A Brief Review of Several Multi-carrier Transmission Techniques for 5G and Future Mobile Networks

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Abstract. In 5G and future mobile networks, multi-carrier techniques will greatly multiply data rate to meet people's requirements of high-speed mobile services. Traditionally, Orthogonal Frequency Division Multiplexing (OFDM) got a wide application for past decade. While OFDM has many nice aspects, it also has some disadvantages making it less attractive in the fifth generation (5G). Based on this, several advanced techniques supposed in latest literature were expected to replace OFDM because of their respective technical advantages in spectrum efficiency, complexity, compatibility and some aspects. Filter Bank Multi Carrier (FBMC), Generalized Frequency Division Multiplexing (GFDM) and Filter Bank OFDM (FB-OFDM) were reviewed in this paper. Also, their characteristics were compared with each other briefly.

Keywords: Mobile network · Multi-carrier transmission · OFDM · FBMC · FB-OFDM

1 Introduction

As the most popular signal transmission technique, Orthogonal Frequency Division Multiplexing (OFDM) has enjoyed its dominance on broadband wired and wireless channels, which was listed in the technical specifications, such as LTE-A of 3GPP. It is obvious that OFDM has high spectrum efficiency, low complexity and easy

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combination with Multiple Input Multiple Output (MIMO). However, its deficiencies also apparent: high Peak-to-Average Power Ratio (PAPR), sensitive to frequency offset and low out-of-band power decay [1]. The long-term vision of the fifth generation (5G) and future mobile network includes providing higher spectrum efficiency, supporting massive MIMO and distributed low-power terminal. In view of these requirements, OFDM may not be the optimal solution to the physical layer of 5G and future mobile network partially due to the rectangular pulse shaping adopted in OFDM. With strict specifications, innovative multi-carrier modulation techniques with different pulse shaping filters are proposed as alternative solutions.

As the typical representatives, three multi-carrier techniques proposed lately were addressed in this paper: Generalized Frequency Division Multiplexing (GFDM), Filter Bank Multi-Carrier (FBMC) and Filter Bank OFDM (FB-OFDM). GFDM adopts flexible pulse shaping so that have lower out-of-band radiation. Compared with OFDM, it is featured by lower complexity. FBMC havs higher spectral efficiency and avoids inter-symbol interference (ISI) effectively. On the basis of FBMC, FB-OFDM well deals with two aspects: complexity and compatibility. Thus, the technique is easier to realize. Each technique has its merits, which will be analyzed in the following sections.

The remainder of the paper is organized as follows: Sects. 2, 3 and 4 introduce the design principles and characters of GFDM, FBMC and FB-OFDM respectively. Then, In Sect. 5, comparison and analysis, the compatibility and complexity of each multi-carrier technique are presented and analyzed. Finally, the conclusions of this paper are drawn.

2 GFDM

GFDM is a kind of alternative solution on physical layer in the future 5G mobile communications which incorporates with tail-biting technique [2]. Since OFDM uses rectangular pulse shaping causing extensive spectral leakage, GFDM system adopts flexible pulse shaping (generally Root Raised Cosine or Raised Cosine) aiming to lower out-of-band radiation.

The transmitter part of GFDM technique is shown in Fig. 1. First, binary data is modulated and then divided into several sequences. Next, by applying circular convolution the transmitted signal implements filtering function. Then, sub-carrier up-conversion is performed. Similar to OFDM, GFDM also needs to add cyclic prefix (CP) in transmitter to transmit the signal flow. Further, the modulated signal is concerted to analog signal from digital signal by D/A converter and sent to the channel. The receiver part of GFDM multi-carrier system is shown in Fig. 2. After analog-to-digital (A/D) conversion, CP is removed from the receiver. Then, after channel equalization, sub-carrier down-conversion is realized [3]. Next, the signal goes through the matched received filter, the signal finally obtained after sampling and detection process.

In GFDM, due to the flexibility of shaping pulse, orthogonality is lost between sub-carries leading to the increase of Inter-Carrier Interference (ICI). So compared with

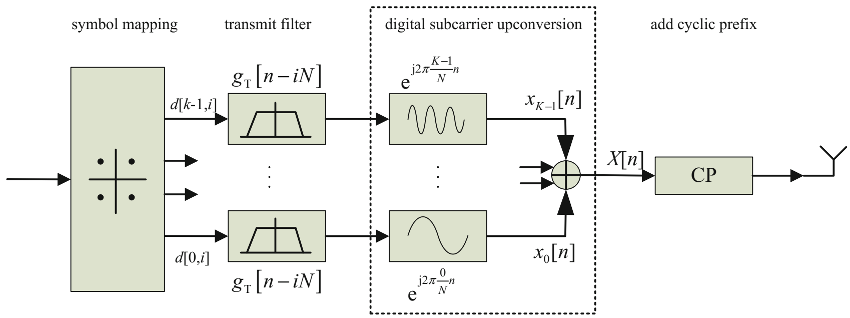

Fig. 1. The transmitter part of GFDM system

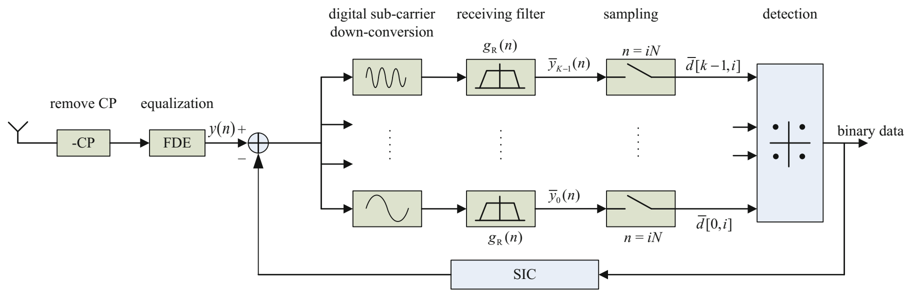

Fig. 2. The receiver part of GFDM system

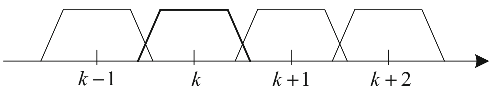

Fig. 3. The adjacent sub-carries interference in frequency domain

OFDM, GFDM has worse BER performance. As shown in Fig. 3, in frequency domain, the adjacent sub-carries interference causes ICI.

To solve the problem, Serial Interference Cancellation (SIC) is adopted in GFDM system [3]. Once a sub-carrier is detected, it is modulated once again and pulse shaping is done before up-conversion to generate the approximate transmitted signal. Then, the estimated signal is subtracted from the received signal. The same procedure is executed when the next sub-carrier comes.

There exist three differences between OFDM and GFDM: (1) GFDM does not apply rectangular pulse while OFDM does. This results in not only faster out-of-band decay but also decreased ICI for GFDM. (2) GFDM applies circular convolution in filtering process which makes GFDM less in time delay and lower computation complexity. (3) The different ways to add CP: OFDM adds CP after the modulation of each sub-carrier, while GFDM adds CP after the arrival of superposed signal. Under this circumstance, GFDM can improve spectrum efficiency apparently.

3 FBMC

FBMC is regarded as an alternative transmission technique in future 5G mobile communications which can replace OFDM since FBMC has the advantages of smaller out-of-band radiation and without adding CP [4].

FBMC suppresses the side lobe by means of a bank of parallel filters. The filter bank can be obtained by low-pass prototype filters and modulate to different carrier frequency respectively [5]. The first filter in the bank, the filter associated with the zero frequency carriers, is called prototype filter, because the other filters are deduced from it through frequency shifts. It is crucial that how to design prototype filter. The design of prototype filter is based on Nyquist theory. The global Nyquist filter is generally split into two parts, a half-Nyquist filter in the transmitter and a half-Nyquist filter in the receiver. Then, the symmetry condition is satisfied by the squares of the frequency coefficients. The frequency coefficients of the half-Nyquist filter obtained for $K = 2$, 3 and 4 are given in Table 1. Where, K is the overlapping factor, which is defined as the ratio of the filter impulse response duration to the multi-carrier symbol. And it is also the number of multi-carrier symbols which overlap in the time domain. Generally, in FBMC technique K is 4 [6]. In frequency domain, when the overlapping factor is K, the corresponding number of filter impulse response is $2K-1$.

Table 1. Frequency domain prototype filter coefficients

K	H_0	H_1	H_2	H_3
2	1	0.707106		
3	1	0.911438	0.411438	
4	1	0.971960	0.707106	0.235174

A particular realization structure of FBMC is called poly-phase network (PPN). PPN realizes the filtering function at time domain which can reduce calculation amount notably. The implementation of FBMC using PPN is shown in Fig. 4. In the transmitter, first of all, IFFT is applied to the input signals. And then, filtering is achieved by PPN. Finally, the output of the transmitter is the total of sub-channel filtering output.

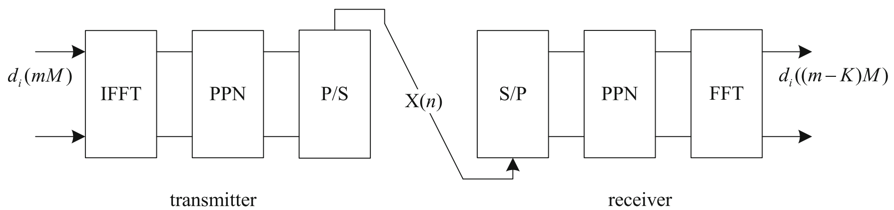

Fig. 4. The construction of PPN-FBMC

Because of the overlapping of adjacent sub-channels in frequency domain, FBMC uses a special modulation called Offset Quadrature Amplitude Modulation (OQAM) [7]. OQAM separates the input into real part and imaginary part, but the imaginary part is delayed by half the symbol duration, so that the real part and the imaginary part can output separately. OQAM makes sure all the sub-channels are exploited.

The most obvious distinction between OFDM and FBMC is that FBMC abandons CP to gain higher spectral efficiency. OFDM suffers from significant spectral leakage, while FBMC overcomes this shortcoming.

4 FB-OFDM

FBMC is a huge step forward to the technical level with good spectrum containment and relaxing synchronization condition. However, there exist two problems suspended, i.e. compatibility and complexity. The complexity is related to modulation and demodulation for a multi-carrier system, channel estimation, equalization, MIMO pre/decoding, etc. The compatibility means that FBMC should be able to reuse the existing Long-Term Evolution (LTE) techniques in a straightforward manner. To solve these two problems, a new solution called FB-OFDM has been put forward.

The steps of signal processing of FB-OFDM are shown in Fig. 5. The modulation is consists of four parts: (1) symbol extension; (2) filtering process; (3) mapping and the last (4) *MK*-point IFFT, where *M* refers to sub-carries number and *K* is the extension factor [8].

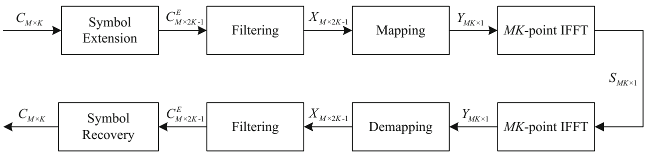

Fig. 5. The signal processing of FB-OFDM

Since OQAM processes the real part and imaginary part symbols separately to achieve high spectral efficiency, which leads to double complexity, in the first part of FB-OFDM, QAM symbol extension is used instead of OQAM compared with FBMC by some specific algorithms. The QAM symbols need to be extended according to some pre-defined pattern. Once the extension is accomplished, it then goes to the filtering part. Next, it goes to the mapping process by some overlap-sum operation which is later fed to the IFFT entries. The last step is using an *MK*-point IFFT to transform the combinational symbols from frequency domain to time domain. In theory, FB-OFDM also keeps full Nyquist rate as the classical FBMC. The difference between them is that FB-OFDM transmits QAM symbols instead of OQAM.

The FB-OFDM demodulation process is completely dual to the modulation process. The received signal uses *MK*-point FFT to transform to frequency domain at first. Then, each sub-carrier goes to the de-mapping part. Next, the filtering process is identical to the modulation part [9]. At last, the dual operation is taken to the extension process to recover the transmitted QAM symbol.

In a practical multi-carrier system, only some parts of sub-carriers are used. Moreover, these sub-carriers are separated into several chunks so that the chunks can be allocated to multiple users. In FB-OFDM, overlapping at the extended symbol layer will cause inter-user interference when adjacent chunks are allocated to different users. To solve the problem, null symbols are inserted to the first or the last sub-carrier of the extended symbols. However, transmitting null symbols leads to the decrease of spectral efficiency. Fortunately, the loss is not significant when the chunk number is equal or greater than two.

FB-OFDM has two advantages over FBMC: complexity and compatibility. FB-OFDM does not process the real parts and the imaginary separately which makes the system more concise. Moreover, FB-OFDM does not overlap in time domain which makes system more flexible.

5 Brief Analysis

The technical implementation processes of FBMC, GFDM and FB-OFDM were expounded in previous sections. Their technical features were also mentioned. As a summary, the following technical comparisons were presented.

In general, FBMC is an asynchronous transmission technique with high spectral efficiency. The outstanding feature of FBMC is without CP. However, to keep the high spectral efficiency, FBMC has to adopt OQAM modulation. It causes the highly difficult compatibility with MIMO.

Since GFDM reserves CP, it is easy to implement relatively because complex filter design is unnecessary. GFDM can be thought of as a generalized case of frequency division multiplexing, while OFDM is degenerated version of GFDM [10–12].

FB-OFDM is a newly proposed modulation mode in 2015. It relieves two difficulties in traditional FBMC multi-carrier technique: complexity and compatibility. Actually, OFDM can be seen as one special case of FB-OFDM. Thereby, the techniques already suitable for OFDM, such as channel estimation, equalization can be easily applied to FB-OFDM system.

When it is comes to implementation complexity, we suppose the total number of the carriers is N, and M sub-carriers are used in practice. The evaluation criterion of complexity is the multiplication times when SM signal flows are transmitted. The expressions of complexity of OFDM, PPN-FBMC, GFDM and FB-OFDM are given below, respectively [8]:

$$\begin{gathered} SN\log_2 N \\ SK(N\log_2 N + 2M + N\log_2 K) \\ S(N\log_2 N + (N+M)\log_2 M) \\ (2N(K-1) - K + 1)/2 \end{gathered} \tag{1}$$

where K is overlapping factor. It is apparent that FB-OFDM is easiest to be implemented, while PPN-FBMC and GFDM are relatively difficult because their complexity depends on parameters setting.

6 Conclusion

In 5G and future mobile networks, high-speed multimedia applications will dominate the majority of services. It requires that new multi-carrier techniques keep pace with the trend. In view of this situation, several multi-carrier transmission techniques proposed in recent years were reviewed. In contrast to traditional OFDM, FBMC, GFDM and FB-OFDM are now attracting more and more attention. These techniques overcome drawbacks of OFDM in this aspect or another, in the meantime, focus on the easy implementation.

From the perspective of computation complexity, FB-OFDM is the simplest. FBMC and GFDM can suppress the side lobe leakage effectively. The sub-band filters of FBMC are allowed to overlap each other, so it has high spectrum efficiency compared with GFDM and FB-OFDM. On the other hand, FBMC is restricted in the combination with MIMO due to OQAM modulation. But, GFDM and FB-OFDM have simplified and flexible structure.

Concentrating on three typical cases, the developmental trend of multi-carrier techniques was reviewed in this paper. So far, multi-carrier transmission technique has still been the hot focus for 5G and future mobile networks and more suspended issues have been under investigations.

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