32nd URSI GASS, Montreal, 19–26 August 2017

Non-orthogonal Waveforms for Machine Type Communication

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Abstract

Machine type communication (MTC) is a typical scenario in 5G communication systems, and massive machine type communication (MMTC) is a main type of MTC. One prominent characteristic of MMTC is massive connections and sporadic transmission with short packets. To embrace the new challenge in 5G emerging scenarios, flexible filter-based waveforms have been widely studied recently. In this paper, we evaluate three candidate waveforms, i.e., orthogonal frequency division multiplexing (OFDM), universal filtered multi-carrier (UFMC) and filtered-OFDM (F-OFDM) in MMTC. We conclude that UFMC and F-OFDM significantly reduce the out of band emission (OOBE) compared to OFDM. On the other hand, OFDM performs better than the other two non-orthogonal waveforms in terms of error performance for both frequency synchronous and asynchronous cases.

1 Introduction

Regarding the current commercialization of 4G mobile communication systems (MCS), it is expected that the upcoming 5G is going to be operable by 2020 [1]. The future 5G system needs to adapt to various scenarios. Machine type communication (MTC) will be a dominant demand of the future communication market. It is further divided into two main types, i.e., massive machine communication (MMTC) and ultra-reliable low latency communication (URLLC) [2].

MMTC is regarded as a specific type of random access which has a large number of connected users, low data rates, sporadic traffic and small packets. This communication scenario imposes resilience requirements for short and asynchronous bursts of data [3]. Therefore, alleviating the synchronism requirements can significantly improve operational capabilities and network performance. To meet the requirements of waveforms in 5G networks, flexible filter-based waveforms have been widely studied recently. Universal filtered multi-carrier (UFMC) filtering is performed per sub-band which suppresses the spectral side-lobe levels. And thus the adjacent channel interference between different resource blocks is significantly reduced [4]. Hence, the UFMC waveform is an appealing technique for communication with short bursts in MTC [5]. Another flexible waveform filtered-OFDM (F-OFDM) also meets the requirement on asynchronization and inter-subband asynchronous transmission [6]. Filter-bank multi-carrier (FBMC) is performed per subcarrier, thus it is not efficient for short packets transmissions and low latency service due to the long tail of the filter response compared to other waveforms [7]. In this paper, we focus on three typical candidate waveforms OFDM, UFMC and F-OFDM and evaluate their performances in massive machine type communication scenario.

This work was supported in part by Nokia Bell Labs, the National Natural Science Foundation under Grant 61571034 and under Grant U1334202, the State Key Laboratory of Rail Traffic Control and Safety under Grant RCS2016ZT013, and the Fundamental Research Funds for the Central Universities under Grant 2017JBM304.

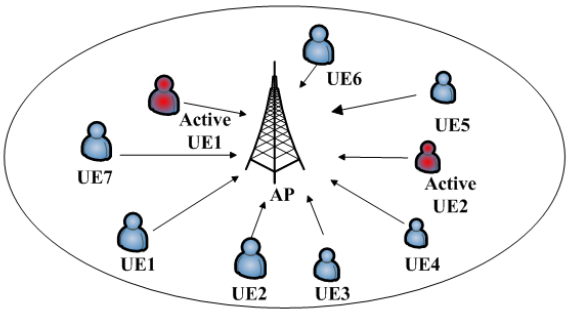

Figure 1. Massive machine type communication Scenario.

The remainder of this paper is organized as follows. In Section 2, the system model of MMTC is presented. Then, we briefly introduce the principles of UFMC and F-OFDM in Section 3. Various performance metrics of these multi-carriers are evaluated in Section 4. At last, we conclude the paper in Section 5.

2 System Model

We consider an MMTC scenario in uplink with an access point (AP) and K connected users where K is much larger than the spreading factor N_c, as shown in Fig.1. We assume each user has an active probability P_a which determines the number of active users K_a in a statistical sense. The activity probability is rather small with $P_a \ll 1$ due to the sporadic nature of MMTC. In addition, it is assumed that

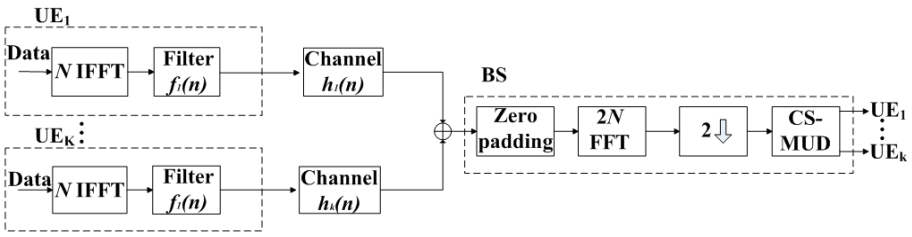

Figure 2. UFMC structure

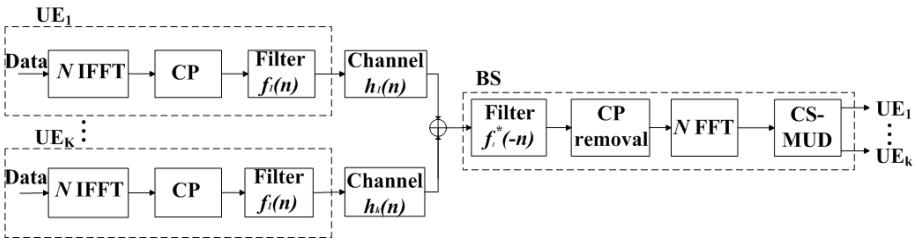

Figure 3. F-OFDM structure

$K_a \leqslant N_c$ because the number of independent transmissions cannot be larger than the amount of the radio resource [8]. To separate different users' data, we use compressive sensing based multi-user detection (CS-MUD) for this scenario [9]. Moreover, different multi-waveforms are used in this spreading system to find out which non-orthogonal waveform is suited for MMTC.

3 Previews of UFMC And F-OFDM

3.1 UFMC

UFMC is a type of sub-band filtering based waveform which is meant to overcome the disadvantages of the sub-carrier filtering based waveform as shown in Fig.2. Compared to the sub-carrier filter, the length of the sub-band filter impulse response is short. Therefore, it can be better served due to short packet transmission especially for massive machine type communication. The key characteristic of UFMC is the use of $2N$ point FFT so that it does not need cyclic prefix (CP) compared with other waveforms. However, it is still able to do so in order to further reduce inter-symbol interference. After N point IFFT and through the filter, the frequency domain signal $S_{i,k}$ is transformed into the time domain transmit vector X_k as:

$$\underbrace{X_k}_{[(N+L-1)\times 1]} = \sum_{i=1}^{B} \underbrace{F_{i,k}}_{[(N+L-1)\times N]} \underbrace{V_{i,k}}_{[N\times n_i]} \underbrace{S_{i,k}}_{[n_i\times 1]} \tag{1}$$

where L is filter length, N is the FFT length and k is the user. $V_{i,k}$ is composed of the relevant columns of the inverse Fourier matrix $F_{i,k}$ which is a Toeplitz matrix including the filter impulse response and can be changed according to the propagation condition and sub-band width [10]. Considering the length of the transmitted signal N and the filter length L, the length of the received signal is $N+L-1$. $L-1$ is the length of the tail of the filter. We combined 12 sub-carriers into a single sub-band. UFMC turns into OFDM with $L = 1$. When $L \gg 1$ and $n_i = 1$, it is similar to FBMC.

At the receiver side, by padding zeros to $2N$ point, efficient demodulation can be achieved through $2N$ point FFT. Then, we extract N length data by a down sampler with a factor of 2. After that, the data can be recovered. UFMC is an attractive waveform for short bursts according to related work so that we evaluate it in massive machine type communication.

3.2 F-OFDM

F-OFDM can be seen as an extension of the standard OFDM by using a pair of transmit and matched filter at the transmitter and the receiver respectively as shown in Fig.3. As a result, F-OFDM is able to overcome the drawbacks of OFDM, which is that OFDM needs global synchronization and it requires extra signaling overhead. In F-OFDM, the whole band can be split up into different sub-bands. Each sub-band uses different filters, subcarrier spacing, CP length and IFFT point. It means that F-OFDM can support flexible parameter configuration so that it is adaptive to different scenarios in 5G. In this paper, we only consider one sub-band for simplify. The transmitter obtains N length IFFT of data with CP. Mathematically, the transmit signal is written as:

$$s(n) = \sum_{l=0}^{L-1} s_l\left(n - l(N+N_{cp})\right) \tag{2}$$

where

$$s_l(n) \triangleq \sum_{m=a}^{a+M-1} d_{l,m}\, e^{(j2\pi mn/N)}, \quad -N_g \leq n \leq N \tag{3}$$

where N_{cp} is the CP length, $d_{l,m}$ is the data symbol on sub-carrier m of OFDM symbols, L represents the number of

Table 1. Simulation parameters

FFT Size	1024
Symbols	14
Subcarriers per RB	12
Modulation Scheme	QPSK
Channel Coding	Turbo Code, $R = 1/2$
Speed of UE	3km/h
Channel	AWGN
Channel Estimation	Ideal
Spreading Factor	5
Connected users K	20
Active Users Ka	2

OFDM symbols, and a to $a+M-1$ is the assigned subcarrier range. The F-OFDM signal $x(n)$ is then obtained through the soft truncated filter with Hanning window to achieve a trade-off between time and frequency localization:

$$x(n) = s(n) * f(n). \tag{4}$$

At the receiver, the received signal is first passed through the filter which matches to the transmitter filter. Then, after removing the CP and N point FFT transforming, the data is obtained [11]. With sub-band based filtering, F-OFDM relaxes the requirement on global synchronization and supports inter sub-band asynchronous transmission better than OFDM. In addition, F-OFDM significantly reduces the guard band, which leads to a more efficient spectrum utilization.

4 Numerical Results

In this section, we evaluate the block error rate (BLER) performance with and without carrier frequency offset (CFO) of OFDM, F-OFDM and UFMC in the uplink when the signals from active users arrive at the receiver simultaneously. The power spectrum density (PSD) of the three waveforms is also evaluated. For the sake of small packet transmission, the spreading factor is set to 5 here. The main simulation parameters are given in Table 1. In the simulation, we assume the carrier frequency is 2 GHz. The subcarrier spacing is 15 KHz with 15.36 MHz sampling frequency, and 60 subcarriers which corresponds to 5 RBs are employed for data transmission. Quadrature-phase-shift-keying (QPSK) is considered with $1/2$ rate Turbo coding. We simply consider AWGN channel. To focus on different waveforms performance in massive machine type communication scenario, we assume 20 connected users and each time 2 users is active randomly, which means we randomly select two spreading sequences from the non-orthogonal spreading sequences pool for the two active users. Meanwhile, user activity sparsity can be exploited at the receiver where matching pursuit (MP) algorithm is employed for user identification and data detection.

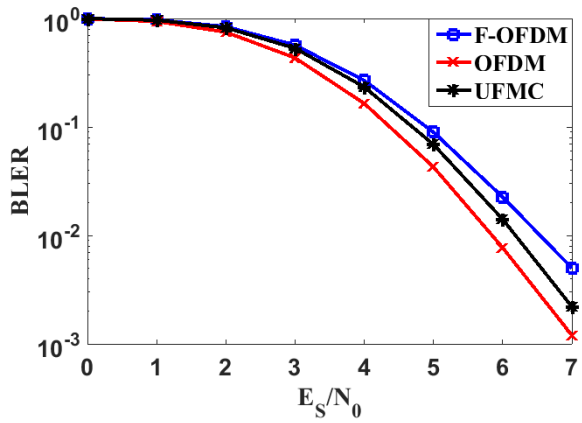

Figure 4. BLER performance of synchronous user with OFDM, UFMC and F-OFDM

4.1 BLER Comparison

In Fig.4, it shows the BLER of different waveforms versus SNR using QPSK. OFDM outperforms the other waveforms because non-orthogonal waveforms suffer from extra ISI using filter design due to non-orthogonal. Thus performance degradation of the two non-orthogonal waveforms can be observed from the Fig.4. In addition, we can observe UFMC outperforms F-OFDM because the latter's filter tail is longer than UFMC.

4.2 OOBE Comparison

In order to reduce out of band emission (OOBE), the filtering based waveform is proposed by employ filter at the transmitter for each sub-band or sub-carrier. Hence, The prominent advantage of non-orthogonal waveforms is the reduction of OOBE so that it is suitable for asynchronous transmission such as massive machine type communication scenario. It is because strong OOBE will cause severe adjacent channel interference. All waveforms including OFDM is no longer orthogonal in asynchronous case. Thus it is significant to reduce the adjacent channel interference to improve the performance in this case. In addition, the relax of synchronization can reduce extra power consumption which is especially better support for MMTC since many terminals are driven by batteries. In Fig.5, the OOBE of non-orthogonal waveforms achieve 60-70 dB improvement over OFDM. Meanwhile, UFMC outperforms F-OFDM although the gap is slightly. The performance of the reduction of OOBE also depends on the filter design.

4.3 CFO Robustness

Carrier frequency offset (CFO) degrades the system performance as severe inter carrier interference. In Fig.6, it shows that there is no improvement of the two non-orthogonal waveforms with different CFO due to the filter-based waveform is sub-band based. Therefore, ICI from adjacent subcarriers cannot be removed efficiently by sub-band filtering.

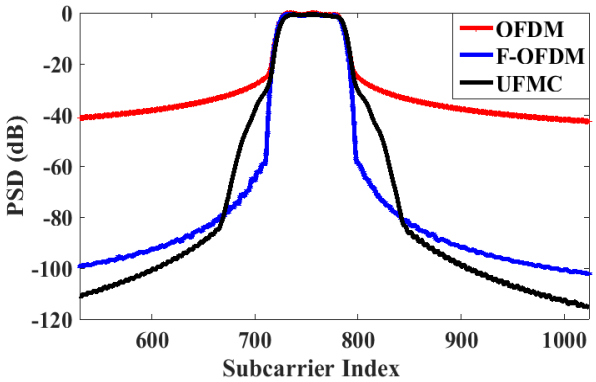

Figure 5. PSD of OFDM, UFMC and F-OFDM

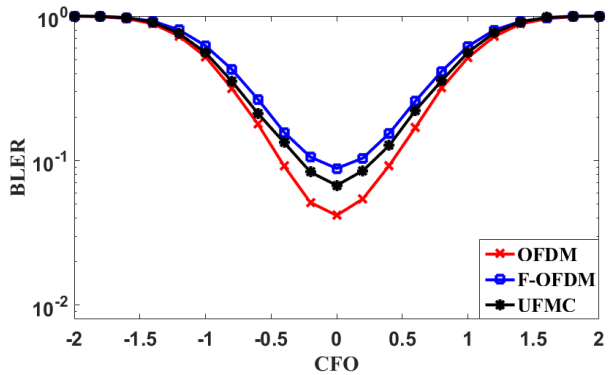

Figure 6. BLER performance of with OFDM, UFMC and F-OFDM with different CFO

The BLER performance degrades compared to OFDM because the non-orthogonality of two waveforms.

5 Conclusion

In this paper, we evaluate OFDM, UFMC and F-OFDM performance in massive machine type communication scenario when active users arrive at the receiver simultaneously. From the simulation results of the BLER versus SNRs with and without CFO, it proves that UFMC and F-OFDM reduce the OOBE significantly than OFDM which is a key advantage for asynchronous transmission especially good for massive machine type of communication scenario. Though there is no improvement of the non-orthogonal waveforms compared to OFDM when active users arrive at the receiver simultaneously.

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