Pilot-aided Channel Estimation for Universal Filtered Multi-Carrier

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Abstract— **Universal Filtered Multi-Carrier (UFMC, a.k.a. UF-OFDM) is a novel multi-carrier modulation technique, which aims at replacing OFDM for next generation wireless communication systems (5G). It is a generalization of OFDM and filter bank based multi-carrier (FBMC-FMT), which combines the advantages of OFDM and FBMC while avoiding its main drawbacks. UFMC is shown to be more robust in relaxed synchronization conditions i.e. time-frequency misalignment compared to conventional CP-OFDM systems. As required in potential scenarios of 5G systems, UFMC is more efficient to support short uplink bursts communications. Without the insertion of cyclic prefix, we investigate the procedure and performance of pilot-aided channel estimation for UFMC in an uplink multi-user FDMA scenario and show that almost the same performance as CP-OFDM can be achieved despite the lack of cyclic prefix. In case of timing and frequency offset, UFMC shows its robustness over CP-OFDM in terms of symbol error rate (SER). Simulation results show that the error floor is reduced applying UFMC for considered different types of channels.**

I. INTRODUCTION

With the fast growing amount of devices which are to be connected to the Internet, future 5G wireless communication systems have to be able to support a very diverse traffic types such as normal broadband traffic, sporadic short packet and urgent low latency transmission [1]. The strict synchronism approach by enforcing synchronicity and orthogonality applied in Long Term Evolution (LTE) is not likely to efficiently fulfill the upcoming challenges such as Internet of Things (IoT) and Massive Machine-type Communications (MMC) [2]. In order to support both high-end and low-end devices, a new air interface based on non-orthogonal waveform, Universal Filtered Multi-Carrier (UFMC) [3], has been proposed and its abilities under relaxed synchronization conditions, e.g. time-frequency misalignment, are investigated [4].

UFMC is a novel waveform technology, which aims at replacing the conventional Cyclic Prefix-based Orthogonal Frequency Division Multiplexing (CP-OFDM) technique. Consider a multi-user Frequency Division Multiple Access (FDMA) scenario, a time-frequency misaligned device causes comparatively high out-of-band radiation to other well-synchronized neighboring users or devices, since the side-lobe level of the so-called si-function in OFDM is quite large. To reduce the side-lobe level of OFDM and consequently out-of-band radiation under time-frequency misalignment, a per-subcarrier based filtering approach is applied in Filter Bank-based Multi-Carrier (FBMC) systems [5]. Each subcarrier is individually filtered so that Inter Carrier Interference (ICI) can be significantly suppressed. However, long filters are typically required in FBMC systems (filters of the length of multiple times of total samples per multi-carrier symbol) in order to be able to design a time-frequency well-localized pulse shape. The long filter-ramps makes FBMC vulnerable for short burst transmission [6]. Compared to the per-subcarrier filtering approach in FBMC, UFMC filters a group of consecutive subcarriers (sub-band like). Hence, the filter length can be considerably reduced. This leads to a reduced complexity of receiver in UFMC, while robustness against time-frequency misalignment is still available. An interactive Webdemo for UFMC and FBMC already exists in [7], illustrating the time and frequency properties of the respective multicarrier signals. In [8], [9], it is shown that great performance gain in terms of Signal-to-Interference Ratio (SIR) improvement of more than 10dB is achievable in UFMC, compared with conventional CP-OFDM systems. Since UFMC combines the simplicity of OFDM and robustness of FBMC, it is considered as a very attractive waveform technique for 5G. Furthermore, UFMC is also known as Universal Filtered OFDM (UF-OFDM) due to its similarity to OFDM [10].

Channel estimation is another crucial task in wireless communication systems. The Channel Impulse Response (CIR) causes overlapping of consecutive transmitted symbols, which results in Inter Symbol Interference (ISI). In CP-OFDM, ISI can be completely mitigated at the receiver by removing the inserted CP, provided that CP is longer than CIR duration. The well-established pilot-aided channel estimation for CP-OFDM systems employs known pilot symbols at known frequency and time indexes. Thus, channel can be estimated at the corresponding time-frequency positions without any ISI thanks to CP. However, both FBMC and UFMC allow the deletion of CP for better spectral efficiency. Without the insertion of CP, FBMC suffers from an intrinsic ICI and ISI which makes the channel estimation procedure more complicate [11]. To eliminate the intrinsic interference in FBMC, Auxiliary Pilot (AP) scheme is suggested in [12]. The AP-scheme requires additional computations and is not applicable when pilot symbols have to be designed close to each other (e.g. fast fading channel) [13]. In this paper, we show that the classical pilot-aided channel estimation method and the pilot structure for CP-OFDM systems are completely applicable in UFMC systems, despite the lack of CP. The ramp-up and ramp-down of UFMC-symbol due to filtering approach act as "soft protection" against channel delay spread, since relatively less signal energy is contained within the ramps. Thus, the resulting channel ISI and ICI can be limited to a negligible level by appropriately designing the Finite Impulse Response (FIR) filter shape and length. We show that the channel can be very conveniently estimated in UFMC systems, using the conventional channel estimation method developed for CP-OFDM systems.

II. EFFECT OF MULTIPATH CHANNEL IN UFMC

Being a candidate of future 5G waveform technologies, UFMC is a very generic multi-carrier scheme based on subband-wise filtering (detailed system model of UFMC in [6], [14]). It can be seen as a generalization of OFDM and FBMC, by designing the filter length and subband size. By appropriately designing the FIR-filter length, shape and the size of subband, UFMC aims at combining the main advantages of both OFDM and FBMC and simultaneously avoiding its drawbacks.

The advantages of UFMC are shown in many different aspects considering relaxed synchronization conditions such as carrier frequency offset (CFO) and timing offset (TO) in [4], [8], [9]. However, the channel therein is either pure Additive White Gaussian Noise (AWGN) or assumed to be perfectly known at the receiver. Wireless communications suffer from the effect of multipath propagation. In CP-OFDM systems, ISI caused by multipath channel can be very efficiently mitigated by the insertion of CP. This makes the channel estimation in OFDM extremely convenient. CP or guard time can definitely also be employed in UFMC to mitigate multipath effect, it sacrifices on the other hand side the spectral efficiency. For better spectral efficiency in UFMC, a transmission without insertion of CP is considered in the following. Thus, the sensitivity against multipath channel-induced ISI in UFMC and its impact on channel estimation have to be investigated.

In Fig. 1, the basic UFMC symbol shapes before filtering, after filtering and after passing through a multipath channel are illustrated. Without loss of generality, it is sufficient to consider three consecutive transmitted UFMC symbols and one subband. The signal before filtering is a normal OFDM signal, i.e. output of Inverse Discrete Fourier Transform (IDFT) of one considered subband. The size of IDFT is denoted by N and a subband is composed of N_B consecutive subcarriers. Hence, zeros are padded at other $N - N_B$ subcarrier positions to perform the N-IDFT operation. A gap with the length of $L-1$ samples is intentionally inserted between two consecutive OFDM signals, where L is the length of the FIR filter. The OFDM signal is then convolved with an FIR filter, which produces UFMC signals with reduced sidelobe level. The length of a UFMC symbol is $N+L-1$ due to the linear convolution. It is noteworthy to mention that consecutive UFMC symbols do not overlap in time and the subband-filtering in UFMC does not cause any interference with proper receiver. As indicated in the symbol shape of UFMC, the ramps act as "soft" protection against multipath effect, since a very limited amount of signal energy is contained within the ramps. Two effects are to be expected, ISI due to absence of CP and ICI due to loss of orthogonality in UFMC. Consider one UFMC symbol, this symbol after passing through a wireless channel with the CIR $h(k)$ can be written as

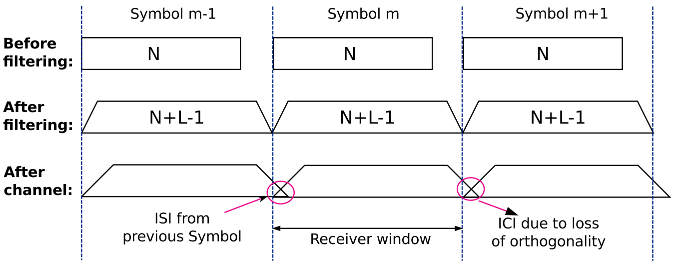


Fig. 1: Symbol shape of UFMC signal before filtering, after filtering and after passing through a multipath channel

$$r(k) = h(k) * \left(\sum_{i=1}^{B} (x_i * f_i)(k) \right) + w(k), \tag{1}$$

where $w(k)$ denotes additive white Gaussian noise (AWGN) with variance σ_n^2 and B denotes the total number of subbands. f_i is the bandpass FIR-filter response with the length L for the subband i and x_i the IDFT output signal of subband i with the length N. The center frequency of f_i is the same as that of the i-th subband. The received signal with the length of $N+L-1$ is then padded with $N-L+1$ zeros. Then $2N$-point DFT is applied to transform the time domain signal into frequency domain. Note that $2N$-DFT is needed to recover the data symbols at N subcarriers from $N+L-1$ received samples. The output of $2N$-point DFT $Y(k)$ is given by

$$Y(k) = \frac{1}{\sqrt{N}} \sum_{l=0}^{N+L-2} r(l) e^{-j2\pi lk/2N}, \quad k = 0, 1, \cdots, 2N-1 \tag{2}$$

Insert (1) into (2), we get

$$\begin{aligned} Y(k) =& H(k)F_i(k)\tilde{X}_i(k) - \alpha_S(k)\tilde{X}_i(k) \\ &+ I_{\mathrm{ICI}}(k) + I_{\mathrm{ISI}}(k) + W(k), \end{aligned} \tag{3}$$

where $H(k)$, $F_i(k)$, $\tilde{X}_i(k)$ and $W(k)$ are the $2N$-point DFT of their corresponding time domain signal. Without loss of generality the considered subcarrier k is assumed to be allocated to the subband i. Furthermore,

- $\alpha_S(k)$ is a signal amplitude reduction factor due to loss of orthogonality
- $I_{\mathrm{ICI}}(k)$ is the ICI caused by all other subcarriers at the subcarrier k
- $I_{\mathrm{ISI}}(k)$ is the ISI caused by previous symbol at the subcarrier k

They are straightforward and given in [15]. It is also noteworthy to mention that the statistical properties of $W(k)$ is changed compared with the in time domain white noise $w(k)$.

Firstly, the noise variance σ_U^2 of $W(k)$ is slightly enhanced in frequency domain and it can be expressed as

$$\sigma_U^2 = \frac{N+L-1}{N}\sigma_n^2. \tag{4}$$

The reason for the noise enhancement is that instead of N samples we use $N+L-1$ samples to perform $2N$-point DFT and the scaling factor remains $1/\sqrt{N}$. Moreover, the frequency domain noise $W(k)$ is not white any more and the covariance of noise between two arbitrary even subcarriers (since only even subcarriers contain data [8]) $l' = 2l$ and $k' = 2k$ is given by

$$c(l',k') = \frac{1}{N}\frac{\sin\left(\frac{\pi\Delta k}{N}(N+L-1)\right)}{\sin\left(\frac{\pi\Delta k}{N}\right)} \cdot e^{j\frac{\pi\Delta k}{N}(N+L-2)}\sigma_n^2, \tag{5}$$

where $\Delta k = l' - k'$. It can be observed from (5), $c(l',k') = 0$ if the filter length is $L = 1$, which corresponds to OFDM systems. The correlation between different subcarriers in UFMC results from the Leakage-Effect of DFT if the DFT size is not an integer multiple of the signal length.

To investigate the effect of channel-induced ISI, simulations are carried out for two different channels

- Vehicular-A channel model with the Power Delay Profile (PDP) according to [16]
- exponentially decaying PDP channel [17] with various asymptotic root mean square (rms) delay spread

Simulation parameters are shown in the following table (LTE-like settings) I. Every subband is filtered by Dolph-Chebyshev filter with a side lobe attenuation of 40dB and the filters are frequency-shifted to the center frequencies of each subband. Furthermore, perfect channel knowledge is assumed at the receiver and the noise is neglected, since we only interest on the effect of channel-induced ISI/ICI. The mean square error (MSE), i.e. squared error magnitude between transmitted and estimated Quadrature Phase Shift Keying (QPSK) symbols, is then calculated at the receiver. In Fig. 2, MSE of the received symbol estimates are plotted over 100 Vehicular-A channel realizations. The MSE for 100 channel realizations is -42.7dB for UFMC. This MSE indicates that the channel-induced ISI is negligible for this channel model. In CP-OFDM, the channel-induced ISI is completely mitigated because CP length is so designed that it is greater than CIR duration. A channel with exponentially decaying PDP is determined by asymptotic rms delay spread, which describes the decaying speed of power density. In Fig. 3, the MSEs are calculated for various rms delay spread, which are already normalized to the FIR-filter duration applied in UFMC. If a target MSE is set to -40dB, 6.8% and 13.5% normalized rms delay spread is allowed for UFMC and CP-OFDM respectively. If the target MSE is set to -30dB, 9.5% and 18.9% normalized rms delay spread is tolerable for UFMC and CP-OFDM respectively. We can roughly conclude that CP-OFDM can tolerate twice more rms delay spread than UFMC for low MSE.

DFT size	Filter/CP Length	subband size	subbands
1024	74/73	12	10

TABLE I: Simulation parameters of investigating channel-induced ISI

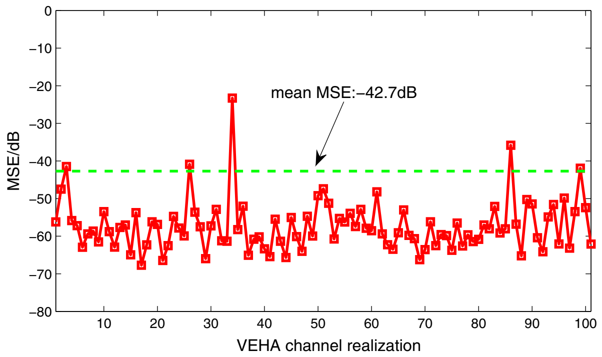


Fig. 2: Impact of channel-induced ISI/ICI of a Vehicular-A channel

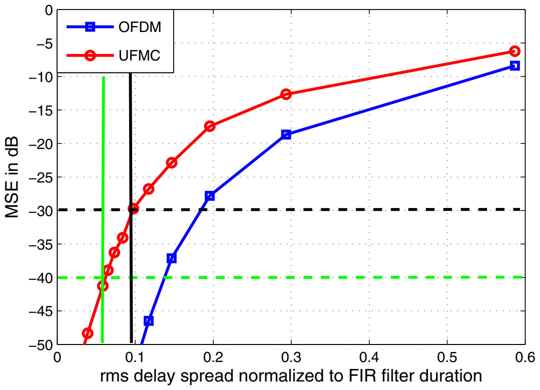


Fig. 3: Impact of channel-induced ISI/ICI of exponentially decaying PDP channels

III. Channel Estimation for UFMC

In previous section, we show that the total power of ISI and ICI in UFMC is below -40dB under Vehicular-A channel model. For channel with larger rms delay spreads, FIR filters either with larger length or with optimized shapes have to be adopted in UFMC in order to keep the channel-induced ICI/ISI below certain level (see Fig. 3). In the following, we assume that FIR-filter is well-designed such that the system performance is mainly limited by noise. Neglecting the channel-induced ICI and ISI for UFMC, the symbol estimates in equation (3) can be simplified as

$$Y(k) = H(k)F_i(k)\tilde{X}_i(k) + W(k). \tag{6}$$

With the above equation, we can conclude that the complete frequency domain channel estimation and channel equalization algorithms for OFDM are reusable in UFMC, except that the FIR-filter response has to be additionally equalized in UFMC. A simple channel estimation scheme for UFMC is shown in Fig. 4. Furthermore, the pilot structure of OFDM are also completely reusable in UFMC, compared to FBMC. Alternatively, this post-equalization of filter response can be

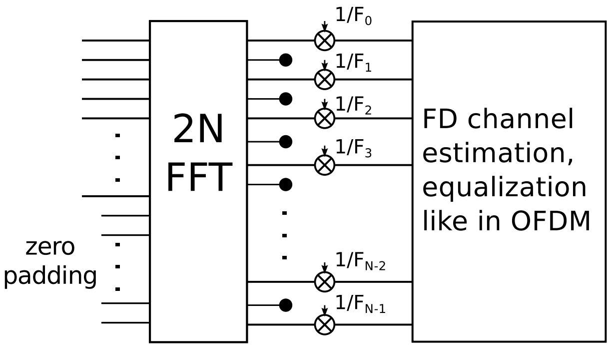


Fig. 4: Channel estimation scheme for UFMC

done at the transmitter side instead of at receiver side, i.e.

$$X_{i,\text{pre}}(k) = \frac{1}{F_i(k)} X_i(k), \forall k \in S_i \quad \text{and} \quad \forall i, \tag{7}$$

where S_i is a set, which contains all subcarrier indexes belong to i-th subband. By applying this pre-compensation method at the UFMC transmitter, the channel estimation can be performed identically as in CP-OFDM without any additional modification. Another advantage of this pre-compensation method is that the signal power is now equally distributed among all pilot tones, which delivers an optimal channel estimation performance. Using the channel estimation algorithms and pilot placement technique developed for OFDM, we investigate the performance in UFMC systems and compare with CP-OFDM systems. The symbol is time and frequency structured as in an LTE/LTE-A uplink physical resource block (PRB) [18], [19] i.e., every 4-th multi-carrier symbol within a slot is the pilot symbol, which is known at the receiver. Moreover, the pilot tones are solely spaced in time. In frequency domain, all allocated subcarriers are used for pilot transmission.

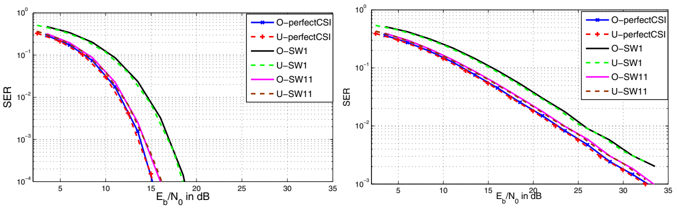
As aforementioned, channel estimation procedure for OFDM can be applied in UFMC systems without any other modifications, if the FIR filter response is pre-compensated at UFMC transmitter. In the following, we discuss our channel estimation method to be applied in UFMC and CP-OFDM systems. Firstly, raw channel estimates at the pilot symbol with corresponding time and frequency indexes are obtained using (6). Then, the accuracy of the raw channel estimates can be further improved by applying the Sliding Window (SW) approach, in which the noise variance is reduced in proportion to the sliding window size [20]. At last, the channel estimates (using pilot symbols in two slots) are interpolated in time in order to get the channel estimates at data symbol positions. Various interpolation algorithms can be applied, such as Least-Squares (LS) and Linear Minimum Mean Square Error (LMMSE). For a simpler comparison between UFMC and CP-OFDM, linear interpolation is adopted here.

IV. Numerical Results

For our evaluation of the basic pilot-based channel estimator with the above described linear interpolation and sliding window algorithm, we consider three types of channels:

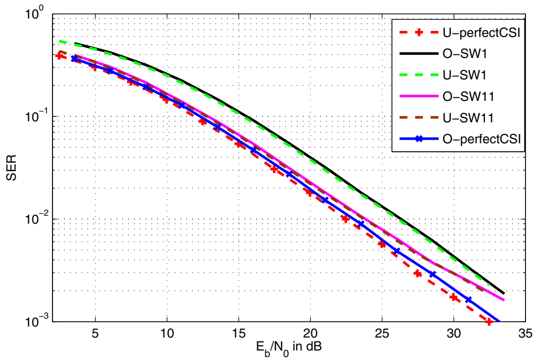
- AWGN, only noise is present
- frequency-flat fading channel, the user moves at the speed of 50km/h
- frequency-selective fading Vehicular-A channel, the user moves at the speed of 50km/h

Simulation parameters are shown in table I. The symbol error rate (SER) of QPSK symbols are shown in the following Fig. 5 for UFMC (denoted by 'U') and CP-OFDM (denoted by 'O') with perfect Channel State Information (CSI) and different SW-sizes respectively. It is clear from the simulation results that UFMC can at least achieve the same or slightly better performance as CP-OFDM under different channel models considered above using the simple sliding window algorithm with linear interpolation. Although the noise variance is about 0.3dB larger than CP-OFDM system (see equation (4)) and the noise is colored, the performance of channel estimation in UFMC is as good as in CP-OFDM.



(a) AWGN channel

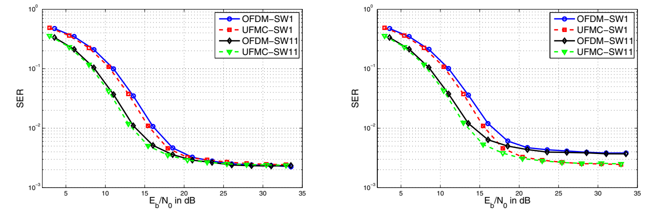
(b) frequency-flat fading channel with 50km/h user's speed



(c) Vehicular-A channel with 50km/h user's speed

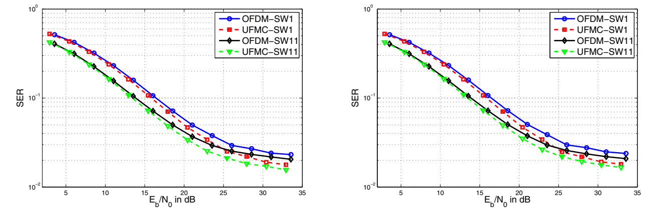
Fig. 5: Performance of the sliding window channel estimator for UFMC and CP-OFDM under different channel models

Now, we consider additionally Timing Offset (TO) and Carrier Frequency Offset (CFO) (residual synchronization error) before performing channel estimation. Consider now a scenario, two users transmit signals simultaneously using adjacent frequency bands. The User of Interest (UoI) is allocated with 3 PRBs and the adjacent user is allocated with 9 PRBs. Because of time and frequency misalignment between the two users, adjacent channel interference is present. We assume that the UoI is perfectly synchronized and the adjacent user is corrupted by 15% CFO and ±15% TO. The carrier frequency offset is normalized to the subcarrier spacing and the timing offset is also normalized to the total length of one multi-carrier symbol. Negative timing offset means that signal arrives earlier than expected. Furthermore, the pre-compensation method is applied in UFMC to compensate the filter response at the transmitter and QPSK is the modulation scheme. The SERs are shown in Fig. 6 for various SNRs. In the left side, SERs are shown for the case of 15% CFO and 15% TO of the adjacent interfering user. SERs are also evaluated for the case with 15% CFO and −15% TO, shown in the right side. In AWGN channels, UFMC only outperforms CP-OFDM slightly, because OFDM benefits from the white noise property, lower noise variance and the protection of cyclic prefix. In case of −15% TO, the performance in UFMC system is much better than that of CP-OFDM, since the insertion of CP is not able to protect against ISI anymore. In flat-fading channel and user moves at the speed of 50km/h, UFMC outperforms CP-OFDM for all sliding window sizes. Moreover, the performance is almost the same for negative and positive TO. From the simulation results, we see that the error floor caused by adjacent interfering users can be further reduced applying UFMC.



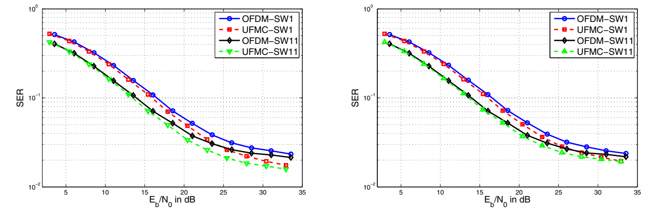
(a) AWGN channel, 15% CFO and 15% TO

(b) AWGN channel, 15% CFO and −15% TO



(c) frequency-flat fading channel, 50km/h, 15% CFO 15% TO

(d) frequency-flat fading channel, 50km/h, 15% CFO −15% TO



(e) Vehicular-A channel, 50km/h, 15% CFO 15% TO

(f) Vehicular-A channel, 50km/h, 15% CFO −15% TO

Fig. 6: Performance of the sliding window channel estimator for UFMC and CP-OFDM under different channel models with timing and frequency offsets

V. SUMMARY

In this paper, pilot-aided channel estimation is investigated for a novel 5G candidate waveform technology universal filtered multi-carrier. We analyzed the effect of multipath channel for UFMC systems in the absence of cyclic prefix.We also show that the classical channel estimation and equalization methods are applicable at the receiver in UFMC as in OFDM, if pre-compensation of filter response is performed at the transmitter. At last, the performance of a simple channel estimator applying sliding window and linear interpolation algorithm is evaluated for simple AWGN channel, frequency-flat fading channel and frequency-selective Vehicular-A channel model. The simulation results show that well-known estimation procedures are applicable to UFMC achieving the same performance as in OFDM. Better performance can be achieved applying UFMC in multi-user FDMA scenarios if adjacent channel interference is considered, since UFMC has significantly reduced side-lobe level.

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