Universal Spatio-Frequency Division Multiple Access for Ultra-Reliable Low-Latency Communications

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Abstract

In this paper, universal spatio-frequency division multiple access (USFDMA) is proposed for ultra-reliable low-latency communication (URLLC) by using user-specific filters both in the frequency and space domains and bit-loaded modulation in each code block. To maximize the spectral efficiency and connectivity while satisfying the reliability and latency requirements of a URLLC, a suboptimal algorithm is proposed to jointly determine the user-specific spatio-frequency filter and the bit-loaded modulation.

Keywords: 5G waveform, 5G multiple access, Spatio-frequency multiple access, OFDMA

1. Introduction

Ultra-reliable low-latency communications (URLLC) is the most interesting new service category in 5G to support mission-critical services, including automated driving, tele-surgery, video-driven interaction, augmented reality applications, and factory automations [1], which requires a very low latency in the order of 1ms or less and ultra-high reliability in the order of 10^{-5} or less [2]. In order to get such high reliability in a wireless fading channel environment, a large amount of diversity is essential. However, the spectral efficiency and connectivity are of importance for a commercial system so that a simple repetition such as in [3][4] is not enough. In addition, even categorized as URLLC services, the traffic characteristics such as the packet sizes, latency and reliability requirements, and traffic arrival models are in a wide range so that it is necessary to adopt a waveform and multiple access multiplexing, i.e., a coexistence of different waveforms and multiple access schemes within one carrier, according to various traffic characteristics for better spectral efficiency and connectivity.

Among various URLLC traffics, one important kind can be specified by its large packet size, periodic packet arrival, and downlink-uplink symmetricity, such as the high-definition video information exchange among machines for applications such as video-driven interaction, augmented reality, and real-time closed-loop machine-type communications [1]. In this case, high spectral efficiency and connectivity become more important to minimize the required resource so that it can be efficiently multiplexed along with other traffic types.

In this paper, a multiple access scheme that has the following characteristics is proposed: 1) for waveform multiplexing, it should be a filtered multicarrier waveform with a low out-of-band emission (OOBE) and orthogonality between different resources allocated to different users, 2) for utilizing spatio-frequency selectivity and diversity in a wideband, it provides a user-specific spatio-frequency filtering using a sufficient number of base station antennas, and 3) for better spectral efficiency and connectivity within a given time-frequency resource and transmission power, a bit-loaded modulation is adopted in each code block and it is jointly optimized with the user-specific spatio-frequency filter.

2. Universal Spatio-Frequency Division Multiple Access

Consider the case of waveform multiplexing and a part of time-frequency resource within a carrier is allocated for URLLC services as shown in Fig. 1. In this case, other waveforms are multiplexed in the outside of the allocated resource so that each waveform needs to provide low OOBE. USFDMA is a kind of filtered multicarrier waveform that allows a low OOBE so that it does not interfere other simultaneously multiplexed waveforms.

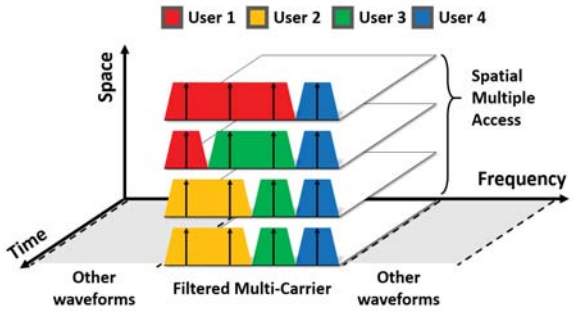

Fig. 1. USFDMA PHY slicing

In addition, it uses block-wise filters with block size according to the resource allocation for each user so that it provides orthogonality among different subcarriers allocated to different users. Also USFDMA allows multiple layers in the spatial domain so that arbitrary resource allocation in the spatio-frequency domain is possible. In order to maximize the spectral efficiency and connectivity while satisfying the challenging latency and reliability requirements in URLLC services, a user-specific spatio-frequency filter is employed by combining a precoding filter in the spatial domain and the pre-equalizer in the frequency domain based on the knowledge of the channel state information (CSI), which can be obtained by using the channel reciprocity of time division duplex (TDD) and the symmetricity in the traffic characteristics. At the receiver, a spatio-frequency post processing is also applied.

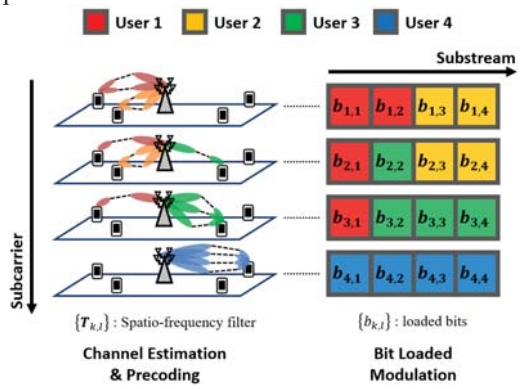

Fig. 2. User-specific spatio-frequency filter and bit loaded modulation in USFDMA

To further improve the spectral efficiency and connectivity while satisfying the latency and reliability requirements, the spatio-frequency filter $\{\boldsymbol{T}_{k,l}\}$ and loaded bits $\{b_{k,l}\}$ on subcarrier k and substream l allocated to user i are jointly determined based on the knowledge of the CSI of each user as

$$\min_{\{\boldsymbol{T}_{k,l}\}\{b_{k,l}\}} tr(\boldsymbol{P}) \;\; s.t \begin{cases} \sum_{(k,l)\in R_i} b_{k,l} = b_i, \\ SINR_{k,l}(\{\boldsymbol{T}_{k,l}\}) \geq \beta(b_{k,l}), \end{cases}$$

where b_i is the code block size for user i, $\boldsymbol{P}$ is the diagonal substream-wise transmission power matrix, and $SINR_{k,l}(\{\boldsymbol{T}_{k,l}\})$ denotes the instantaneous SINR which is a function of CSIs and $\{\boldsymbol{T}_{k,l}\}$, and $\beta(b_{k,l})$ denotes the target SINR which is determined from the reliability requirement and loaded bits $b_{k,l}$. A heuristic algorithm is proposed by decomposing the above problem by the two sub-problems of determining $\{b_{k,l}\}$ at a given $\{\boldsymbol{T}_{k,l}\}$ and vice versa and iteratively solving each sub-problem. Then, within the scheduling period determined by the packet arrival rate and latency requirements, the rate of each user or the number of served users can be increased until $tr(\boldsymbol{P})$ is equal to the power constraint.

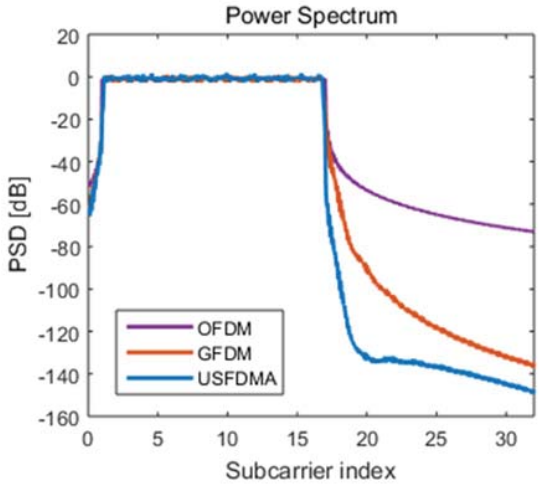

Fig. 3. OOBE comparison of the waveforms

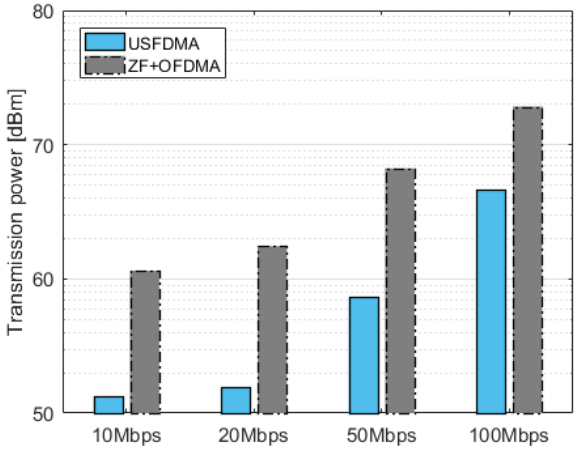

Fig. 4. The transmission power corresponding to the data rate requirement of 4 users with the given 2048 subcarriers and 4 substreams

3. Performance Evaluation

In Fig. 3, the OOBE of the proposed USFDMA is plotted and compared in which the square root raised cosine (SRRC) filter with the roll-off factor of 0.1 is used and is squeezed to fit in the allocated subcarriers for each user. For comparison, orthogonal frequency division multiplexing (OFDM) and generalized frequency division multiplexing (GFDM) using the SRRC filter with the same roll-off factor are also plotted. Note that the use of user-specific spatio-frequency filter can further reduce the OOBE in the proposed USFDMA.

In Fig. 4, the performance of the proposed USFDMA is compared with the orthogonal frequency division multiple access (OFDMA) with zero-forcing (ZF) precoder and uniform bit-loading. Here, we assume $\mathrm{K} = 2048$ subcarriers in 20MHz as the system bandwidth and $\mathrm{L} = 4$ substreams used in each allocated resource. The reliability requirement is set to 10^{-5}. A typical macro cell scenario with path loss and Rayleigh fading is assumed and the required

transmission power is compared at given target rates for users when the path loss is -100dB and the noise spectral density is -174dBm. From the results, it is shown that the proposed scheme can improve the spectral efficiency and/or connectivity while satisfying the requirements of URLLC services.

4. Concluding Remarks

In this paper, a novel multiple access scheme is proposed and is shown to have advantages for improving spectral efficiency and connectivity for URLLC services.

Acknowledgement

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