Spatial Modulation GFDM: A Low Complexity MIMO-GFDM System For 5G Wireless Networks

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***Abstract*—Generalized frequency division multiplexing (GFDM) is a nonorthogonal multicarrier transmission scheme proposed for future fifth generation (5G) wireless networks. Due to its attractive properties, it fulfills the requirements of the scenarios such as Internet of Things. On the other hand, multiple-input multiple-output (MIMO) transmission is regarded as a key promising technology for 5G wireless networks. In this paper, we investigate the combination of GFDM and spatial modulation (SM) techniques. We construct the SM-GFDM system model and evaluate its error performance by comparing to spatial modulation - orthogonal frequency division multiplexing (SM-OFDM) in Rayleigh multipath fading channels. It is shown that SM-GFDM suffers a performance loss; however, due to combination of SM and GFDM, low complexity, high spectral efficiency, low out-of-band (OOB) emission, flexibility and time and frequency error toleration, which possibly surpass the small degradation in error performance, can be achieved. As a result, thanks to SM-GFDM, advantages of GFDM have been brought to MIMO application without increasing the system complexity.**

Keywords—GFDM, MIMO systems, Spatial Modulation, 5G wireless networks, multicarrier modulation, physical layer design

I. Introduction

Orthogonal frequency division multiplexing (OFDM) is the core of the physical layer of the 4G wireless networks and fulfills the requirements and challenges of 4G scenarios. Despite of its proven advantages, OFDM has some shortcomings that make it difficult to address the scenarios foreseen for future 5G wireless networks. In OFDM, every symbol requires a cyclic prefix (CP), which depends on the tap length of the channel. The insertion of CP reduces the spectral efficiency and prevents obtaining a low latency by shortening the symbols. Furthermore, OFDM is very sensitive to time and frequency synchronization errors and has high out-of-band (OOB) emission due to rectangular pulse shaping. Due to these shortcomings, OFDM can fulfill the requirements of 5G wireless networks in a limited way. As a result, new multicarrier waveforms are discussed as potential candidates for 5G wireless networks. Asynchronous and nonorthogonal systems have a potential to fulfil the requirements of the new concepts [1]. Amongst the waveforms proposed for the physical layer of 5G wireless networks, filter bank multicarrier (FBMC) [3], universal filtered multicarrier (UFMC) [4] and generalized frequency division multiplexing (GFDM) [5] appear as promising candidates.

GFDM has recently attracted significant attention from the researchers because of its beneficial properties to fulfill the requirements of 5G wireless networks. A GFDM symbol consists KM samples where K subcarriers carry M timeslots each. These parameters can be tuned to match the requirements of the application. So, GFDM has a flexibility to engineer the time-frequency structure according to corresponding scenario [6]. In GFDM, each subcarrier is filtered using circular convolution. Therefore, OOB emission of GFDM is considerably low and it can serve for fragmented and opportunistic spectrum allocation purposes. GFDM uses a single CP for an entire block that contains multiple subsymbols. This enables frequency domain equalization (FDE) and improves the spectral efficiency. Thus, flexible characteristics of GFDM can be easily tuned to address the new requirements.

Multiple-input multiple-output (MIMO) transmission is a key technology to provide higher data rate and better spectral efficiency [7]. Space-time coding (STC), Bell Labs layered space–time (BLAST) and spatial modulation (SM) are the featured methods to implement MIMO transmission. STC maximizes spatial diversity, therefore, it improves the power efficiency [8], [9]. BLAST increases the capacity by transmitting multiple independent data streams from different transmit antennas. Diagonal BLAST (D-BLAST) [10] and vertical BLAST (V-BLAST) [11] are widely used BLAST realizations. SM employs the transmit antenna indices to carry additional information [12]. In SM, input bits select the constellation point in the signal set and the index of the activated transmit antenna. At each transmit interval, the selected antenna transmits the selected symbol and other antennas do not take part in transmission, i.e., remain silent. As a result, inter antenna interference (IAI) is prevented and inter antenna synchronization (IAS) is avoided by SM systems.

Any physical layer proposal for 5G wireless networks is expected to be compatible with MIMO transmission. Thus, the combination of MIMO transmission and GFDM has to be investigated. In [6], [13]-[15], application of STC with GFDM is investigated. In [16]-[18], a MIMO system using spatial multiplexing and GFDM modulation is considered and near-optimum detection schemes are proposed. In [19], the first attempt to apply SM technique for a MIMO-GFDM system is performed. On the other hand, in order to avoid self intercarrier interference (ICI) in GFDM, only one symbol is transmitted per GFDM block. Therefore, the spectral efficiency of this scheme is considerably lower than conventional implementations. To the best of our knowledge, there is not any study on the combination

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of SM and GFDM techniques while preserving the inherent high spectral efficiency of GFDM systems.

In this paper, we investigate the combination of the SM technique with GFDM. The contribution of the paper is the construction of the SM-GFDM system structure and the evaluation of its bit error ratio (BER) performance for Rayleigh multipath fading channels. It is shown that, by combining SM with GFDM, a MIMO-GFDM system which provides flexible time and frequency partitioning, low OOB emission, improved spectral efficiency and loosely synchronization can be developed without increasing the system complexity.

The remaining sections are organized as follows. Section II reviews the GFDM background. Section III presents the combination of SM with GFDM. Section IV investigates the BER performance of the SM-GFDM system with respect to the SM-OFDM system for Rayleigh multipath fading channels. Finally, section V concludes the paper.

Notation: Vectors and matrices are denoted by boldface lowercase and boldface capital letters, respectively. $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\mathrm{H}}$ denote transposition and Hermitian transposition of a vector or a matrix, respectively, and $(\cdot)^{-1}$ indicates the inverse of a matrix.

II. GFDM BACKGROUND

In this section, GFDM system model is given first and then, MIMO-GFDM system model is presented analogue to MIMO-OFDM.

A. GFDM System Model

GFDM is a circularly-filtered multicarrier communications scheme. A GFDM block consists of K subcarriers, each filtered with a circular transmit filter, and each block contains M subsymbols on each subcarrier. The total number of symbols becomes $N = KM$. The system is modeled in the digital baseband and the overall GFDM transmit signal $x[n]$ is given by

$$x[n] = \sum_{k=0}^{K-1}\sum_{m=0}^{M-1} d_{k,m} g_{k,m}[n], \quad n = 0, \dots, N-1 \qquad (1)$$

where n denotes the sampling index, $d_{k,m}$ denotes the complex valued data subsymbol, taken from an Ω–QAM (Ω-ary quadrature amplitude modulation) constellation, belonging to the kth subcarrier and mth subsymbol, and

$$g_{k,m}[n] = g[(n - mK)_{mod\ N}]\, exp(j2\pi \frac{kn}{K}) \qquad (2)$$

is the transmit filter circularly shifted to the mth subsymbol and modulated to the kth subcarrier. Collection of the filter samples in a vector $\mathbf{g}_{k,m} = [g_{k,m}[0] \dots g_{k,m}[N-1]\,]^{\mathrm{T}}$ allows to formulate (1) as

$$\mathbf{x} = \mathbf{Ad} \qquad (3)$$

where $\mathbf{d}$ is a column vector containing $d_{k,m}$ as its $(mK + k)$th element and $\mathbf{A}$ is a $KM \times KM$ transmitter matrix [20] with the following structure

$$\mathbf{A} = [\mathbf{g}_{0,0} \ \cdots \ \mathbf{g}_{K-1,0} \ \ \mathbf{g}_{0,1} \ \cdots \mathbf{g}_{K-1,1} \cdots \mathbf{g}_{K-1,M-1}]\,. \qquad (4)$$

Finally, in order to avoid intersymbol interference (ISI), a CP with length N_{CP} is added to the transmitted signal.

At the receiver side, we assume that the channel length is shorter than the CP and perfect synchronization is ensured. The received signal after CP removal can be expressed as

$$\mathbf{y} = \mathbf{Cx} + \mathbf{w} = \mathbf{CAd} + \mathbf{w} \qquad (5)$$

where $\mathbf{C}$ is the $N \times N$ circular convolution matrix constructed from a channel impulse response, $\mathbf{w}$ is additive white Gaussian noise (AWGN) samples vector with elements having the variance of σ_w^2. After zero-forcing (ZF) channel equalization,

$$\mathbf{z} = \mathbf{C}^{-1}\mathbf{CAd} + \mathbf{C}^{-1}\mathbf{w} = \mathbf{Ad} + \bar{\mathbf{w}} \qquad (6)$$

is obtained and linear demodulation of the signal can be expressed as

$$\hat{\mathbf{d}} = \mathbf{Bz} \qquad (7)$$

where $\mathbf{B}$ is the $KM \times KM$ receiver matrix. Different linear approaches, e.g. matched filter (MF) receiver $\mathbf{B}_{\mathrm{MF}} = \mathbf{A}^{\mathrm{H}}$, ZF receiver $\mathbf{B}_{\mathrm{ZF}} = \mathbf{A}^{-1}$ and minimum mean square error (MMSE) receiver $\mathbf{B}_{\mathrm{MMSE}} = (\mathbf{R}_{\mathrm{W}} + \mathbf{A}^{\mathrm{H}}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{H}}$ can be used to recover the data symbols from the equalized GFDM symbol. Here, $\mathbf{R}_{\mathrm{W}}$ denotes the covariance matrix of the noise. Additionally, MMSE approach can be directly used in (5) to joint equalization and detection by using $\breve{\mathbf{B}}_{\mathrm{MMSE}} = (\mathbf{R}_{\mathrm{w}} + \mathbf{A}^{\mathrm{H}}\mathbf{C}^{\mathrm{H}}\mathbf{CA})^{-1}\mathbf{A}^{\mathrm{H}}\mathbf{C}^{\mathrm{H}}$. Note that for the case of joint equalization and detection, the ZF channel equalizer block is not required.

B. MIMO-GFDM System Model

For an $N_t \times N_r$ MIMO-OFDM channel, where N_t and N_r denote the number of transmit and receive antennas respectively, the received vector $\mathcal{y}_k$ of the kth subcarrier can be expressed as

$$\mathcal{y}_k = \mathcal{H}_k \mathcal{x}_k + \mathcal{w}_k, \qquad k = 0,1, \dots N-1 \qquad (8)$$

where N is the number of subcarriers, $\mathcal{w}_k$ is the channel noise vector, $\mathcal{H}_k$ is the $N_r \times N_t$ frequency response channel matrix and $\mathcal{x}_k$ is the transmit data vector at the kth subcarrier frequency [21]. An estimate of $\mathcal{x}_k$ can be obtained by applying a ZF or a MMSE equalizer to (8). Since each GFDM block contains KM subcarriers, the same model can be used for MIMO-GFDM application. Note that in MIMO-GFDM receiver, an FFT (Fast Fourier Transform) of size KM must be performed for received signal vector of each receive antenna after CP removal.

Optimum GFDM receiver has to handle both ICI and ISI. Other interference sources such as IAI and IAS are added to

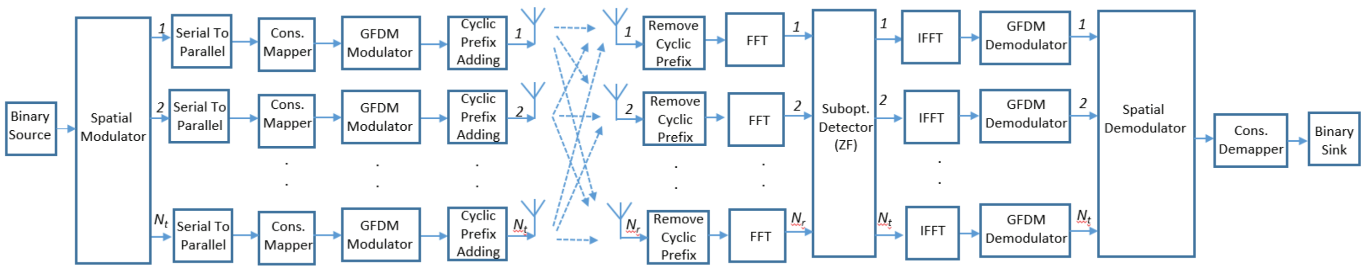

Fig. 1. SM-GFDM system model.

these interferences for MIMO systems which use spatial multiplexing. Therefore, in a spatial multiplexing GFDM system, the complexity of the receiver becomes higher. Since IoT devices have very tight power and space constraints, a low complexity MIMO-GFDM implementation is needed to address the scenarios foreseen for future 5G wireless networks.

III. SPATIAL MODULATION GFDM SYSTEM

SM is regarded as one of the key promising 5G wireless technologies due to its advantages over classical MIMO transmission [23]. For SM multicarrier schemes, each subcarrier is transmitted by only one transmit antenna. Therefore IAI and IAS are efficiently avoided and significant complexity reduction is provided. Resulting from these improvements, SM-GFDM system has a potential to bring all of the advantages of GFDM scheme to MIMO setups without increasing the system cost and complexity. As mentioned earlier, SM-GFDM system can be developed similar to SM-OFDM system. The proposed SM-GFDM system is presented in Fig. 1.

A. SM-GFDM Transmitter

At the transmitter side, spatial modulator processes the incoming bits in blocks of size $m = \log_2(N_t) + \log_2(\Omega)$, where Ω is the size of the complex signal constellation, and arranges in a matrix $\mathbf{X}$ of size $N_t \times KM$, where each row vector $\mathbf{x}_i$ contains the symbols to be transmitted from the transmit antenna i and each column vector contains the symbols to be transmitted on the kth subcarrier and mth subsymbol. First $\log_2(N_t)$ bits of the block identify the row of the matrix and the remaining $\log_2(\Omega)$ bits select the symbol from the signal constellation diagram. Then, selected symbol is placed in an empty column on the corresponding row. When a symbol is placed in a column, all other elements in that column are set to zero. As a result, the matrix $\mathbf{X}$ has one nonzero element in each column. Therefore, at each GFDM subcarrier, only one antenna transmits the information symbol selected from signal constellation and all other antennas remain silent. Then, each row vector $\mathbf{x}_i$ is modulated using a GFDM modulator according the system model in (3). At the GFDM modulator output, $\mathbf{s}_i$ vector is created. A CP with length N_{CP} is appended to the $\mathbf{s}_i$ and resulting vectors are arranged as row vectors of a matrix $\mathbf{S}$. Finally, row vectors of matrix $\mathbf{S}$ are simultaneously transmitted from the N_t transmit antennas over the MIMO channel $\mathbf{H}$ and corrupted by an AWGN matrix $\mathbf{W} = [\mathbf{w}_1 \ \mathbf{w}_2 \ ... \ \mathbf{w}_{N_r}]^{\mathrm{T}}$. $\mathbf{H}$ is a block matrix containing $N_r \times N_t$ vectors each of length p. Each vector corresponds to the multipath channel gains between each transmit and receive antenna and p is the number of channel paths. Note that when the transmitter part of the SM-GFDM system and SM-OFDM system is compared, it is seen that there is only one difference: The GFDM modulator, which implements the pulse shaping and subcarrier upconversion.

B. SM-GFDM Receiver

At the receiver side, under the assumption that the CP is longer than the channel impulse responses and perfect synchronization is ensured, the received signal after the CP removal is given by

$$\mathbf{Y} = \mathbf{H} \otimes \mathbf{S} + \mathbf{W} \tag{9}$$

where $\otimes$ denotes time convolution. When an FFT of size KM is applied to each row of $\mathbf{Y}$, the received vector $\boldsymbol{y}_{k.m}$ of the kth subcarrier and mth subsymbol can be expressed as in (8). In SM-OFDM, since OFDM demodulation is performed by FFT operation, spatial demodulation can take place at this point. In [12], a SM-OFDM system with suboptimal receiver is proposed. In [22], unlike the MRRC (maximum receive ratio combining) algorithm in [12] which comprise two stages estimation process, a joint ML (maximum likelihood) detection method is used to detect the active antenna index and the transmitted symbol for SM-OFDM system. In SM-GFDM, GFDM demodulation stated by (7) must be performed before the spatial demodulation. Since inherently existing ICI due to pulse shaping prevents straightforward implementation of ML detection; in this paper, a suboptimal detection approach is preferred to limit the receiver complexity. After ZF channel equalization,

$$\boldsymbol{z}_{k,m} = \mathcal{H}_{k,m}^{-1} \boldsymbol{y}_{k,m} \tag{10}$$

where $\mathcal{H}_{k,m}$ is the $N_r \times N_t$ frequency response channel matrix at the kth subcarrier and mth subsymbol, is obtained as the estimate of the transmitted vector of the kth subcarrier and mth subsymbol. Rearranging of vectors $\boldsymbol{z}_{k,m}$ as column vectors of a matrix gives the matrix $\boldsymbol{Z}$ where each row contains an estimate of the frequency domain representation of the transmit vector for the corresponding antenna. Then, an IFFT of size KM is applied to the each row of $\boldsymbol{Z}$ and the resulting row vectors are passed from GFDM demodulation block as in (7). Rearranging GFDM demodulator output vectors as row vectors of a matrix gives the matrix $\boldsymbol{\mathcal{D}}$ where each row vector contains an estimate of the outputs of the spatial modulator at the transmitter. After this point, spatial demodulator processes the matrix $\boldsymbol{\mathcal{D}}$ and estimates the transmit antenna index and information symbol. Transmit antenna index estimation is done by finding the location of the maximum of the absolute value of the columns of $\boldsymbol{\mathcal{D}}$ for each GFDM subcarrier as follows:

$$\hat{l}_{k,m} = \text{argmax}\left|\boldsymbol{d}_{k,m}\right| \tag{11}$$

where $\boldsymbol{d}_{k,m}$ is the column vector of $\boldsymbol{\mathcal{D}}$ for the kth subcarrier and mth subsymbol. The transmitted symbol is estimated using the following operation:

$$\hat{d}_{k,m} = \text{Q}\left(d_{k,m,\hat{l}_{k,m}}\right) \tag{12}$$

where $d_{k,m,\hat{l}_{k,m}}$ is the element belonging to estimated transmit antenna index number $\hat{l}_{k,m}$ in the column vector $\boldsymbol{d}_{k,m}$ and $\text{Q}(\cdot)$ is the constellation quantization (slicing) function. SM demodulator uses the transmit antenna index estimation and information symbol estimation to obtain the corresponding information bits on this particular GFDM subcarrier by applying the mapping process that was used at the transmitter in a reverse manner.

IV. RESULTS AND DISCUSSION

The BER performance of the proposed SM-GFDM system has been compared with SM-OFDM system for Rayleigh multipath fading channels with exponential power delay profile. Table I presents the system parameters used in computer simulations. ZF receiver is used as a GFDM demodulator and the chosen pulse shaping for the GFDM prototype filter is the root-raised cosine (RRC) with roll-off factor (α) of 0.1 and 0.5. It has been considered that the perfect synchronization is established between the transmitter and the receiver and perfect channel state information is available at the receiver. Both systems use ZF MIMO detection.

Fig. 2 shows the BER performance of the SM-GFDM system and the SM-OFDM system with four transmit and four receive antennas. RRC filter with a roll-off factor (α) of 0.1 and QPSK modulation have been used in this scenario.

From Fig. 2, it is observed that error performance of the SM-GFDM system and SM-OFDM system is approximately the same in low signal-to-noise ratio (SNR) region. For high SNR values, SM-GFDM error performance becomes worse than SM-OFDM system approximately 1 dB for a BER value of 10^{-3}.

Fig. 3 shows the BER performance of the SM-GFDM system and the SM-OFDM system with a roll-off factor (α) of 0.5. In this scenario, it is observed that the BER performance of SM-GFDM is worse than SM-OFDM system approximately 2 dB for a BER value of 10^{-3}. As seen from these results, it is possible to conclude that BER performance difference between the SM-GFDM system and the SM-OFDM system is quite similar to the difference between SISO-GFDM system and SISO-OFDM system in [20].

The error performance difference between the two MIMO systems is mainly arising from self-created interference of the nonorthogonal subcarriers in GFDM. Furthermore, increasing the roll-off factor increases the SNR gap between SM-GFDM

TABLE I. SIMULATION PARAMETERS

Description	Parameter	Value
Number of subcarriers	K	128
Number of subsymbols	M	5
GFDM demodulator	$\mathbf{B}$	ZF
Pulse shaping filter	g	RRC
Length of cyclic prefix	N_{CP}	32
Exponent of power delay profile	γ	0.1
Number of channel taps	N_{TAP}	10
Constellation size	Ω	4 (QPSK)
Number of transmit antennas	N_t	4
Number of receive antennas	N_r	4

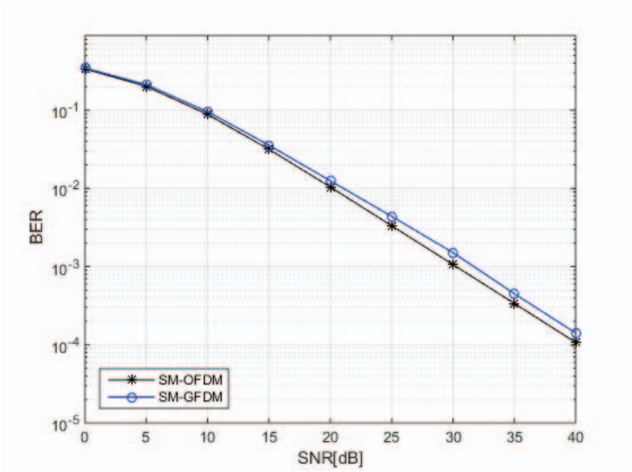

Fig. 2. SM-GFDM and SM-OFDM BER performance for QPSK transmission in Rayleigh multipath channel for root-raised cosine filter with roll-off factor (α) of 0.1.

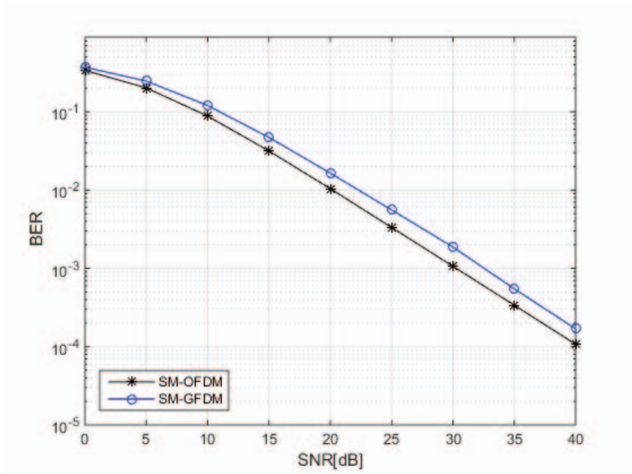

Fig. 3. SM-GFDM and SM-OFDM BER performance for QPSK transmission in Rayleigh multipath channel for root raised cosine filter with roll-off factor (α) of 0.5.

and SM-OFDM BER curves. Although SM-GFDM suffers a small degradation in error performance, it has several improvements such as higher spectral efficiency, lower OOB emission, flexibility and loosely synchronization with respect to SM-OFDM. As it can be seen from Table I, while CP ratio in SM-OFDM is 0.25, CP ratio in SM-GFDM is 0.05. Therefore, SM-GFDM improves the spectral efficiency by 19% for the configuration given in Table I with respect to SM-OFDM. The OOB emission of the SM-GFDM system can be controlled by the adjusting the roll-off factor of pulse shaping filter. As a non-orthogonal waveform, SM-GFDM can tolerate time and frequency errors.

V. CONCLUSION

The expected implementation scenarios for future 5G wireless networks have challenges which current physical layer technologies can only fulfill in a limited way due to their shortcomings. GFDM is one of the promising physical layer solutions to cope with these shortcomings. Additionally, MIMO technology will be a key approach for future 5G wireless networks. Thus, a combination of MIMO and GFDM has to be investigated.

Inherently existing ICI due to pulse shaping and ISI are the stringent interference sources that the GFDM receiver has to handle. Spatial multiplexing MIMO transmission is the prominent method to provide high data rates. IAI and IAS are the stringent interference sources of the receiver which take place in the spatial multiplexing transmission. If one wants to combine spatial multiplexing and GFDM, the receiver has to cope with four dimensional interference which requires very high detection complexity. SM is novel MIMO technique in which IAI and IAS are efficiently avoided. In this paper, a novel MIMO-GFDM system, which uses SM, is proposed. The system model of the SM-GFDM system is constructed and its BER performance is compared to SM-OFDM system for Rayleigh multipath fading channels. It is demonstrated that SM-GFDM suffers a performance loss because of the nonorthogonal subcarriers; however, due to the combination of SM and GFDM, low complexity, high spectral efficiency, low out-of-band (OOB) emission, flexibility and time and frequency error toleration, which possibly surpass the small degradation in error performance, can be achieved. Therefore, thanks to SM-GFDM, advantages of GFDM have been brought to MIMO application without increasing the system complexity. We conclude that SM-GFDM can be considered a promising scheme for future 5G wireless networks.

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