IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 1, 2017, accepted January 27, 2017, date of publication February 6, 2017, date of current version October 12, 2017.
Digital Object Identifier 10.1109/ACCESS.2017.2664980

Waveform Design for 5G Networks: Analysis and Comparison

YINSHENG LIU[1], XIA CHEN[2], (Member, IEEE), ZHANGDUI ZHONG[1], BO AI[1], DESHAN MIAO[3], ZHUYAN ZHAO[3], JINGYUAN SUN[3], YONG TENG[3], AND HAO GUAN[3]
[1]State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, China
[2]School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing 100044, China
[3]Nokia Beijing Bell Labs, Beijing, China

Corresponding author: Y. Liu (ys.liu@bjtu.edu.cn)

This work was supported in part by the Nokia Beijing Bell Laboratory and in part by the Natural Science Foundation of China under Grant 61601018.

ABSTRACT The next-generation cellular network is to provide a large variety of services for different kinds of terminals, from traditional voice and data services over mobile phones to small packet transmission over massive machine-type terminals. Although orthogonal-subcarrier-based waveforms are widely used nowadays in many practical systems, they can hardly meet the requirements in the coming 5G networks. Therefore, more flexible waveforms have been proposed to address the unprecedented challenges. In this paper, we will provide comprehensive analysis and comparison for typical waveforms. To offer an insightful analysis, we will not only introduce the basic principles of the waveforms, but also reveal the underlying characteristics. Moreover, a comprehensive comparison in terms of different performance metrics will also be presented in thispaper, which provides an overall understanding of the new waveforms.

INDEX TERMS 5G, waveform, analysis, comparison.

I. INTRODUCTION

With the development of technology, new demands for information transmission have posed an unprecedented challenge for the next generation cellular system. Besides the traditional voice and data services over mobile phones, 5G network is also expected to support traffics that are fundamentally different from the traditional ones, such as small packet transmission over massive machine-type communications (MTC) or Internet of things (IoT) [1].

As an underlying technique, flexible waveforms are required in 5G networks to address the coming challenges [2]. In 5G networks, a fundamental requirement of the waveform design is to support asynchronous transmission in order to avoid the large overhead of synchronization signaling caused by massive terminals [3]. Although orthogonal frequency division multiplexing (OFDM) has been used in long-term evolution (LTE), it can hardly meet the above requirement because the orthogonality among subcarriers cannot be maintained in asynchronous transmission. In this case, the strong out-of-band (OOB) emission of OFDM signal will cause severe adjacent-channel interference (ACI). Moreover, the synchronization signaling will also cause extra power consumption, and thus reduce the lifetime of the terminals since many terminals in MTC will be driven by batteries [4]. In addition to the asynchronous transmission, the waveform in 5G is also required to have a good localization property in the time domain in order to provide low-latency services and to support small packet transmission efficiently [5].

To meet the requirements of the waveform design in 5G networks, filter-based waveforms have been widely studied recently. The key factor that filter-based waveforms can outperform OFDM in 5G networks is that they can support asynchronous transmission by reducing the OOBs via different filter designs [2]. In general, the filter-based waveforms can be divided into three types based on the filter granularity: subcarrier filtering, sub-band filtering, and full-band filtering.

The subcarrier filtering based waveform, such as filtered multi-tone (FMT), is originally proposed to reduce OOB of multi-carrier signal by adopting a pair of transmit and receive filters for each subcarrier [6]. Filter-bank multi-carrier (FBMC) is also a subcarrier filtering based waveform which adopts offset quadrature-amplitude-modulation (OQAM) to avoid the waste of bandwidth in FMT [3], [7]. By inserting a cyclic prefix (CP) in front of the transmit signal, the inter-symbol interference (ISI) can be mitigated through cyclic block FMT [8] and generalized frequency division multiplexing (GFDM) [9]. Despite the advantages, the long tail of the filter's impulse response makes subcarrier filtering based waveforms not suitable for low-latency service in 5G networks [10].

Sub-band filtering based waveforms are proposed to overcome the disadvantage of the subcarrier filtering based waveforms. For sub-band filtering, the filters are designed with respect to a sub-band, which has more-than-one subcarriers. The length of the filter's impulse response can be thus reduced since the filter bandwidth is larger than that of the subcarrier filtering. As a sub-band filtering based waveform, the sub-band of resource block filtered OFDM (RB-F-OFDM) is as wide as one RB, which contains 12 subcarriers in LTE [11], [12]. Universal filtered multicarrier (UFMC) is another type of sub-band filtering based waveform, where only a transmit filter is used while the demodulation in the receiver relies on the oversampled discrete Fourier transform (DFT) [4], [5], [10].

The filters can also be designed with respect to the full bandwidth such that only one filter is enough as in filtered OFDM (F-OFDM). In this case, F-OFDM will be equivalent to the RB-F-OFDM if only one RB is available in the bandwidth [13], [14].

In this article, we will make a comprehensive comparison of different types of waveforms. Since many new waveforms have been proposed and we cannot take everything into account in one article, only four typical waveforms are chosen, that is, FBMC, RB-F-OFDM, UFMC, and F-OFDM, because they are not only typical representatives but have also gained more attention from the industry and the academia. For in-depth understanding, we will introduce the basic principles of those waveforms as well as revealing the underlying characteristics of each waveform.

The rest of this article is organized as follows. In Section II, we will introduce the basic principle and underlying characteristics of various waveforms. In Section III, we will introduce the applications of those waveforms in wireless channels. A comprehensive comparison will be presented in Section IV, and finally summary and conclusions are in Section V.

II. PRINCIPLES OF WAVEFORMS

In this section, we will introduce FBMC, RB-F-OFDM, UFMC, and F-OFDM, respectively. Since different users can be separated by the filters, we only consider the single-user case without specification.

A. SUBCARRIER FILTERING: FBMC

The system structure for FBMC is shown in Fig. 1 (a), where T denotes the time interval of FBMC symbols and K denotes the number of subcarriers. For each subcarrier, the complex QAM symbols are first split into real parts and imaginary parts. After a time delay of $T/2$ for the imaginary parts, the combined OQAM signals are fed to the transmit filter, and then modulated by the corresponding subcarrier frequency before sending to the channel. The receiver follows a reverse procedure for signal demodulation.

For a general multi-carrier system such as FMT, the orthogonality among subcarriers cannot hold due to the transmit and the receive filters. To avoid the inter-carrier interference (ICI), the filter spectra for different subcarriers should have no overlap [6]. This will result in a waste of the bandwidth since roll-off transitions are required in practical raised cosine filters, as in Fig. 2 (a). To make full use of the available bandwidth, FBMC first relaxes the requirement of the filter design by allowing spectrum overlapping for adjacent subcarriers, as in Fig. 2 (a). Then, the OQAM scheme is adopted in FBMC to make sure that the interference caused by adjacent subcarriers can be removed by recovering the real and the imaginary parts separately in the receiver. In this manner, FBMC can achieve the same spectrum efficiency as the standard OFDM.

Due to the subcarrier filtering, the tail of the filter's impulse response in FBMC systems will typically cover four symbol intervals [3], which is much longer than other filter-based waveforms. The long tail makes FBMC not suitable for small packet transmission and low latency service. Data transmission and reception can occur within a symbol interval for standard OFDM or other filter-based waveforms. For FBMC as shown in Fig. 2 (b), however, the data transmission will be postponed due to the latency caused by the long tail of the filter's impulse response, and the reception cannot be finished until the whole pulse has been received. In addition, due to the long tail, the demodulation of FBMC symbols relies on the channels over multiple symbol intervals. As a result, the time variation of the channels will be averaged out, making it more difficult to gain Doppler diversity in FBMC systems. We will further elaborate on this issue through simulation results in Section IV.

B. SUB-BAND FILTERING: RB-F-OFDM AND UFMC

The sub-band filtering based waveform is proposed to overcome the drawbacks of the subcarrier filtering. Since the filters are designed with respect to multiple subcarriers, the length of the filter's impulse response is reduced compared to the subcarrier based filtering. Therefore, sub-band filtering based waveform can be used to serve low latency applications in 5G network.

1) RB-F-OFDM

The system structure of RB-F-OFDM is shown in Fig. 1 (b) where N denotes the size of inverse fast Fourier transform (IFFT)/FFT. The data symbols for different subcarriers at each sub-band are first converted to time-domain signal through a standard OFDM modulation. After upsampling, the generated signal is sent to the transmit filter and then shifted to the carrier frequency of the corresponding sub-band. The receiver follows a reverse procedure for signal demodulation. The upsampling in the transmitter and the downsampling in the receiver are used to reduce the sampling rate of FFT/IFFT. Accordingly, the sizes of IFFT/FFT can also be reduced, leading to low implementation complexity.

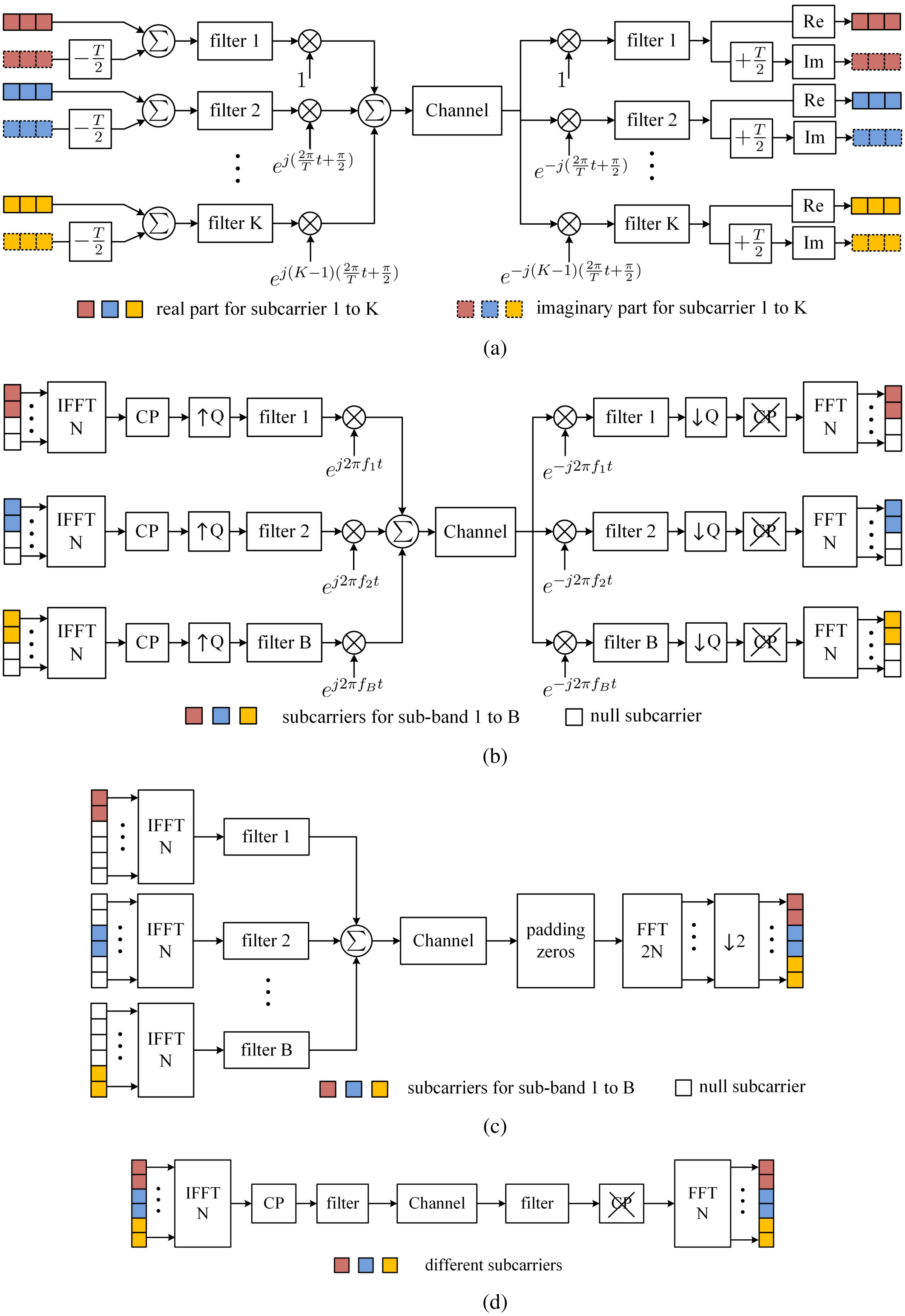

FIGURE 1. System structures for (a) FBMC, (b) RB-F-OFDM, (c) UFMC, and (d) F-OFDM.

Similar to the subcarrier filtering, if multiple RBs for different users are adjacent in the frequency domain, spectrum leakages from adjacent RBs cannot be avoided because of the transition zone of the transmit and receiver filters. However, the spectrum leakage is very small due to the transmit and receive filtering. As a result, the inter-user interference caused

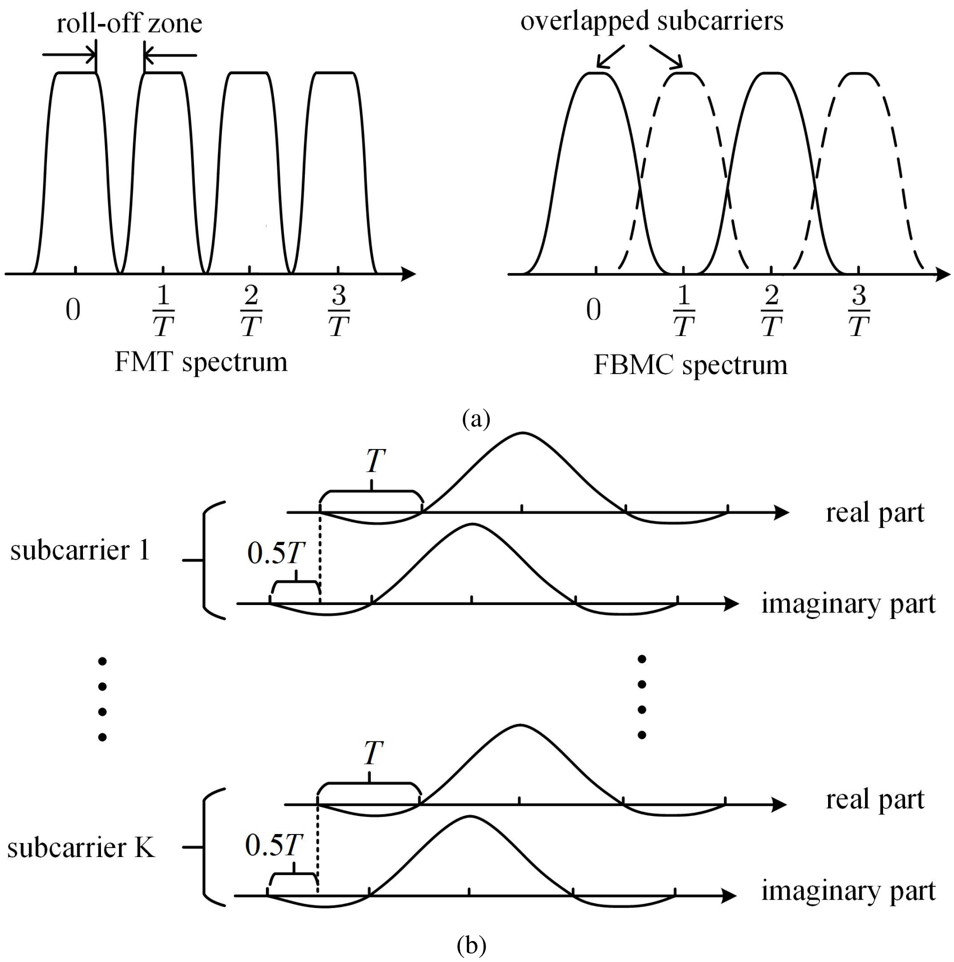

FIGURE 2. (a) spectra for FMT and FBMC and (b) impulse response of the transmit (receive) filter.

by the spectrum leakage is also very small and thus can be ignored [11].

2) UFMC

UFMC is another type of sub-band filtering based waveform. As shown in Fig. 1 (c) where N is the size of the IFFT at the transmitter, the transmitter has a similar structure with that in RB-F-OFDM, except the insertion of CP and the upsampling. Accordingly, the frequency shift is also not required because the data symbols have been mapped to the corresponding sub-bands before IFFT. Different from other filter-based waveforms where receive filters are also employed, UFMC only uses the transmit filters. The signal demodulation in the receiver depends on a $2N$-point FFT. A key feature of UFMC is the employment of that $2N$-point FFT in the receiver, which can recover the data symbols without the need of CP. Given the length of the transmitted signal, N, and the length of the channel impulse response (CIR), L, the length of the received signal will be $N + L - 1$. By padding $N - L - 1$ zeros at the end of the received signal, the data symbols can be recovered through the $2N$-point FFT followed by a decimation with factor two. Fig. 3 (a) illustrates the procedure of the $2N$-point FFT based demodulation.

Although the $2N$-point FFT can achieve efficient demodulation without CP, it causes a noise enhancement problem to the UFMC reception, and thus degrades the UFMC performance compared to OFDM. To explain the noise enhancement, we consider an additive white Gaussian noise (AWGN) channel for example. For UFMC, if assuming the length of the filter's impulse response is equal to the length of CP in OFDM, L, then $N + L$ time-domain noise samples will contribute to the frequency domain noise, as in Fig. 3 (b). For OFDM, since the CP will be removed before signal demodulation, the additive noise included in the CP can also be removed. Therefore, only N time-domain noise samples contribute to the frequency domain noise. As a result, the noise power in UFMC will be larger than OFDM. Due to the noise enhancement, the signal-to-noise ratio (SNR) of UFMC will be degraded by

$$10 \cdot \log(1 + L/N) \ \text{(dB)}, \tag{1}$$

which corresponds to 0.33 dB for normal CP length and 0.97 dB for extended CP in current LTE standard.

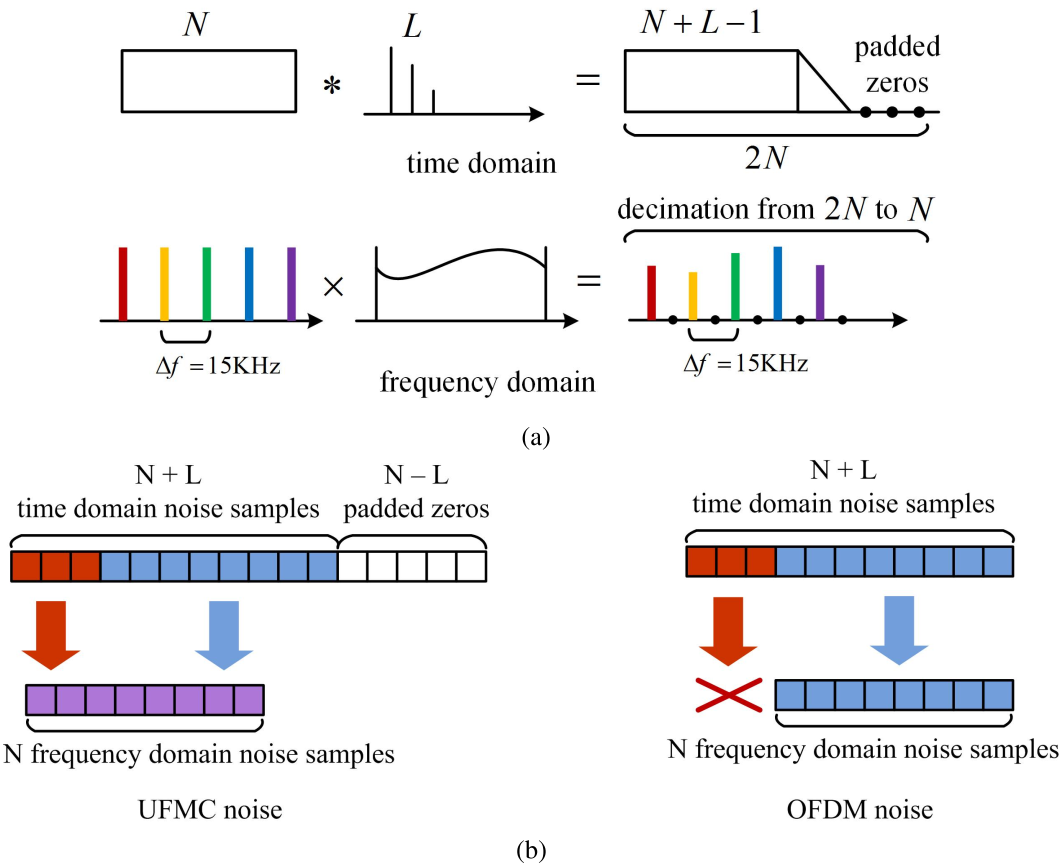

FIGURE 3. UFMC property with (a) 2*N*-FFT based reception and (b) explanation of noise enhancement.

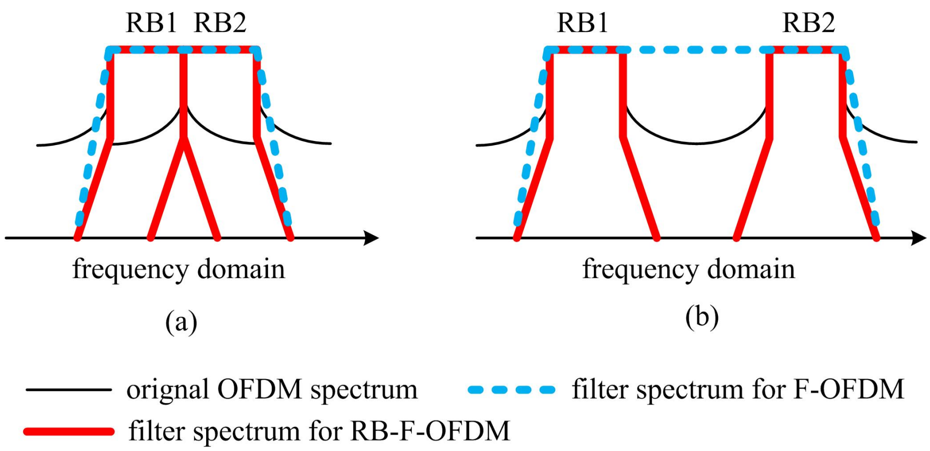

FIGURE 4. OOBs for F-OFDM and RB-F-OFDM for (a) non-adjacent RBs and (b) adjacent RBs.

C. FULL-BAND FILTERING: F-OFDM

For full-band filtering, only one pair of transmit and receive filters is adopted regardless of the spectrum structure in the bandwidth. As shown in Fig. 1 (d), F-OFDM can be viewed as an extension of the standard OFDM by adopting a pair of transmit and receiver filters at the transmitter and the receiver, respectively. Note also that F-OFDM will have a similar structure with RB-F-OFDM when there is only one RB, except that upsampling and decimation are used in RB-F-OFDM to reduce implementation complexity.

For F-OFDM, the OOB depends on the spectrum structure, as shown in Fig. 4. The OOBs for RB-F-OFDM are also included in the figure for comparison. If the allocated RBs are adjacent in the frequency domain, they compose a single bandwidth bulk and thus the OOB can be effectively reduced using the transmit filter, as in Fig. 4 (a). When the RBs are non-adjacent in the frequency domain, however, the transmit filter can only reduce the OOB in the stop-band. The OOB between the RBs is in the pass-band of the transmit filter and thus cannot be reduced, as in Fig. 4 (b). In this situation, RB-F-OFDM can achieve smaller OOB than F-OFDM because the filters in RB-F-OFDM can reduce the OOB between the RBs.

III. APPLICATION IN WIRELESS CHANNELS

The principles of different waveforms in the above section are introduced under AWGN channels. In this section, we will analyze the impact of ISI caused by multipath propagation in practical wireless channels, and discuss the corresponding channel estimation and equalization techniques.

A. ISI ANALYSIS

In standard OFDM, CP is used to avoid the ISI caused by the adjacent OFDM symbols. Usually, the length of CP should be larger than or equal to the length of the physical CIR such that the ISI can be completely removed. The CP can also be used in filter-based waveforms, such as RB-F-OFDM, UFMC, and F-OFDM, to protect the signal from the ISI. However, due to the transmit or receive filtering, the length of the effective CIR, which is composed of the transmit or receive filter and the physical CIR, is usually larger than that of the CP. In this case, the residual ISI will exist since ISI cannot be completely removed. For FBMC, CP is not used and the signal is directly sent to the channel without any protection from the ISI.

Although the ISI cannot be completely avoided, the ISI power is actually very small. For filter-based waveforms that adopt CP, most power of the effective CIR concentrates within the range of CP. Only a small portion of the power of the effective CIR leaks to the next symbol. Therefore, the resulted ISI is also very small. For FBMC, the signal impulse has a raised-cosine form, as shown in Fig. 2 (b). Since the symbol duration in FBMC is much larger than the maximum delay spread, only the low-amplitude portion of the signal impulse can cause the ISI and thus the power of the signal impulse leaks to the next symbol is very small. Therefore, the ISI in FBMC is still very small even though it adopts no ISI-mitigation scheme.

The above analysis shows that the ISI power is small for filter-based waveforms. Therefore, the performance degradation due to ISI is tiny and thus can be ignored.

B. CHANNEL ESTIMATION & EQUALIZATION

The key advantage of OFDM is that it can greatly simplify the receiver design through a group of single-tap equalizers. For filter-based waveforms, if the ISI can be ignored, each subcarrier of the transmit signal will approximately experience a flat fading channel. As a result, similar to OFDM, channel estimation and equalization for filter-based waveforms can also be conducted for each subcarrier in the frequency domain.

For RB-F-OFDM, UFMC, and F-OFDM, the schemes of the waveforms are similar to that of standard OFDM. Therefore, traditional channel estimation and equalization techniques can be directly used with respect to the effective CIR [15]. For FBMC, channel estimation and equalization can also be conducted for each subcarrier. However, due to the restriction on the OQAM modulation, channel estimation and equalization in FBMC systems are less explored than in traditional OFDM systems [3].

IV. COMPARISON

To offer an insightful understanding of different waveforms, a comprehensive comparison is presented in this section. Numerical simulations are conducted to assess the OOB and the block error rate (BLER). In the simulation, we assume the carrier frequency is 2 GHz. The subcarrier spacing is 15 KHz with 15.36 MHz sampling frequency (corresponds to 1024 FFT in current LTE standard), and 36 subcarriers (corresponds to 3 RBs) are employed for data transmission. In particular, the sub-band of UFMC is as wide as one RB for simplicity. A normal CP length is used when CP is required. Quadrature-phase-shift-keying (QPSK) and 16QAM are both considered in the simulation with $1/3$ rate turbo coding. The extended typical urban (ETU) channel model is used with a maximum delay spread of 5μs. To focus on the link-level performance, we only consider a single user in the cell with one transmit antenna at the user terminal and one receive antenna at the base station. Perfect channel information is considered in the simulation so that we can focus on the performance difference caused by the schemes of the waveforms.

A. OOB

The key advantage of filter-based waveforms is that they can significantly reduce the OOB to support asynchronous transmission. It is therefore necessary to compare the OOBs of different waveforms with the standard OFDM.

Fig. 5 shows the power spectrum density (PSD) for different waveforms. The nonlinearity of the power amplifier (PA) is also taken into account [16]. From Fig. 5 (a) where ideal linear PA is assumed, the OOBs of filter-based waveforms can achieve $15-20$ dB improvement over the standard OFDM. In this case, the OOB of the waveform depends heavily on the filter design. On the other hand, however, if the nonlinear of PA is taken into account, the OOB will be mainly determined by the output power and thus the OOB of different waveforms will be similar, as shown from Fig. 5 (b) to (d). It is shown that the OOB becomes worse with the rising of the output power because the PA with larger output power works near the nonlinear zone. The nonlinearity of the PA will introduce extra frequency components and thus the OOBs will increase accordingly.

Our results show that all kinds of filter-based waveforms can significantly reduce the OOB compared to the standard OFDM, even in the presence of the nonlinearity of PA. In this sense, the filter-based waveforms are more suitable for

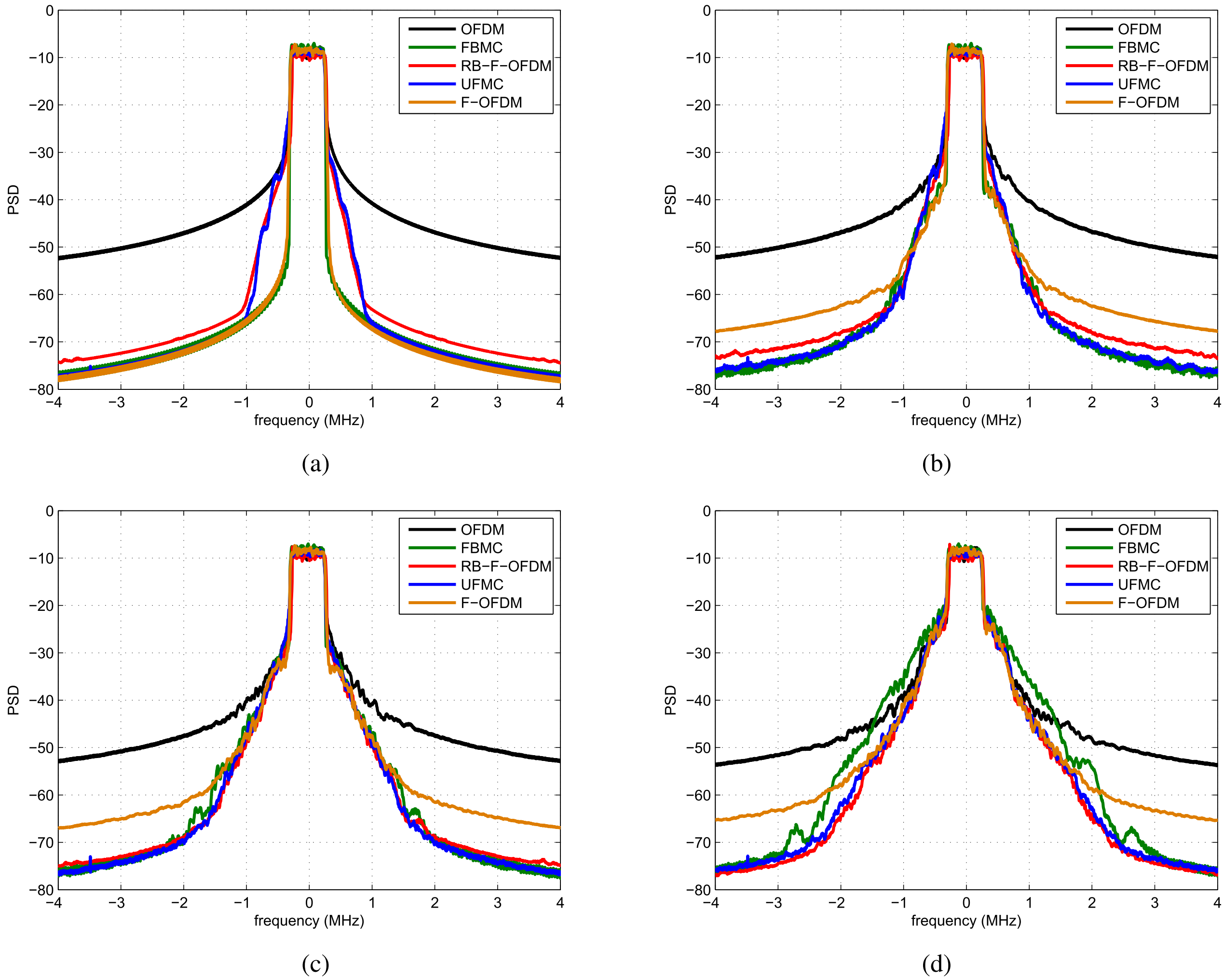

FIGURE 5. PSDs for different waveforms under different conditions (a) no PA (b) 20 dBm output power with PA (c) 25 dBm output power with PA (b) 29 dBm output power with PA. The PSDs have been normalized so as to be presented with the same scale.

asynchronous transmission because the ACI can be greatly reduced.

B. BLER

In this subsection, BLERs of different waveforms are assessed with respect to SNR, carrier-frequency-offset (CFO), and terminal mobility. In practical systems, the performance depends heavily on the nonlinearity of the PA. However, in order to highlight the difference caused by the schemes of various waveforms, the ideal linear PA is considered in the simulation to avoid the impact caused by the PA nonlinearity.

1) BLER VERSUS SNR

Fig. 6 shows the BLER versus SNRs under different modulation schemes. As expected, standard OFDM can achieve the best performance since ISI has been completely removed. For filter-based waveforms, however, performance degradation can be observed because they will suffer extra ISI. The degradation is more severe for high-order modulation because the dense constellation makes it more sensitive to the interference. Despite of the ISI, the performance degradation is very tiny because the ISI power is very small, as we have explained in Section III.

We can also observe that the UFMC has the worst performance among all the waveforms because of the noise enhancement caused by the $2N$-point FFT based reception. Our results in Fig. 6 (a) show that performance degradation due to noise enhancement is about 0.3 dB, which agrees with our theoretical analysis in Section III.

2) CFO ROBUSTNESS

In multi-carrier systems, CFO will cause severe ICI and thus degrade the performance. It is therefore necessary to evaluate the robustness of different waveforms in the presence of CFO. Fig. 6 (b) shows the BLER versus CFO for different waveforms with different SNRs. In general, the performance will degrade with the increasing CFO, especially for high SNR conditions. The reason is that the additive noise is small in this case and thus the ICI will become dominant.

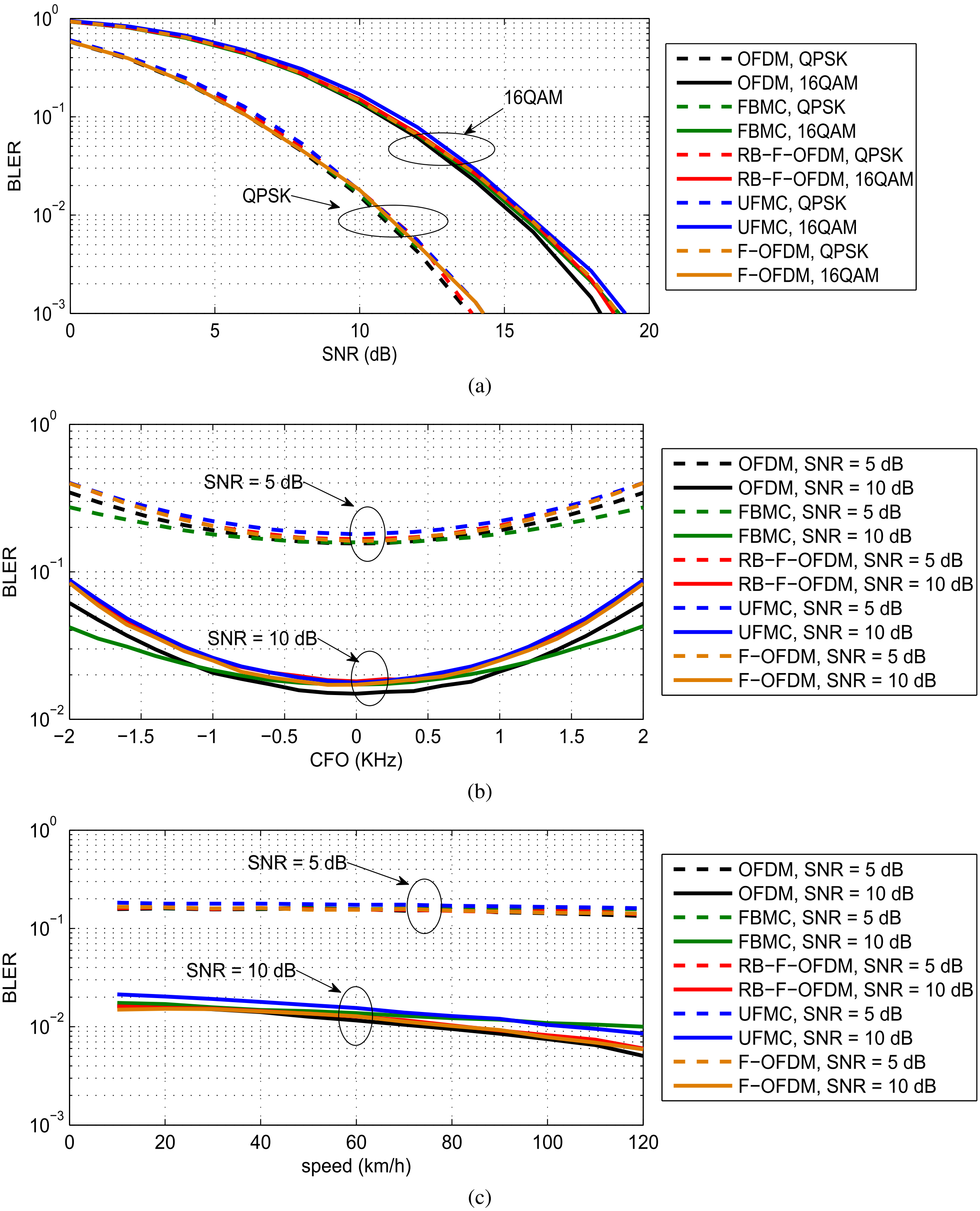

FIGURE 6. **BLERs for different waveforms versus (a) SNR (b) CFO and (c) terminal speed.**

From the figure, FBMC is most robust against the CFO. This is because the transmit filter of FBMC has much better frequency-domain localization than other waveforms [7], and therefore the ICI can be filtered out efficiently for each subcarrier, leading to much smaller ICI. Theoretically, the ICI is also supposed to be reduced for sub-band filtering based waveforms because the interference caused by other sub-bands should also be removed using receive filters. In practice, however, Fig. 6 (b) shows that the sub-band filtering based waveform suffers from similar interference

TABLE 1. Summary for different waveforms. Grades A to C indicate from good to bad.

Metrics \ Waveform	OFDM	FBMC	RB-F-OFDM	UFMC	F-OFDM
Filter granularity	–	subcarrier	sub-band	sub-band	full-band
OOB without PA	C	A	B	B	A
OOB with PA	C	B	B	B	B
Low latency	A	C	A	A	A
BLER vs SNR	A	B	B	C	B
CFO robustness	B	A	B	B	B
Doppler diversity	A	B	A	A	A

with OFDM. This is because the ICI is mainly determined by the adjacent subcarriers that are in the same sub-band with the subcarrier of interest. Therefore, the ICI cannot be effectively removed since the whole sub-band is in the pass-band of the filter. For F-OFDM, the ICI is also the same with the standard OFDM since the full-band filtering cannot remove any ICI.

3) MOBILITY

To support high mobility users is an important feature of future 5G system. It is therefore necessary to investigate the impact of terminal mobility on different waveforms. Fig. 6 (c) evaluates the performance with respect to different terminal speeds up to 120 km/h, which corresponds to a maximum Doppler frequency about 222 Hz for a 2 GHz carrier frequency. Since we have assumed perfect channel information in the simulation, the performance can be improved by increasing the terminal speed because more Doppler diversity can be captured by the receiver for higher speed. Better performance is achieved at high SNR situation because the diversity gain is more obvious when the noise power is small. However, compared to other waveforms, the performance of FBMC only has marginal improvement even when the terminal speed is 120 km/h. This is because the time variation of channels over adjacent symbol intervals have been averaged out due to the long tail of filter's impulse response. It is therefore more difficult for FBMC to gain the Doppler diversity.

C. SUPPORT FOR LOW-LATENCY SERVICE

In addition to low OOB, good time localization property is also required for 5G waveforms to support low-latency services. From the above section, the schemes of RB-F-OFDM, UFMC, and F-OFDM are actually similar to that of standard OFDM. Therefore, data transmission and reception can occur immediately within a symbol interval for those waveforms. However, the data transmission for FBMC will be postponed due to the latency caused by the long tail of the filter's impulse response, and the reception cannot be finished until the whole pulse has been received. In this sense, FBMC is not as suitable as the other filter-based waveforms for low-latency services.

V. SUMMARY AND CONCLUSIONS

As a summary, different features of various waveforms have been listed in Tab. 1 where grades A to C indicate from good to bad. To achieve asynchronous uplink transmission, all waveforms rely on the transmit and receiver filters with different filter granularity. All kinds of filter-based waveform can achieve lower OOBs than the standard OFDM even in the presence of PA nonlinearity. Due to the extra ISI, the filter-based waveforms will suffer from small performance degradations compared to that of standard OFDM. In particular, UFMC has the worst performance because it has to suffer from extra noise enhancement. Although the per-subcarrier filtering feature makes FBMC most robust against CFO, it also makes FBMC hard to obtain the Doppler diversity since the time variation of the channel has been averaged out by the long tail of filter's impulse response. Meanwhile, the long tail of the filter also makes FBMC not suitable for low-latency services.

Due to the requirement of asynchronous transmission in future 5G networks, filter-based waveforms have gained a lot of attention recently. In this article, we have discussed the basic principles and revealed the underlying characteristics of typical filter-based waveforms. In addition, a comprehensive analysis has also been presented in this article to provide in-depth demonstration of the waveforms. Our results show that the filter-based waveform can achieve much lower OOB compared to the standard OFDM with negligible performance degradation. Therefore, as a replacement of OFDM, the filter-based waveform is expected to be used for asynchronous transmission in future 5G networks.

REFERENCES

[1] J. G. Andrews *et al.*, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[2] G. Wunder *et al.*, "5GNOW: Non-orthogonal, asynchronous waveforms for future mobile applications," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 97–105, Feb. 2014.

[3] B. Farhang-Boroujeny and C. Yuen, "Cosine modulated and offset QAM filter bank multicarrier techniques: A continuous-time prospect," *EURASIP J. Adv. Signal Process.*, vol. 2010, Dec. 2010, Art. no. 165654.

[4] T. Wild, F. Schaich, and Y. Chen, "5G air interface design based on universal filtered (UF-)OFDM," in *Proc. Int. Conf. Digit. Signal Process.*, Aug. 2014, pp. 20–23.

[5] F. Schaich, T. Wild, and Y. Chen, "Waveform contenders for 5G—Suitability for short packet and low latency transmissions," in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Seoul, South Korea, May 2014, pp. 1–5.

[6] G. Cherubini, E. Eleftheriou, and S. Olcer, "Filtered multitone modulation for very high-speed digital subscriber lines," *IEEE J. Sel. Areas Commun.*, vol. 20, no. 5, pp. 1016–1028, Jun. 2002.

[7] B. Farhang-Boroujeny, "OFDM versus filter bank multicarrier," *IEEE Signal Process. Mag.*, vol. 28, no. 3, pp. 92–112, May 2011.

[8] A. M. Tonello and M. Girotto, "Cyclic block FMT modulation for broadband power line communications," in *Proc. IEEE Symp. Power Line Commun. Appl. (ISPLC)*, Johannesburg, South Africa, Mar. 2013, pp. 247–251.

[9] N. Michailow *et al.*, "Generalized frequency division multiplexing for 5th generation cellular networks," *IEEE Trans. Commun.*, vol. 62, no. 9, pp. 3045–3061, Sep. 2014.

[10] X. Wang, T. Wild, F. Schaich, and A. F. dos Santos, "Universal filtered multi-carrier with leakage-based filter optimization," in *Proc. IEEE GLOBECOM Broadband Wireless Access Workshop*, May 2013, pp. 223–228.

[11] J. Li, E. Bala, and R. Yang, "Resource block filtered-OFDM for future spectrally agile and power efficient systems," *Phys. Commun.*, vol. 11, pp. 36–55, Jun. 2013.

[12] J. Li, K. Kearney, E. Bala, and R. Yang, "A resource block based filtered OFDM scheme and performance comparison," in *Proc. Int. Conf. Telecommun.*, May 2013, pp. 1–5.

[13] J. Abdoli, M. Jia, and J. Ma, "Filtered OFDM: A new waveform for future wireless systems," in *Proc. IEEE Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jun./Jul. 2015, pp. 66–70.

[14] X. Zhang, M. Jia, L. Chen, J. Ma, and J. Qiu, "Filtered-OFDM—Enabler for flexible waveform in the 5th generation cellular networks," in *Proc. IEEE Global Commun. Conf. (GC)*, San Diego, CA, USA, Dec. 2015, pp. 1–5.

[15] Y. Liu, Z. Tan, H. Hu, L. J. Cimini, Jr., and G. Y. Li, "Channel estimation for OFDM," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1891–1908, 4th Quat., 2014.

[16] *On the Evaluation of PA Model*, document R1-165006, 3GPP TSG-RAN WG1, Nokia and Alcatel-Lucent Shanghai Bell, Aug. 2016.

YINSHENG LIU received the B.E. and Ph.D. degrees in communication and information systems from Beijing Jiaotong University, Beijing, China, in 2009 and 2015, respectively. From 2012 to 2013, he was a Visiting Scholar with the Georgia Institute of Technology, Atlanta, GA, USA. He is currently an Associate Professor with the State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University. He has authored over ten journal papers published in international journals as the first author. His research interests include channel estimation and equalization, new waveform design in next generation cellular systems, and generally signal processing with emphasis on wireless communications. He was a recipient of the IBM Excellent Student Award and the Excellent Graduate Award of Beijing Jiaotong University, and the BJTU graduate scholarship during his master and Ph.D. programs.

XIA CHEN (M'14) received the degree and D.E. degree from Beijing Jiaotong University, Beijing, China, in 1997 and 2003, respectively. She has been with Beijing Jiaotong University since 2003, where she is currently a Lecturer with the School of Electronic and Information Engineering. Her research interests include mobile channel modeling, multicarrier transmission, and radio resource management of wireless networks. She is a member of the Chinese Institute of Electronics.

ZHANGDUI ZHONG received the B.E. and M.S. degrees from Beijing Jiaotong University, Beijing, China, in 1983 and 1988, respectively. He is currently a Professor and an Advisor of Ph.D. candidates with Beijing Jiaotong University, as well as the Director of the School of Computer and Information Technology and a Chief Scientist of State Key Laboratory of Rail Traffic Control and Safety. He is also the Director of the Innovative Research Team of Ministry of Education, Beijing, China, and the Chief Scientist of Ministry of Railways, Beijing, China. He has authored or co-authored seven books and over 200 scientific research papers in his research area. He holds five invention papers. His research interests include wireless communications for railways, control theory and techniques for railways, GSM-R systems. His research has been widely used in railway engineering, such as the Qinghai-Xizang railway, the Datong-Qinhuangdao Heavy Haul railway, and many high-speed railway lines in China. He is an Executive Council Member of the Radio Association of China, Beijing, and the Deputy Director of the Radio Association, Beijing. He was a recipient of the MaoYiSheng Scientific Award of China, the ZhanTianYou Railway Honorary Award of China, and the Top 10 Science/Technology Achievements Award of Chinese Universities.

BO AI received the M.S. and Ph.D. degrees from Xidian University, Xi'an, China, in 2002 and 2004, respectively. He was with Tsinghua University, Beijing, China, where he was an Excellent Post-doctoral Research Fellow in 2007. He is currently a Professor and Advisor of Ph.D. candidates with Beijing Jiaotong University, Beijing, where he is also the Deputy Director of the State Key Laboratory of Rail Traffic Control and Safety. He is also with the Engineering College, Armed Police Force, Xi'an. He has authored or co-authored six books and 140 scientific research papers. He holds 26 invention patents in his research areas. His interests include the research and applications of orthogonal frequency-division multiplexing techniques, high-power amplifier linearization techniques, radio propagation and channel modeling, global systems for mobile communications for railway systems, and long-term evolution for railway systems. He is a Fellow of The Institution of Engineering and Technology. He has received many awards, such as the Qiushi Outstanding Youth Award by HongKong Qiushi Foundation, the New Century Talents by the Chinese Ministry of Education, the Zhan Tianyou Railway Science and Technology Award by the Chinese Ministry of Railways, and the Science and Technology New Star by the Beijing Municipal Science and Technology Commission. He was as a Co-Chair or a Session/Track Chair of many international conferences, such as the ninth International Heavy Haul Conference in 2009, the 2011 IEEE International Conference on Intelligent Rail Transportation, the HSRCom in 2011, the 2012 IEEE International Symposium on Consumer Electronics, the 2013 International Conference on Wireless, Mobile and Multimedia, the IEEE Green HetNet in 2013; and the IEEE 78th Vehicular Technology Conference in 2014. He is an Associate Editor of the IEEE Transactions on Consumer Electronics and an Editorial Committee Member of the *Wireless Personal Communications Journal*.

DESHAN MIAO received the Ph.D. degree from the Beijing University of Posts and Telecommunications, Beijing, China, in 2007. He is currently a Senior Researcher with Nokia Beijing Bell Labs, Beijing. He has been involved in TDD system design, multiple antenna technology, and 5G physical layer design. His current research interests include new waveform, massive MIMO and cloud RAN.

ZHUYAN ZHAO received the Ph.D. degree from the Beijing Institute of Technology, Beijing, China, in 2013. He is currently with Nokia Beijing Bell Labs, Beijing, where he is a Senior Researcher. He has been involved in physical design and system evaluation for HSPA and LTE, wireless mesh network and relay. His current research interests include contention based transmission, 5G system design for high-mobility scenarios.

JINGYUAN SUN is currently with Nokia Beijing Bell Labs, Beijing, China, where he is a Senior Research.

YONG TENG received the Ph.D. degree from the Beijing University of Posts and Telecommunications, Beijing, China, in 2003. He is currently with Nokia Beijing Bell Labs, Beijing, where he is a Senior Researcher. He has been involved in advanced antenna technologies, link adaptation and MAC optimization for LTE, LTE-Advanced and 5G. His current research interests include radio resource management, interference management, cognitive radio, spectrum sharing, heterogeneous network, and concept creation for 5G.

HAO GUAN received the M.S. and Ph.D. degrees in electrical engineering from Northern Jiaotong University in 1996 and 1999. She is currently leading Radio Research Beijing Team with Nokia Beijing Bell Labs, Beijing, China. She is responsible for developing new radio technology to ensure Nokia innovation leadership also in the future. She also leads Nokia's Asia 5G activities from internal research and external collaboration with operators, partners, and universities. She is taking Future Forum's 5G SIG Deputy Chair and RRM WG Chair Role. She is member of the China National '863 5G technique experts group'. Her technique focus area, including 5G radio, 3GPP/LTE network evolution and interference management.