Performance Analysis of 5G for Low Latency Transmission Based on Universal Filtered Multi-Carrier Technique and Interleave Division Multiple Access

A. Asgharzadeh, M. Maroufi

***Abstract*—**5G mobile communication system has drawn more and more attention. The 5G system needs to provide three different types of services, including enhanced Mobile BroadBand (eMBB), massive machine-type communication (mMTC), and ultra-reliable and low-latency communication (URLLC). Universal Filtered Multi-Carrier (UFMC), Filter Bank Multicarrier (FBMC), and Filtered Orthogonal Frequency Division Multiplexing (f-OFDM) are suggested as a well-known candidate waveform for the coming 5G system. Themachine-to-machine (M2M) communications are one of the essential applications in 5G, and it involves exchanging of concise messages with a very short latency. However, in UFMC systems, the subcarriers are grouped into subbands but f-OFDM only one subband covers the entire band. Furthermore, in FBMC, a subband includes only one subcarrier, and the number of subbands is the same as the number of subcarriers. This paper mainly discusses the performance of UFMC with different parameters for the UFMC system. Also, paper shows that UFMC is the best choice outperforming OFDM in any case and FBMC in case of very short packets while performing similarly for long sequences with channel estimation techniques for Interleave Division Multiple Access (IDMA) systems.

***Keywords*—**UFMC, IDMA, 5G, subband.

I. Introduction

ABOUT each decade, a new generation of digital wireless communication systems is introduced [1]. As a first digital wireless network, the second generation was presented in Global System for Mobile (GSM) in 1990. The third generation arrived around 2000, Universal Mobile Telecommunications System (UMTS). The fourth generation, Long Term Evolution (LTE), offered broadband data services worldwide, which is an essential step towards the ubiquitous Internet [2]. It is anticipated that the Internet of Things (IoT) and MTC will play a vital role in the future of communication traffic [3]. Therefore, the new generation of the digital wireless system should provide low latency, high data rate, and ultra-reliable communication for these applications [4]. As predicted by The Mobile and Wireless Communication Enabler for the Twenty-twenty, Information Society (METIS) [5], 5G is a multi-rate system, covering the user's communication and machine type communication. Compared to the 4G network, the Quality of Experience (QoE) of 5G system is sufficiently improved, including 1000 times capacity, 10-100 times typical user's data rate, support 10-100 times connections, ten times battery life, and one fifth End-to-end (E2E) delay compared to the 4G network [6], [7].

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Due to the 5G targets, the new Radio (NR) has been standardized to allow tight interworking with LTE, which supports the interconnection within their Base Stations. These Base Stations can then be used in combination to serve the population of User Equipment (UE) [8]. 5G network architectures based upon tight collaboration between LTE and NR are known as Non-Standalone (NSA) [9]. However, Standalone (SA) NR Base Stations provide connectivity to a 5G Core Network. The combination of NR Base Station and 5G Core Network is known as a 5G System (SGS) [10].

The Radio Communications Sector of the International Telecommunications Union (ITU-R) [11] has specified a set of requirements for IMT2020 technologies within the report ITU-R-M.2410-0 [12]. These requirements will be used when evaluating candidate technologies, e.g., the 5G solution specified by 3rd Generation Partnership Project (3GPP) [13]. NR radio-access technology in 3GPP, the overall system architectures of both the Radio Access Network (RAN) and the Core Network (CN) were revisited, including the split of functionality between the two networks [14].

Several researches compare the performance of OFDM and UFMC in different aspects [15]-[17]. 4G modulation methods suffer from the problem of high Peak to Average Power Ratio (PAPR). Sideband leakage is another problem in OFDM. Our current 4G systems rely on the OFDM waveform, which is not capable of supporting the diverse applications 5G will offer. The traffic generated by 5G is expected to have very different characteristics and requirements when compared to current wireless technology [15]. Moreover, the combination of IDMA technique with OFDM and UFMC is widely discussed in many researches. OFDM-IDMA systems are analyzed and designed in [18]. Also [19] evaluates the OFDM-IDMA approach to wireless communication systems. On the other hand, the combination of UFMC with IDMA is considered as a next wireless communication system [20], [21].

This paper attempts to discuss the performance of the 5G system with UFMC and IDMA. The remainder of the paper is structured as follows: In Section II, we introduce multicarrier transmission technologies in mobile networks. In Section III, we explain the concept of UFMC signal generation and filtering. Section IV evaluates the IDMA system module performance in 5G architecture. In Section V, we discuss waveform and multiple access schemes. Finally, we provide conclusions in the last section.

II. Multicarrier Transmission Technologies in Mobile Networks

FBMC has gained great attraction in the last years as a potential candidate for 5G. Indeed, FBMC has some advantageous characteristics rendering it a promising contender. Instead of digitally filtering the entire band, the modulator includes a filtering functionality on a per subcarrier basis. So, instead of sinc-pulses, the subcarriers have a more suitable shape according to the filter design with reduced sidelobe levels (e.g. [8]).

OFDM high spectral efficiency is achieved by several closely spaced orthogonal sub-carrier signals [22]. In the third-generation (3G) of cellular wireless network, OFDM and OFDMA are employed for several reasons, such as the ease of implementation, the ability to offset multipath distortion, eliminate inter-cell interference (ICI) and simple integration with multi-antenna device [23]. OFDM executes the inverse Fast Fourier Transform (IFFT) blocks in a transmitter and direct fast Fourier transform (FFT) in a receiver by digital processing, which makes the OFDM system more easy to implement with less computation complexity. Also, it prevents ICI by providing orthogonality within subcarriers [8].

FBMC is considered advantageous in comparison to OFDM by offering higher spectral efficiency. Due to the per subcarrier filtering, it incurs a more considerable filter delay (in comparison to UFMC) and also requires offset Quadrature amplitude modulation (OQAM) processing, which requires modifications for Multiple-input and Multiple-output (MIMO) processing [24]-[25].

III. The Concept of UFMC Signal Generation and Filtering

Fig. 1 shows the UFMC transceiver system block diagram. Note that the sub-band in UFMC is consistent with LTE physical resource block (PRB), i.e., each sub-band contains 12 consecutive subcarriers. In Fig. 1, the total number of subcarriers of UFMC is denoted by N_c, note that N_c should be divided precisely by 12. Assume that the index of each sub-band in B frequency bands is $i(1 \leq i \leq B)$, the time domain transmission vector X is a specific symbol of multi-carrier, it is superimposed by each subband data stream X_i, and can be represented by:

$$X = \sum_{i=1}^{B} X_i \tag{1}$$

In other words, UFMC can be defined as a generalization form of FBMC and filtered OFDM while the previous filters each subcarrier, and the last filters the entire band. The whole transceiver chain block diagram in the uplink (UL) is illustrated in Fig. 1 [7].

The time-domain transmit vector X_k for a particular multicarrier symbol of the user k is the superposition of the sub-band wide filtered components, with filter length L and FFT length N, and can be represented by:

$$\underset{[(N+L-1)\times 1]}{X_k} = \sum_{i=1}^{B} \underset{[(N+L-1)\times 1]}{F_{i,k}} \cdot \underset{[N\times n_i]}{V_{i,k}} \cdot \underset{[n_i\times 1]}{s_{i,k}} \tag{2}$$

For the i_th subband $(1 \leq i \leq B)$, the N_i complex QAM symbols are transformed to time-domain by the tall Inverse Discrete Fourier Transform (IDFT) matrix $V_{i,k}$, which consists of the relevant columns of the IFT matrix according to the respective sub-band position within the overall available frequency range. In UFMC, the block of QAM symbols s_k $(k\epsilon 1 \dots N)$ is divided into B sub-blocks, each consists of N_i QAM symbols $s_{1k}(i\epsilon 1 \dots B)$, $F_{i,k}$ is a Toeplitz matrix, composed of the Finite Impulse Response (FIR) filter, performing the linear convolution. The spectral requirements of the system determine the number of spectral subbands B. It can be determined according to the number of available spectrum portions, and dynamically changed based on a load of other communication systems signal range, while the system is used in a range of the fragmented spectrum. $F_{i,k}$ is a design parameter, adjustable to propagation conditions, and time-frequency offset requirements [3], [8].

Due to the L length prototype filter and N-points FFT, the time domain waveform of the UFMC signal lasts $N + L - 1$ sample points after transformation. So, the B sub-bands can be expressed as:

$$X = \underset{[(N+L-1)\times(N.B)]}{F} \cdot \underset{[(N.B)\times(N_B.B)]}{V} \cdot \underset{[(N_B.B)\times 1]}{s} \tag{3}$$

where

$$\underset{[(N+L-1)\times(N.B)]}{F} = \left[\underset{[(N+L-1)\times N]}{F_1} \; \underset{[(N+L-1)\times N]}{F_2} \; \cdots \; \underset{[(N+L-1)\times N]}{F_B} \right] \tag{4}$$

$$\underset{[(N.B)\times(N_B.B)]}{V} = diag\left(\underset{[N.N_B]}{V_1} \; \underset{[N.N_B]}{V_2} \cdots \underset{[N.N_B]}{V_B} \right) \tag{5}$$

$$\underset{[(N_B.B)\times 1]}{S^H} = \left[\underset{[N_B\times 1]}{S_1} \; \underset{[N_B\times 1]}{S_2} \; \cdots \; \underset{[N_B\times 1]}{S_B} \right] \tag{6}$$

Equations are under the assumption that no overlaps exist between adjacent UFMC time-domain symbols. In Fig. 1, the block decoding filtering brings flexibility since different sub-bands can be combined into a UFMC signal that can be used to get deep cuts on the frequency domain leaked outside the band [26].

UFMC is a more beneficial scheme than OFDM in terms of spectral efficiency due to its ability to reduce guard bands and avoids cyclic prefix (CP) in the receiver. The same as OFDM receiver in UFMC receiver, the FFT block can be employed for CP cancelation. The receive time window prepares zeros supplemented to the next power of two; an FFT is carried out where each second frequency value matches to a subcarrier main lobe. Comparable to CP-OFDM, single-tap per-subcarrier frequency domain equalizers can be used, which equalize the collective impact of the radio channel and the respective subband-filter. This effect leads to a similar complexity order as CP-OFDM. Before performing the FFT, the time domain signal optionally is weighted with a window, e.g., with the raised-cosine shape at the symbol edges [3].

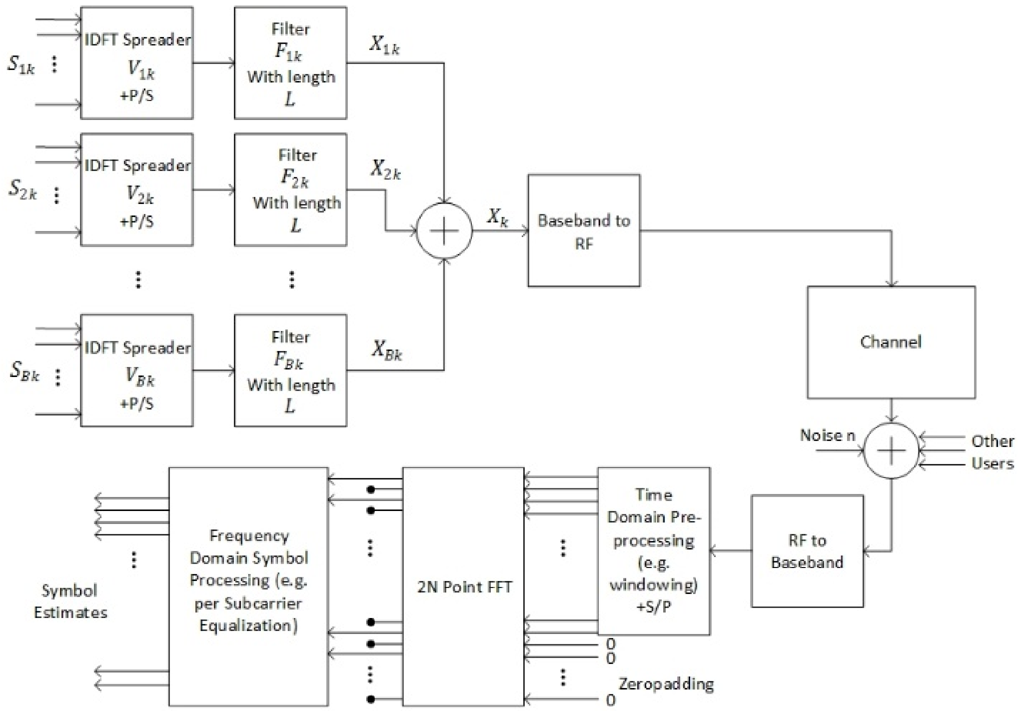

Fig. 1 UFMC Transceiver (UL)

In UFMC, the frequency range is formed from B consecutive subbands, and n_i information subcarriers are transmitted in each i_th subband (Fig. 2).

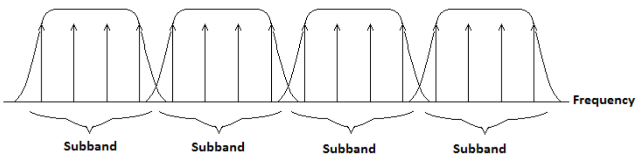

Fig. 2 Example of UFMC signal forming in the frequency domain

The digital FIR filters are calculated via the weight sequence of finite length and its specified parameters, such as the ideal filter infinite impulse response and weight windows. A forming method of the digital filter characteristics by restricting the impulse response of the perfect filter using a weight window is called the weighting method [27].

The UFMC signal long length out-of-band radiation can be reduced by utilizing the weighting sequences. In addition, UFMC resistance to timing errors and distortion in a multipath channel increased at the same time, with the increasing length of the weighing sequence [9].

The output signals of subband filters are aggregated, and then the resulting signal is transferred to the carrier radiofrequency and propagated in the communication channel. Therefore, the UFMC transmitted signal X in the time domain can be expressed using the following equation [28], [29]:

$$X = \sum_{i=1}^{B} F_i V_i s_i \tag{7}$$

where s_i is a vector of QAM symbols of the i_th subband; V_i are columns of IDFT dimension $(N.N_i)$, corresponding to the position of the i_th subband in the general range of frequencies; F_i is a Toeplitz matrix with dimension $((N+l-1).N)$, which implements the signal convolution with the filter characteristic [8].

Fig. 3 illustrates the evaluation within UFMC and OFDM in terms of Power Spatial Density (PSD) based on normalized frequency. In the simulation, while the UFMC utilizes 10 subbands, which consist of 20 subcarriers in each one, the OFDM employs 200 subcarriers in just one subband.

IV. IDMA System Module

We consider an asynchronous IDMA system with K users transmitting with equal power over a multipath fading channel using Quadrature Phase Shift Keying (QPSK) modulation. In QPSK, we employ in-phase and quadrature components as a data and pilot layer, respectively. It is worth noting that we can apply our channel estimation methods to multilayer IDMA systems directly [30].

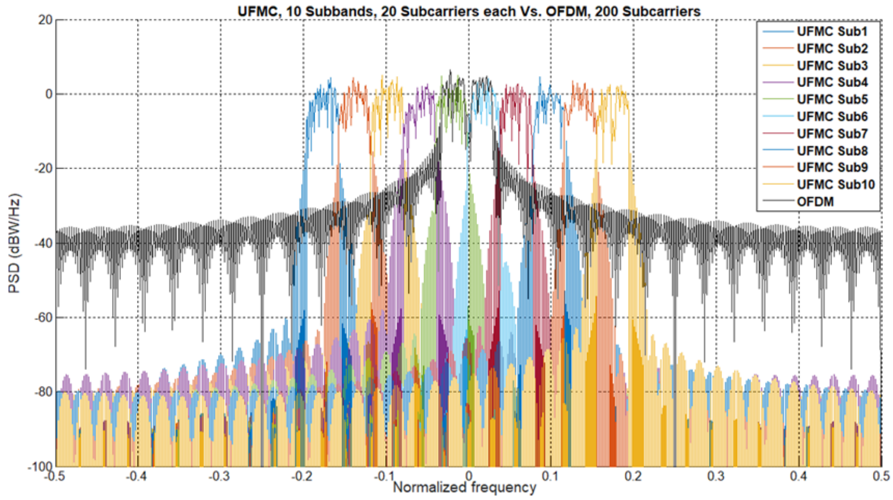

Fig. 3 The PSD comparison within UFMC and OFDM

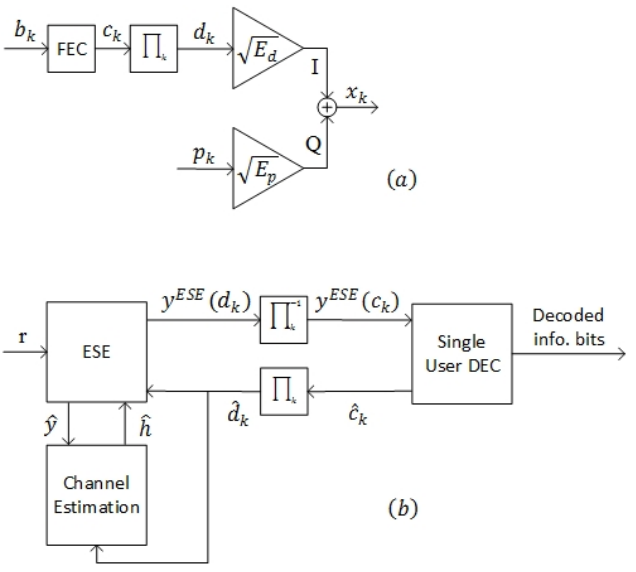

Fig. 4 IDMA transmitter and receiver structure

A. Transmitter Structure

Fig. 4 (a) shows the transmitter structure of an IDMA system for user k. The input bit sequence b_k of user k is encoded using a low-rate code, producing a coded sequence $c_k = \{c_k[1], \dots, c_k[m], \dots, c_k[M]\}$, where M is the length of the data frame. The coded sequence c_k is then permutated by an interleaver to generate the transmitted data sequence $d_k = \{d_k[1], \dots, d_k[m], \dots, d_k[M]\}$. A pilot sequence $p_k = \{p_k[1], \dots, p_k[m], \dots, p_k[M]\}$ is generated separately. Finally d_k and p_k are in-phase and quadrature modulated respectively, and multiplexed together to form transmitted signals x_k, given by:

$$x_k[m] = \sqrt{E_d}d_k[m] + \sqrt{E_p}p_k[m] \tag{8}$$

where E_d and E_p are the transmitting powers for data and pilots [11].

B. Receiver Structure

The tapped delay line is used to model the multipath channel. Each tap fluctuates independently, where perfect timing is assumed. The received signal can be determined via chip-matched filtering as:

$$r[m] = \sum_{k=1}^{K}\sum_{l=1}^{L} h_{k,l}[m]x_k[m-\tau_1] + n[m] = \sum_{k=1}^{K}\sum_{l=1}^{L} h_{k,l}[m]\left(\sqrt{E_d}d_k[m-\tau_1] + \sqrt{E_p}p_k[m-\tau_1]\right) + n[m] \tag{9}$$

where $h_{k,l}$ is the channel gain of the lth path for user k, τ_1 represents the delay in lth path, and n is the complex Gaussian noise with variance N_0.

Fig. 4 (b) illustrates an iterative sub-optimal receiver structure which, at each decoding iteration, cancels the multiple access interference (MAI) and inter-symbol interference (ISI) through the elementary signal estimator (ESE) block. Therefore, the partial signal of l-th path for user k, after this block represents as:

$$\hat{y}_{k,l}[m] = r[m] - \sum_{j\neq k}\sum_{l=0}^{L}\tilde{y}_{j,l}[m] - \sum_{i\neq 1}\tilde{y}_{k,i}[m] = h_{k,l}[m]\left(\sqrt{E_d}d_k[m-\tau_1] + \sqrt{E_p}p_k[m-\tau_1] + I[m]\right) \tag{10}$$

where $\tilde{y}_{j,l}$ is the estimated signal transmitted through lth path from user j, and I denotes the residual error after interference cancellation. In the first iteration, the transmitted signals are estimated by pilots and pass out through the channel estimation module after interference cancellation. Channel estimation updates each user's path with the re-estimation of channel coefficients feedback to the ESE. Then the ESE concentrates on the multiple access constraints, producing extrinsic log-likelihood ratios (LLRs) $\lambda^{ESE}$of the transmitted data sequence for each user. Subsequently, A posteriori probability (APP) is performed by the bank of K single-user decoders (DECs) and decodes the ESE outputs and produce extrinsic LLRs of the transmitted data. The output LLRs from the DECs provide soft decoded data, which are defined by $\tilde{d}$. These decoded data are used as a feedback parameter to the channel estimator and ESE for the next iteration [31].

V. Waveform and Multiple Access Schemes

In the case of IDMA, the so-called ESE provides an efficient low-complex multi-user detection scheme. In this section, we will briefly introduce UFMC modulation and the IDMA encoding and decoding process, mainly the ESE [20].

Alternative: UFMC can be considered as a generalization of filtered FBMC. In other words, while FBMC employs a filtering per subcarrier, UFMC relies on a per sub-band filtering for a group of subcarriers or a Physical Resource Block (PRB) the LTE terminology. Fig. 5 contains the essential multi-carrier modulator for UFMC [20].

The time-domain multi-carrier symbol of each user is transmitted through a user-specific uplink propagation channel, characterized by the Toeplitz matrix $\widetilde{H}_k$, which perform the linear convolution by the time-domain channel impulse response of length L_{CIR}. At the receiver, the White Gaussian Noise z is added to the users' signals as:

$$y = \widetilde{H}_k X_k + \sum_{i \neq k} \widetilde{H}_i X_i + z \quad (11)$$

The receiver can use some optional time-domain preprocessing, e.g., a frequency offset compensation by continuous phase rotations in time. In principle also matched filtering could be done, but as this would imply subband-specific processing due to the filters matched on each subband filter, we have skipped this step, for the sake of reduced complexity, to achieve a similar order as conventional OFDM. The next processing step is a $2N$-point FFT for realizing a frequency domain processing receiver with:

$$\tilde{Y} = FFT\{[y^T, 0, \ldots, 0]\} \quad (12)$$

where $N - L - L_{CIR} + 1$ zeros are appended. We discard each second subcarrier point to get the length N frequency-domain to receive signal Y. In the case of single-user reception, e.g., pure FDMA reception, the receiver can be based on a simple scalar equalization per subcarrier. The QAM-symbol estimated for subcarrier n is just $Y_n/(H_{k,n}F_{k,n})$, with $H_{k,n}$ being the complex scalar channel transfer function coefficient and $F_{k,n}$ the filter frequency response of the subband of interest i, belonging to the respective subcarrier n.

From these results, it is shown that UFMC is a candidate scheme potentially able to replacing OFDM. IDMA is better over FDMA can be mixed with UFMC, for users transmitting with low code rates.

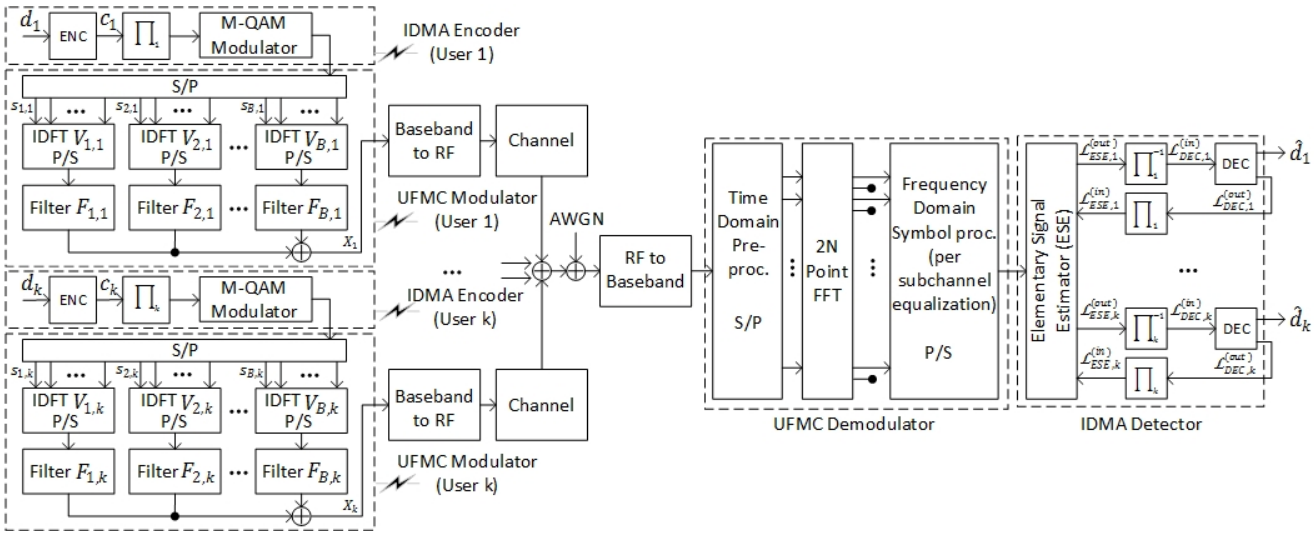

Fig. 5 A generic UFMC-IDMA transceiver structure

Although UFMC gains are not larger than OFDM in low-rate operations, its filters protect adjacent users from ICI and enhance suitability to a fragmented spectrum. The equal power assumed for each user to prevent ICI results in contention-based access. In the unbalanced power condition, ICI robustness becomes more critical; thus, UFMC gain will be much more reliable [20].

VI. Conclusion

In this paper, multi-carrier waveform schemes have been studied under the future 5G wireless systems prospect. One of the essential requirements of 5G is to take advantage of the unused piece of time-frequency spectra. In this way, the new methods are required to support very heterogeneous device and service classes within one radio frame structure in addition to reduced signaling overhead. The simulation results were compared to a well-known CP-OFDM approach to evaluate the UFMC performance. In the UFMC approach, a filtering operation is implemented on a group of consecutive subcarriers to reduce out-of-band side lobe levels that result in a better ICI robustness and better suitability for fragmented spectrum operation. UFMC uses short length FIR filters,

ISSN: 2692-5079

reducing out-of-band radiation, which increases the robustness against ICI, e.g., caused by timing offsets. Compared to FBMC, the UFMC method serves outperformance in short-burst/low latency transmission scenarios and can provide complex orthogonality evading many traps. We can illustrate that IDMA outperforms FDMA at a low rate, and UFMC can effectively combat against misalignments and indicate that the proposed UFMC-scheme can be a promising candidate for future 5G wireless systems. Future work will deal with optimizing the UFMC filters.

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