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Research Article

Service Group Based FOFDM-IDMA Platform to Support Massive Connectivity and Low Latency Simultaneously in the Uplink IoT Environment

Lin Shi, Ishtiaq Ahmad, YuJing He, and KyungHi Chang

Electronic Engineering Department, Inha University, Incheon, Republic of Korea

Correspondence should be addressed to KyungHi Chang; khchang@inha.ac.kr

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Fifth generation (5G) mobile communications have many aspects of services, including the one by the technology of Internet of things (IoT). To support the diverse service types of IoT applications, heterogeneous requirements for massive connectivity and low latency are mandatory. In this paper, service group based filtered orthogonal frequency division multiplexing (FOFDM) combined with interleaved division multiple access (IDMA), i.e., FOFDM-IDMA, is proposed in order to simultaneously support massive connectivity and fulfill the low-latency requirements in the uplink (UL) IoT environment. The proposed FOFDM-IDMA platform has two focal points: first, it enables the coexistence of various time-frequency granularities suitable to diverse service groups, and second, it supports massive connectivity with low latency to provide reliable communications. Thus, the proposed FOFDM-IDMA framework can simultaneously support the requirements of uRLLC (ultrareliable low-latency communications) and mMTC (massive machine-type communications) for the next-generation communication systems. However, the 5G new radio (NR) can solely support the requirements of uRLLC and mMTC independently. Simulation results show that the proposed FOFDM-IDMA platform performs remarkably well, compared to the conventional scheme in the IoT environment.

1. Introduction

IoT connectivity is growing significantly faster than mobile broadband connectivity and is estimated to reach 30 billion connected devices by 2025 [1]. Therefore, a large fraction of IoT applications requires massive connectivity, wide coverage, and low device costs. However, there are still some applications that require low latency, such as tactile Internet [2] and connected cars [3].

To meet the heterogeneous requirements of various service types [4], Huawei proposed FOFDM scheme [5], which is a flexible waveform to coexist with various parameter configurations. Moreover, it utilizes a filter for each sub-band to suppress high side lobes in conventional OFDM techniques. It is a multicarrier modulation scheme and introduces the filtering process in the time domain. The filter bandwidth is designed for a certain sub-band.

IDMA is a multiple access technique [6] in which the main principle is to distinguish the users (UEs) through user-specific interleavers at the receiver (Rx) side. The advantages of IDMA are power efficiency by using low-cost multiuser detection (MUD), suitability for wide- or narrowband transmission, and support for high numbers of users with high spectral efficiency, which can definitely benefit IoT connectivity. Also, OFDM combined with IDMA (OFDM-IDMA) [7] is proposed to adopt most of the benefits from both techniques. Unlike the contributions on resource allocation [8–13] and power control schemes [14–16] for cellular networks and the work on drone sound recognition [17, 18], this paper addresses the service group based FOFDM-IDMA platform to support massive connectivity in the uplink IoT environment.

In this paper, service group based FOFDM combined with IDMA (FOFDM-IDMA) is proposed, which enables the coexistence of various time-frequency granularities suitable to diverse service groups, and it supports massive connectivity with low latency to provide reliable communications in the IoT environment. In addition, the proposed FOFDM-IDMA framework can simultaneously support the requirements of uRLLC and mMTC for the next generation communication systems. However, the 5G NR can only support the requirements of uRLLC and mMTC independently.

The remainder of this paper is organized as follows: Section 2 introduces the conventional OFDM-IDMA scheme. In Section 3, the details of the proposed service group based FOFDM-IDMA platform are provided, and the frame structure of the IoT environment is designed. The simulation results are discussed in Section 4, and we conclude the paper in Section 5.

2. Conventional OFDM-IDMA Scheme

Figure 1 shows the block diagram of the OFDM-IDMA transceiver structure in the uplink for user k. At the transmitter, information bits d_k for user k are first encoded by the encoder (ENC) module and are then spread by a length S spreading sequence. Afterwards, the chips within the spread data sequence $\widetilde{c}_k$ are interleaved by a user-specific interleaver, $\{\pi_k\}$. Then, the resultant signal x_k is modulated and mapped onto subcarriers by inverse fast Fourier transform (IFFT). After cyclic prefix (CP) insertion, the serial symbols in time domain $\widetilde{x}_k$ are transmitted through the multipath fading channel.

At the Rx side, the received signals represented in equation (1) go through the inverse process of OFDM modulation before the MUD procedure.

$$r(j) = \sum_{k=1}^{K} \sum_{l=0}^{L} h_{k,l} \widetilde{x}_k (j-l) + n(j), \quad j = 1, \ldots, J + L - 1. \tag{1}$$

We write

$$r(j+l) = h_{k,l} \widetilde{x}_k (j) + \zeta_{k,l} (j), \tag{2}$$

where $h_{k,l}$ is the channel impulse response for user k with channel length L, $n(j)$ is the additional white Gaussian noise (AWGN), and $\zeta_{k,l}(j) = r(j+l) - h_{k,l}\widetilde{x}_k(j)$ is the interference from other UEs to user k and the AWGN.

Elementary signal estimator (ESE) is applied to perform the chip by chip interference cancellation for each subcarrier. The inputs of the ESE consist of the received signal in equation (2) and log-likelihood ratio $L_{\mathrm{ESE},k}^{(\mathrm{in})}$ [6]. Log-likelihood ratio $L_{\mathrm{ESE},k}^{(\mathrm{in})}$ is given by the decoder in the previous iteration and will be used to reestimate the transmitted signal in order to perform interference cancellation in the next iteration. The output of ESE $L_{\mathrm{ESE},k}^{(\mathrm{out})}$ is soft information after interference cancellation, and the deinterleaved version $L_{\mathrm{DEC},k}^{(\mathrm{in})}$ through π_k^{-1} is fed into the a posteriori probability (APP) decoder (DEC) module. The DEC despreads $L_{\mathrm{DEC},k}^{(\mathrm{in})}$ and spreads the sequence again and then subtracts $L_{\mathrm{DEC},k}^{(\mathrm{in})}$, giving rise to $L_{\mathrm{DEC},k}^{(\mathrm{out})}$. $L_{\mathrm{DEC},k}^{(\mathrm{out})}$ is interleaved again and fed into the ESE. The ESE and the DEC perform a turbo process iteratively until the refined decoded bits are obtained in the final iteration.

3. Service Group Based FOFDM-IDMA Platform for IoT Connectivity

In this section, a multiuser system of service group based FOFDM-IDMA platform for IoT connectivity in the uplink is proposed. Then, the dedicated parameters are configured to support diverse service groups according to latency requirement.

3.1. System Model for the Service Group Based FOFDM-IDMA Platform. Figure 2 shows the block diagram of the service group based FOFDM-IDMA platform as depicted for user k in service group g. The IDMA encoder and decoder processes are the same as in the conventional OFDM-IDMA scheme, but the difference is that an alternative waveform of FOFDM is applied, taking advantage of scalable numerology, such as various transmission time intervals (TTI) and subcarrier spacing in the communication systems in order to meet various requirements of IoT applications. Moreover, this scheme can overcome typical OFDM weak points through a sub-band filter [19], including high peak-to-average power ratio (PAPR) and high side lobes in the frequency domain.

The transmitted signal is represented as

$$\widetilde{x}_k^{(g)} = \sum_{i=1}^{B} F_{k,i}^{(g)} \cdot V_{k,i}^{(g)} \cdot x_{k,i}^{(g)}, \tag{3}$$

where $x_{k,i}^{(g)}$ is the modulated symbol, $V_{k,i}^{(g)}$ is the IFFT matrix, and $F_{k,i}^{(g)}$ is the sub-band filter of the i^{th} sub-band with total B sub-bands for user k in group g.

Then, the received signal can be represented as

$$r(j) = h_{k,l} \widetilde{x}_k^{(g)} (j) + \zeta_{k,l} (j), \tag{4}$$

where $\zeta_{k,l}(j)$ is the distortion (including interference from other UEs and AWGN) in $r(j)$ with respect to user k and can be approximated as a Gaussian variable according to the central limit theorem.

Therefore, the operational procedure for the service group based FOFDM-IDMA platform can be described in the following steps, considering that users are required to be served in the uplink.

Step (1). User Grouping:

Group the K UEs to be served in $G_{\max}$ subcategories $\{G^{(g)}\}$, $g \le G_{\max}$, where $G_{\max}$ is the total number of service groups.

Step (2). Assigning Parameter Configuration

Assign the predefined parameter configuration suitable to the g^{th} service group, $G^{(g)}$, to apply to user k.

Step (3). FOFDM-IDMA Tx Side Processing

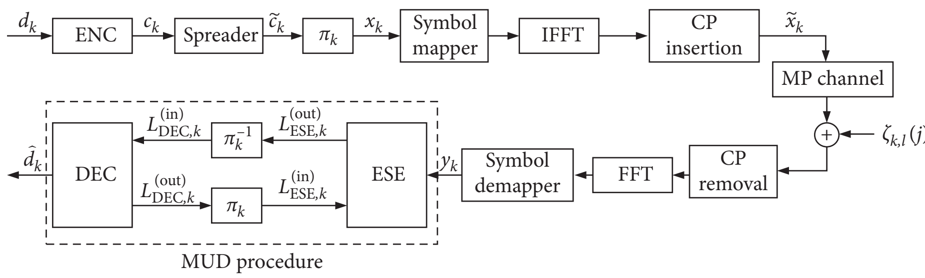

Figure 1: Block diagram of OFDM-IDMA transceiver in the uplink for user k.

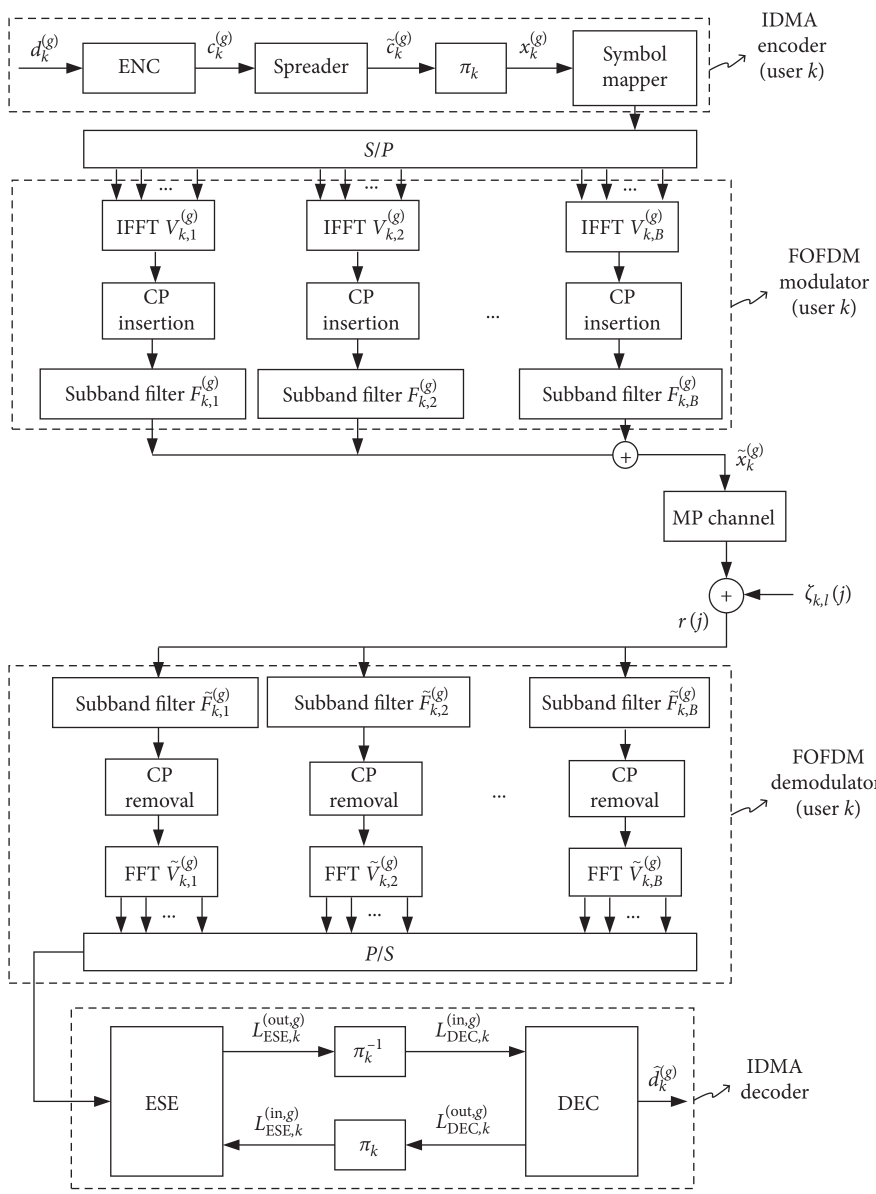

Figure 2: Block diagram of the service group based FOFDM-IDMA transceiver.

All K UEs belong to their relevant service groups with their specific predefined parameter configurations and perform IDMA encoding and FOFDM modulation procedures, as shown in Figure 2.

Step (4). FOFDM-IDMA Rx Side Processing

After the FOFDM demodulation procedure at the Rx side, MUD is performed by the ESE and DEC modules. The output of the ESE can be represented as

$$L_{\mathrm{ESE},k}^{(\mathrm{out},g)} = \sum_{l=0}^{L-1} \frac{2h_{k,l}\left(r\left(j+l\right) - E\left(\zeta_{k,l}\left(j\right)\right)\right)}{\mathrm{Var}\left(\zeta_{k,l}\left(j\right)\right)}. \quad (5)$$

Also, the functions of the DEC module can be represented as

$$\begin{aligned} L\left(\widehat{d}_k^{(g)}\right) &= \sum_{i=1}^{S} S_k\left(i\right) L_{\mathrm{DEC},k}^{(\mathrm{in},g)}, \\ L_{\mathrm{DEC},k}^{(\mathrm{out},g)} &= S_k\left(i\right) L\left(\widehat{d}_k\right) - L_{\mathrm{DEC},k}^{(\mathrm{in},g)}, \end{aligned} \quad (6)$$

where S_k is the spreading code for user k.

Finally, the mean and variance of the transmitted signal are estimated by the ESE as

$$\begin{aligned} E\left(\widetilde{x}_k^{(g)}\left(j\right)\right) &= \tanh\left(\frac{L_{\mathrm{ESE},k}^{(\mathrm{in},g)}}{2}\right), \\ \mathrm{Var}\left(\widetilde{x}_k^{(g)}\left(j\right)\right) &= 1 - E\left(\widetilde{x}_k^{(g)}\left(j\right)\right). \end{aligned} \quad (7)$$

It is noted that in Step 1, user k is grouped into the g^{th} group, $G^{(g)}$, according to the service requirement, and then in Step 2, a suitable parameter configuration is assigned to the service group. In Step 3, IDMA encoding and FOFDM modulation are performed. Hence, the first three steps show the flexibility of the FOFDM platform to enable the coexistence of various time-frequency granularities suitable to diverse service groups.

3.2. Frame Structure and Parameter Configuration for FOFDM Platform. Based on Section 3.1, a dedicated frame structure for the IoT environment is designed, and specific parameters are configured for the FOFDM platform. For most IoT applications, a longer TTI is required to enable large coverage and higher spectral efficiency in order to support massive connectivity (MC). On the other hand, a shorter TTI for shorter round-trip latency and low overhead for efficiently transmitting small packets are still required to support part of the UEs with higher low-latency (LL) requirement. Therefore, in this section, a flexible frame structure for two service types in the IoT environment is proposed, as shown in Figure 3. In addition, it is noted that the FOFDM platform enables various TTI and waveform numerology because sub-band based filtering is applied, so specific parameters are configured for the FOFDM platform, as shown in Table 1, by splitting the IoT applications into two subcategories with massive connectivity or low-latency requirement.

In Table 1, the bandwidth in long-term evolution for machine-type communications (LTE-M) [1] is employed, which restricts machine-to-machine transmissions to a small amount of the available bandwidth that is orthogonal to the broadband UEs. Parameter configuration for MC refers to a new random access technology (RAT) for 5G with a longer TTI and a CP longer than 10 μs. Conversely, for low-latency service, the physical transmission should be performed using very small packets to enable one-way physical layer transmission within 100 μs; thus, each packet cannot exceed a 33 μs duration because of structural additional latency, including the encoding procedure at the transmitter and the detection and decoding procedure at the receiver [20]. Therefore, the 30 μs symbol duration is configured. And then, the value of subcarrier spacing is obtained by taking the reciprocal of symbol duration. In addition, CP length configuration is considered in terms of overhead, which should be extremely small for low-latency applications [21].

4. Simulation and Performance Evaluation

In this section, we perform the simulations for the filtered orthogonal frequency division multiple access (FOFDMA), OFDM-IDMA, and the proposed FOFDM-IDMA with parameter configuration for MC.

The parameters for the waveforms are configured according to Table 1, and a convolutional code with 1/2 code rate followed by a length-8 spreading sequence is employed for each UE. The simulation is under a multipath fading channel applying an extended typical urban (ETU) model [22] with mobility of 1 km/h and employing perfect channel estimation. Ten subcarriers per sub-band are assigned, and ten iterations for the IDMA decoder are assumed to finally obtain the decoded bits for each UE.

The BER performance varying number of UEs of FOFDMA, OFDM-IDMA, and the proposed FOFDM-IDMA schemes when $(E_b/N_o) = 8$ is shown in Figure 4. Figure 4 shows that the BER performance gets worse with the increasing number of supported UEs. When $(E_b/N_o) = 8$ and the number of UEs equals to 64, the BER of FOFDMA, OFDM-IDMA, and FOFDM-IDMA is 1.9×10^{-2}, 4.83×10^{-3}, and 2.32×10^{-3}, respectively. FOFDM-IDMA gives the best performance while FOFDMA gives the worst. It illustrates that the waveforms with IDMA are much more suitable to support massive connectivity.

The BER performance of the three schemes: FOFDMA, OFDM-IDMA with parameter configuration for MC, and the proposed FOFDM-IDMA (including two service groups with parameter configurations for both MC and LL) are further investigated in (E_b/N_o) perspective. Eight and sixteen UEs are assumed to share the resource. For the FOFDM-IDMA platform, we assume a small fraction of UEs with higher low-latency requirement, i.e., two UEs for LL, and six UEs for MC when eight UEs are considered. In addition, there are four UEs for LL and twelve UEs for MC when sixteen UEs are considered. BER performances for the three schemes are compared in Figure 5.

Figure 5 shows that conventional OFDM-IDMA gives better BER performance, about 2.2 dB better at the target BER of 10^{-3}, compared to FOFDMA, which has the worst performance, because IDMA can potentially exploit frequency diversity due to wider frequency bandwidth employed for each user. Our proposed service group based FOFDM-IDMA platform gives the best performance, and the gain is 0.3 dB over the conventional OFDM-IDMA at the target BER of 10^{-3}, which comes from the sub-band filter of the FOFDM to protect neighbor UEs from interference. Moreover, it simultaneously meets the service requirements

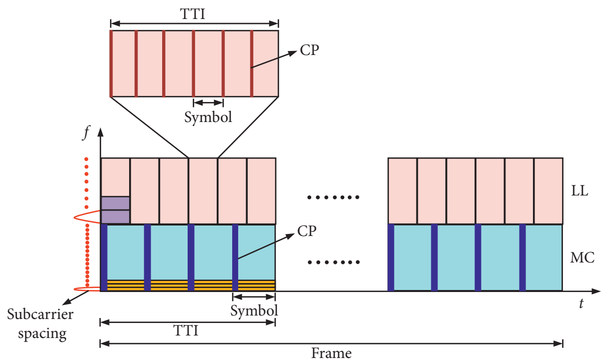

Figure 3: Flexible frame structure to support diverse IoT services of massive connectivity (MC) and low latency (LL).

Table 1: Parameter configuration for MC and LL.

Parameter	MC	LL
Bandwidth	1.4 MHz	
TTI length	1.2 ms	0.2 ms
Subcarrier spacing	3.75 kHz	33.33 KHz
FFT size	512	48
Symbol duration	266.67 μs	30 μs
# of symbols/TTI	4	6
CP length	10.6 μs	2.2 μs

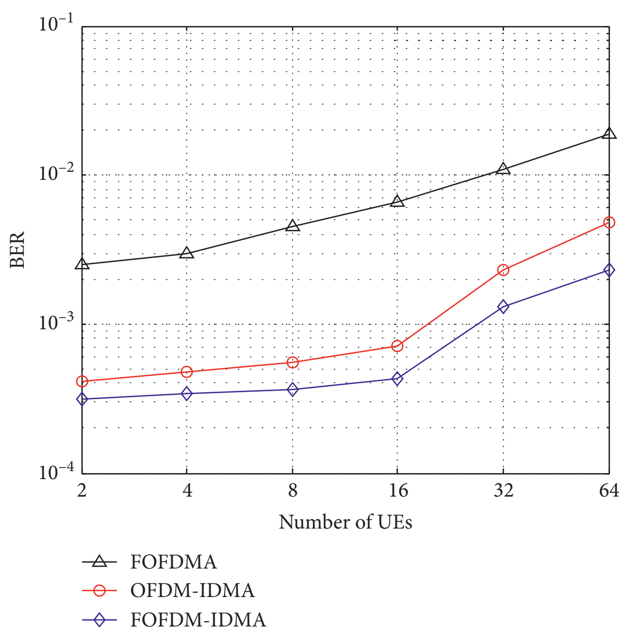

Figure 4: BER performance varying number of UEs of FOFDMA, OFDM-IDMA, and the proposed FOFDM-IDMA schemes.

for UEs in separate service groups, providing suitability with flexible parameters.

5. Conclusions

In this paper, FOFDM-IDMA is proposed, which has the capability of supporting massive connectivity and fulfilling

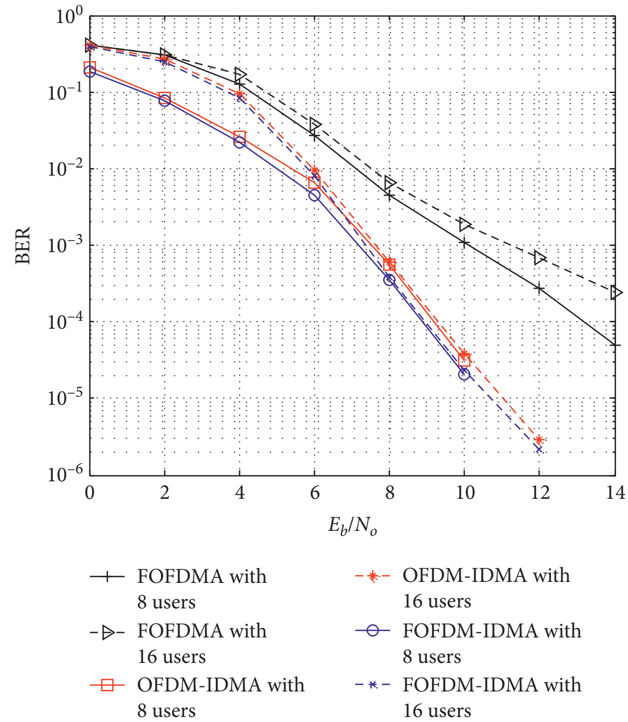

Figure 5: BER performance versus Eb/No of the proposed FOFDM-IDMA, OFDM-IDMA, and OFDMA schemes.

low-latency requirement when providing reliable communications in the IoT environment. Moreover, a dedicated frame structure for the IoT environment is proposed, and specific parameters are configured for the FOFDM platform. In addition, the proposed FOFDM-IDMA framework can simultaneously support the requirements of uRLLC and mMTC for the next generation communication systems. However, the 5G NR can only support the requirements of uRLLC and mMTC independently. The simulation results confirm that, compared with conventional OFDM-IDMA, the proposed scheme shows 0.3 dB SNR gain at the target BER of 10^{-3}. Moreover, the proposed FOFDM-IDMA platform enables the coexistence of various time-frequency granularities suitable to diverse service groups.

Data Availability

We are not supposed to share the data due to project privacy policy.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Lin Shi proposed the idea of the service group based filtered orthogonal frequency division multiplexing (FOFDM) combined with interleaved division multiple access (IDMA), i.e., FOFDM-IDMA, in order to simultaneously support massive connectivity and fulfill the low-latency requirements in the uplink (UL) IoT environment. Moreover, she wrote some technical aspects of the manuscript and also performed the simulations. Ishtiaq Ahmad made all the block diagrams of the manuscript and also drew the flexible frame structure to support diverse IoT services of massive connectivity and low latency. Moreover, he wrote some sections of the manuscript and also corrected all the English mistakes in the manuscript. YuJing He by discussion helped in proposing the FOFDM-IDMA scheme which has the capability of supporting massive connectivity and fulfilling low-latency requirement when providing reliable communications in the IoT environment. Moreover, she wrote some technical equations which helped in the analysis of the proposed scheme. KyungHi Chang was the technical leader of this manuscript. He suggested all the technical issues for the proposed FOFDM-IDMA scheme and also for simulation aspects. In addition, he corrected the whole simulation methodology of this manuscript and also corrected all the mistakes in the simulation environment as well as in the structure of the manuscript.

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