain a response.

To reduce the network delay when using UFMC filtering, it is proposed to use cyclic convolution of the input sequence \( X_{i,k} \) and FIR filter coefficients \( h_{i,j} \). Transform real values of samples \( X_{i,k} \), where \( i \in 1,\ldots,B, \quad k \in 1,\ldots,2N, \) in \( X_{i,k}^* \). Do the same with the FIR filter coefficients \( h_{i,j} \). As a result, we have \( h_{i,k}^* \), where \( i \in 1,\ldots,B, \quad k \in 1,\ldots,L \). Since \( N \) is selected from the condition that it is a power of 2, we will add 2N zeros to the input sequence. Add \( 4N - L \) zeros to the coefficients of the FIR filter. This makes it possible to obtain two sequences that have a length of \( 4N \), to which a cyclic convolution can be applied.

It is possible to use the cyclic convolution property to increase the speed of digital filtering based on the theoretical-numerical transformation. To do this, determine the theoretical and numerical images of the sequences \( X_{i,k}^* \) and \( h_{i,k}^* \): \[
H_{i,n} = \sum_{k=0}^{4N-1} h_{i,k}^* e^{kn} \mod q,
\]

\[
S_{i,n} = \sum_{k=0}^{4N-1} X_{i,k}^* e^{kn} \mod q,
\]

where \( X_{i,k}^* \) and \( h_{i,k}^* \) – processed sequences, \( S_{i,n} \) and \( H_{i,k} \) – transformation results, \( e \) – the core of the theoretical-numerical transformation; \( q \) – prime number; \( n = 0,\ldots,4N - 1 \).

Determine the product of the transformation results.

\[
G_{i,n} = S_{i,n} H_{i,n} \mod q.
\]

After that, the inverse theoretical-numerical transformation is applied to the obtained result. Then we have

\[
g_{i,k} = \frac{1}{4N} \sum_{n=0}^{4N-1} G_{i,n} e^{-kn} \mod q,
\]

where \( N \) and \( q \) – mutually prime natural numbers, \( e \) satisfies the conditions \((e^N) \mod q = 1\).
It is obvious that the gain in the performance of expression (2) - (5) is possible if we use a fast algorithm for calculating the TNT. In [9], we presented an algorithm for fast execution of TNT, which is similar to the fast Fourier transform (FFT). With an input sequence length of $M$, the theoretical and numerical conversion of the signal can be realized during $M \log_2(M)$ multiplication operations.

3. Results and Discussion

Consider the development of a fast algorithm for performing theoretical and numerical signal transformations for 5G systems using OFDM technology. The simulation model was developed for comparative analysis in Matlab 2017. The Dolf-Chebyshev FIR filter was selected as the FIR UFMC filter. The window size, determined by the pulse response of the digital filter, is 74 samples. The attenuation of the UFMC filter outside the bandwidth is 60 dB. The selected size of the theoretical-numerical transformation is 2048 samples. The module used in the TNT implementation is equal to $q = 974849$.

It is obvious that when implementing the fast TCHP algorithm of the convolution, it will be necessary to perform $8BN\log_2(4N)$ modulation operations. In this case, the TNT images of the Dolf-Chebyshev FIR filter coefficients can be obtained in advance. Therefore, to implement the fast algorithm, it is necessary to solve equations (3) - (5).

The comparative analysis of the fast algorithm will be conducted following the classical approach by determining the response of the digital UFMC filter. Figure 2 shows the dependence of the number of multiplications when filtering in UFMC and UFMC NTT technologies on the size $N$ of the binary stream of transmitted data in one subchannel of the OFDM signal. Since the multiplication operation requires more time compared to other arithmetic operations, reducing the number of this operation will have a positive effect on the calculation time of the TNT.

Figure 2. The number of multiplications when filtering in UFMC and UFMC NTT technologies

Figure 2 shows that the use of the fast algorithm for TNT can reduce the number of multiplication operations compared to the classical digital filtering methods. Thus, with the length of the input sequence $N = 512$ samples, the number of integer multiplications will be 36,864. This will require 81,178 multiplication operations for UFMC filtering. This means that the use of the fast TNT algorithm can reduce the number of multiplication operations by 2.2 times compared to the classical UFMC filtering method. Thus, it is obvious that the fast TNT algorithm will reduce the network delays when using UFMC signal filtering technology.
4. Conclusion
The paper described the application of the fast algorithm for performing theoretical and numerical signal conversion in 5G wireless systems. The use of the algorithm reduced the number of multiplication operations when UFMC filtering. Thus, when processing a discrete input sequence consisting of $N = 512$ samples, the number of integer multiplications was 36,864. This will require 81,178 multiplication operations for UFMC filtering, which is 2.2 times more. Since the multiplication operation is time consuming, it is obvious that the use of the fast TNT algorithm can reduce the network delay when using the technology of filtering UFMC signals.

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