Full-Duplex Quasi-Gapless Carrier Aggregation Using FBMC in Centralized Radio-Over-Fiber Heterogeneous Networks

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Abstract—Filter-bank multicarrier (FBMC) is proposed to demonstrate a full-duplex asynchronous quasi-gapless (only one subcarrier spacing) carrier aggregation for millimeter-wave (MMW) radio-over-fiber radio access technology (RAT) in next-generation 5G heterogeneous mobile-data-network (Het-Net). Fourteen broadband FBMC signals are aggregated with only one subcarrier guard band in the 60-GHz MMW downlink. In the uplink quasi-gapless asynchronous inter-RAT carrier aggregation between 60-GHz MMW and 4G long-term evolution (LTE) signals are also demonstrated. System performances assessment of FBMC and orthogonal frequency-division multiplexing (OFDM) under different operation condition are studied. Our results also show that the FBMC-based new RAT is also backward compatible with existing LTE systems in the Het-Net. Compared with OFDM-based signals with large guard bands, FBMC achieves higher spectral efficiency with better error vector magnitude performance at less received power and smaller guard bands.

Index Terms—carrier aggregation, filter-bank multi-carrier, 5G, multi-RAT, radio-over-fiber.

I. INTRODUCTION

Driven by video stream, mobile internet and cloud service on smartphones and tablets, the overall traffic volume in wireless communication systems has grown tremendously in recent years, fueled primarily by the uptake in mobile broadband [1]–[12]. This trend is expected to continue into the future, which encourages the industry to look for new radio-access technologies (RATs) to meet future extreme capacity and performance demands for the next generation access network, namely the fifth-generation (5G) system [1]–[4]. It is expected that the 5G wireless access network promises to support higher access data rate with more than 1,000 times capacity with respect to current long-term evolution (LTE) systems [1]–[3]. New RATs based on higher carrier frequencies to millimeter-wave (MMW)-over-fiber, and carrier-aggregation using multi-band resources are intensively studied to support the high data rate access and effectively use of frequency resources [1]–[10]. At the physical layer, RATs based on new waveforms have also attracted lots of research interests to achieve higher spectral-efficiency (SE) [11]–[15]. Lots of new waveforms have been proposed and intensively studied recently as the candidate formats in the radio access system [15].

Cyclic-prefix orthogonal frequency division multiplexing (CP-OFDM), the widely used waveform in 4G-LTE, however, is not taken for granted in the next generation 5G system, due to several significant drawbacks. First, OFDM has large out-of-band emissions, due to the rectangular inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT) window [15]. It will lead critical cross-band interference in multi-band scenarios when carrier aggregation is used [11]–[19]. Therefore, large guard-band are required to protect adjacent channels. For instance, it will result in the loss of spectral-efficiency in the multi-band carrier-aggregation system. Second, CP is required for OFDM due to the sensitivity to multi-path delays, which further reduces the SE. Finally, OFDM requires strict frequency synchronization between sub-carriers, which is a key issue in the uplink of a cellular network since different users transmit separately [11]–[15].

Among all the candidate waveforms for 5G system, filter bank multicarrier (FBMC) is a promising format for 5G that not only reduces out-of-band emissions but also lowers the requirement for synchronization [11]–[16]. Since each subcarrier band in FBMC is confined to an assigned range with much lower out-of-band emissions, FBMC can achieve quasi-gapless carrier-aggregation. It also reduces the requirement of synchronization for uplinks due to the greater robustness to frequency misalignments. In addition, the combination of poly-phase network (PPN) filter banks and offset-QAM (OQAM) leads to no need for CP, which will further improve SE. Adaptively-modulated optical FBMC is also proposed for multiple access passive optical network (PON) system [17], [18] and also in fiber transmission system [19]. Our recent results of FBMC is very suitable
for future ultra-density asynchronous carrier-aggregation in 5G heterogeneous mobile network (Het-Net) with higher SE [12].

This paper is an invited extension of our recent work presented in OFC 2016 [12]. In this paper, we extend our work and cover in detail of the proposed full-duplex asynchronous quasi-gapless (only 1 sub-carrier spacing) carrier-aggregation scheme for MMW radio-over-fiber (ROF) inter-/intra-RAT in next generation 5G mobile-data-network based on the FBMC. Fourteen broadband FBMC signals are aggregated with only 1 sub-carrier guard-band in the 60-GHz MMW down-link. In the up-link, quasi-gapless asynchronous inter-RAT CA between 60-GHz MMW and 4G- Long Term Evolution (LTE) signals are also demonstrated. The results of LTE signals with FBMC signals under coexisting condition also show that the FBMC-based new RAT is backward compatible with existing LTE systems in the Het-Nets. System performances assessment of FBMC and OFDM under different operation condition are studied. Compared with OFDM-based signals with large guard-bands, FBMC achieves higher spectral-efficiency with better EVM performance at less received power and smaller guard-bands. A portion of the experimental results have been presented in [12]. This paper presents a more detailed discussion of the utilized technologies as well as the additional results.

The rest of this paper is organized as follows. In Section II, we give a description of the operation principles of RoF based centralized wireless access networks and also the detailed digital signal processing (DSP) of FBMC compared with OFDM. Section III is devoted to the detailed experimental setup of full duplex quasi-gapless carrier aggregation based on FBMC in RoF Het-Net. The experimental results and system performances assessment of FBMC and OFDM under different operation condition are presented in Section IV. Finally, we summarize this paper in Section V.

II. OPERATION PRINCIPLE

A. Centralized RoF Heterogeneous Access Network

The concept of the multi-RAT and centralized RoF Het-Net is shown in Fig. 1. New waveforms are expected to be used on the higher frequency bands. Cooperation and aggregation of both new RAT and also legacy services in lower frequency can support high performance, high data rate Het-Net. To support efficient operation of small cells with coordinated multi-point process, cloud radio access network (C-RAN) architecture has attracted lots of research interest for next-generation wireless network [1]–[10]. A base station of C-RAN is separated into principal radio components at remote radio heads (RRHs) and processing with control functions in baseband units (BBUs). The architecture of centralized or cloud-based BBU pools enables advanced resource sharing, function virtualization, handover, coordination and carrier-aggregations to support high performance mobile data network. Compared with the traditional mobile fronthaul (MFH) networks based on common public radio interface (CPRI), the analog fronthaul schemes as the proposed cloud or centralized RoF, increase the bandwidth efficiency and reduce the latency [5]–[10]. To support future 5G mobile communication systems employing MMW and small cells, fiber and wireless access networks will be integrated to provide MFH solutions with higher capacity, flexibility, and SE.

Next generation 5G network is believed to be a Het-Net using different frequency bands for different data rate requirement and coverage to increase the reliability and coverage, namely a multi-RAT network architecture (e.g., LTE, Wi-Fi, MMW) [1]–[4]. Therefore, to effectively utilize the wireless resource, enrich the users’ experience, and reduce the latency, the coordination and aggregation of different RATs have become more and more important, which has attracted a lot of research interests [1]–[10]. Recently, RoF-based technologies have also been discussed in standardization studies for access networks [9]. Carrier aggregation technology has been specified in LTE-A to aggregate multiple mobile channels into a single channel through electrical frequency conversion and RF combining and splitting [3]–[5]. Along that line, both industry and academia has looked into research topics on inter-RAT CA to further increase the peak data rate in the multi-RAT Het-Net, including LTE, WiFi and even intra-RAT CA for MMW and inter-RAT CA between lower radio frequencies (LTE) and MMW bands. As analyzed above, the new RATs based on new waveforms is expected to achieve higher SE, and higher reliability. Reducing the system requirement of synchronization and also the spectral guard bands will be very helpful in the next generation multi-RAT Het-Net. It is believed that FBMC, compared with CP-OFDM, is very suitable for future ultra-density asynchronous carrier-aggregation in 5G Het-Net with higher SE.
Fig. 2. (a) and (b) depict the transmitter and receiver design of OFDM and FBMC.

B. The Principle of FBMC

In this part, we introduce the principle of FBMC, as well as the DSP for signal modulation and demodulation, in comparison with CP-OFDM. To provide improved out-of-band spectrum characteristics, the basic idea of FBMC is to apply filtering on each subcarrier. A flexible approach of baseband filtering, is to use polyphaser network (PPN) and replace the rectangular window in OFDM with a bank of filters [14], [15]. Fig. 2(a) and (b) compares the transmitter and receiver diagrams of OFDM and FBMC. The typical IFFT process with CP insertion in OFDM is replaced by the synthesis filter bank (SFB) in FBMC, while CP removal with FFT process is replaced by the analysis filter bank (AFB). The SFB and AFB in FBMC are achieved using FFT/IFFT with a PPN, as proposed in [14]. The modulated data of FBMC at each subcarrier is shaped by a well-designed prototype filter that is different from the rectangular pulse filter in OFDM. In our scheme, the prototype filter is based on PHYDYAS filter-design with 4-tap length [14].

For OFDM signals generation based on IFFT/FFT processing, the response of IFFT or FFT is equivalent to a special filter. Assuming the FFT is running at the same sampling rate as serial data rate, the output of a FFT block with subcarrier index \( k = 0 \) can be expressed as a low-pass linear phase FIR filter to the input data \( x(n) \) as

\[
y_0(n) = \frac{1}{M} \sum_{i=1}^{M} x(n-i) \tag{1}
\]

Here \( M \) is the FFT size and the frequency response of such FIR filter is as Sinc-shaped function as

\[
H(f) = \frac{\sin(\pi f M)}{M \sin(\pi f)} \tag{2}
\]

Therefore, infinite tails extend to both high and low frequencies as shown in Fig. 3(a).

When considering other subcarriers of an OFDM signal, their center frequency should be strictly defined to maintain the orthogonality. The orthogonality condition can only be achieved through the zero crossings. At the frequencies which are integer multiples of \( 1/M \), only one filter frequency response is non-zero as shown in Fig. 3(b). It is clearly apparent in Fig. 3(b) that there is a large out-of-band spectral leakage. The OFDM signals exhibit strong side lobes, due to the rectangular windowing by FFT with Sinc-shaped frequency response and the side-lobe-attenuation of a typical OFDM signal is 13-dB. In addition, OFDM requires a very tight synchronization and orthogonality between each sub-carrier in order to prevent intercarrier-interference (ICI) as analyzed above. Therefore, OFDM is not a good choice for seamless and asynchronous carrier aggregations and requires large guard-bands to avoid cross-band interferences.

In order to reduce the out-of-band spectra leakage, it is necessary to construct a filter to each subcarrier and have better control of the out-of-band frequency response. FBMC is based on this theory, and lots of prototype filters have been studied from the perspectives of performance, energy concentration, rapid decay, spectrum nulling, and complexity [14], [15]. Here we choose a prototype filter based on Mirabbasi-Martin filter (MM-filter), which is widely used for FBMC generation with both good performances and low complexity [14]. The frequency response of the MM-filter can be expressed as

\[
H(f) = \sum_{k=-(K-1)}^{K-1} H_k \frac{\sin(\pi(f-kMK))}{MK \sin(\pi(f-kMK))} \tag{3}
\]

Here the coefficients \( H_k \) is well defined to have a better control of out-of-band filter frequency response, which can be found in [14], and \( K \) is the number of filter taps and also the overlapping factor.

Fig. 4(a) shows the frequency response of the MM-filter with different tap numbers. It becomes a Sinc-shaped response when \( K = 1 \), and the side-lobe-attenuation or the reduction of out-of-band leakage gets higher with the increasing of the number of taps or overlapping times. We can see that the \( \sim 40 \) dB side-lobe-attenuation can be guaranteed when \( K = 4 \), which is enough for...
practical systems. Fig. 4(b) shows the spectra of FBMC signals with negligible out-of-band spectra leakage, and here $K$ is 4.

We have also analyzed the performances of FBMC signals with different filter lengths. Noting that additional complexity is introduced by these filter banks in PPN, and it depends on the number of subcarriers in the system and also the number of filter taps or overlapping factor $K$. Therefore, it is reasonable to choose the shortest filter but with the smallest operation penalty. We have simulated the performances of the aggregated OFDM and FBMC signals with different filter lengths in an asynchronous system, and the results are shown in Fig. 5. Here, two pairs of 100-MHz signals, with FFT-size of 128 and SNR of 18 dB signals are used for asynchronous CA. The filter length $K$ is $l$ when OFDM signals are tested. As expected, FBMC signals with filter length $K = 6$ has the best error vector magnitude (EVM) performance. With the increasing of filter length, the FBMC signal gets less sensitive to the ICI. However, we also observed that there is negligible penalty for FBMC signal with $K = 4$ compared with that with $K = 6$. Therefore, we believe the filter length $K = 4$ is long enough for FBMC signals used in quasi-gapless asynchronous CA scenario.

Above defined MM-filter in Eq. (3) is used as SFB and AFB pair for the subcarrier signals multiplexing and demultiplexing. Different from OFDM with strict requirements of frequency and time synchronization, the orthogonality of FBMC is achieved by using OQAM for data to subcarrier mapping due to the fact that the inter sub-channel interference function in time-domain is symmetrical staggered in T/2-time length ($T$ is the symbol period) [14]. In particular, the imaginary part of the interference function crosses the zero axis at the integer multiples of the symbol period $T$ while the real part crosses the zero axis at the odd multiples of $T/2$. Fig. 6 shows the principle of OQAM mapping in both frequency-domain (subcarriers) and time-domain (symbols). In frequency-domain, I and Q components in FBMC are interleaved and each subcarrier only carries one real PAM symbols (I or Q); while in time-domain, the symbols are with a halved symbol period of $T/2$ offset to each other. Based on above setup, full-capacity with the same data rate to OFDM can be guaranteed.

It is worth noting that both OFDM and FBMC share the same IFFT/FFT processing, however, instead of CP insertion for CP-OFDM, FBMC require the PPN to filter each subcarrier. However, the benefit of FBMC over OFDM is still distinct. The over 40-dB side-lobe-attenuation of FBMC, makes it negligible to other bands. Therefore, this significant reduction out-of-band leakage leads to an ultra-density CAs without the need of wasteful guard bands. Our results also show that the requirement of synchronization is significantly relaxed, which is another advantage of FBMC.

III. EXPERIMENTAL SETUP

Fig. 7 shows the downlink and uplink experimental setup of full-duplex asynchronous quasi-gapless carrier-aggregation for MMW-ROF inter-/intra-RAT based on the OFDM/FBMC and LTE signals. For downlink carrier aggregation, we use one DFB laser working at 1554.66 nm as the light source. After optical coupler (OC), one branch is used for MMW-ROF signal generation with OFDM or FBMC signal modulation, the other is directly modulated with LTE inter-frequency (IF) signals. In the upper branch, optical MMW generation is realized by optical
carrier suppression (OCS) method based on a 40-GHz Mach-Zehnder modulator (MZM). The MZM is driven by a 27.2-GHz RF signals with bias at null point.

To study the asynchronous intra-RAT carrier aggregation, the fourteen 100-MHz OFDM or FBMC IF signals are divided into two groups as the odd and even channels, which are generated by two different digital-to-analog-convertors (DACs) from a arbitrary waveform generator (AWG) with 128-FFT-size before combination. In the lower branch, three 20-MHz standard LTE signals at around 701, 819 and 937 MHz are generated by another DAC. After modulation, these two branches optical signals are combined together for 20-km fiber transmission. At the radio-access unit (RAU) side, the optical signals are separated by a 33/66-GHz interleaver. One port of the output is for MMW signal generation and the other is for LTE base-band signal processing. The optical spectra of signals before and after interleaver (two ports) are shown in insets (i)–(iii). The two optical side bands with 54.4-GHz separation are preserved from one port as shown in insert (ii). The optical side-band signals are detected by a 60-GHz photodiode (PD) and up-converted to MMW frequency. A pair of horn antennas with 25-dBi gains is used to deliver the MMW signal, with 3-ft of line of sight.
(LoS) wireless transmission distance. At the use-end (UE), the MMW is down-converted to IF by an envelope-detector (ED), the broadband signals are sampled and stored by a digital scope for off-line signal processing.

For uplink inter-RAT carrier aggregation, eight broad-band 100-MHz OFDM or FBMC signals are aggregated with the three bands of LTE uplink (SC-FDM) signals by an electrical combiner. The up-link LTE signals are generated with the same frequency for down link for simple operation. However, the eight broadband channels are generated by two sets of DACs for asynchronous aggregation, which are carried by two pairs of 60 GHz MMW links. The uplink 60 GHz MMW is generated by a mixer with 60.4-GHz center frequency and it is down-converted to IF signals again by an ED before 6-dB electrical combiner. After that, the aggregated signals are externally modulated on an optical carrier from a DFB laser for uplink transmission. At the center office, the uplink optical signals are detected a 12.5-GHz PD for offline digital signal processing.

IV. EXPERIMENTAL RESULTS AND ANALYSIS

We first test the down-stream MMW signals with intra-RAT carrier aggregation. Fig. 8 shows the spectral of the broadband 100-MHz signals. The spectra of odd channels (1, 3, 5, 7) are shown in Fig. 8(a), where clear out-of-band power leakage suppression can be observed by using FBMC (in blue) over OFDM (in red). Fig. 8(b) shows the spectra of 14-band DL FBMC signals. All odd and even channels are aggregated together with only 1 sub-carrier spacing to achieve a quasi-gapless carrier aggregation.

Noting that the odd and even channels are generated separately, different delays can be added between them to study the impact of timing mismatch on the quasi-gapless carrier aggregated signals. Fig. 9 shows the impact of delays between adjacent channels on the EVM performances of FBMC and OFDM signals. Here the OFDM and FBMC have same received optical power and 1-subcarrier guard-band between different channels. The results in Fig. 9 clear shows that OFDM is very sensitive to delays, it cannot work under synchronized conditions. However, the EVM performances of FBMC signal is almost independent of delays. Therefore, asynchronous aggregations with large timing mismatch tolerance can be realized based on FBMC.

Fig. 10(a) shows the average EVMs of MMW 14 DL intra-RAT aggregated OFDM or FBMC signals versus the guard-band spacing. Here about 40% symbol’s delay is added between odd and even channels. We can see that only 1 sub-carrier spacing is required to achieve ICI-free for FBMC signals. However, the OFDM signals is much sensitive to the guard-band spacing, and they need more than 26 sub-carriers to achieve ICI-free due to the large out-of-band emissions.

Under the quasi-gapless carrier aggregation with 1-sub-carrier spacing and the asynchronous working condition (40% symbol delay), we also measure the average EVMs of MMW 14 DL intra-RAT OFDM/FBMC signals as a function of re-
OFDM has a large EVM floor due to the ICI and FBMC shows much better performances. The constellations of OFDM and FBMC with 0-dBm received power are also shown as insets (i) and (ii) in Fig. 10(b). The EVMs of all 14 DL channels are shown in Fig. 10(c) after fiber transmission at different receiver power. The 14 channels exhibit similar performances.

For UL signals, we also test EVM performances under asynchronous operation conditions. Fig. 11(a) shows the EVM performances of LTE upstream signal band A (SC-FDM) and FBMC/OFDM signals as a function of guard band spacing, in the asynchronous aggregation case with both broadband MMW signals and narrowband LTE signals after the UL fiber transmission. Here the total guard band is kept at least 50% of FBMC/OFDM subcarrier spacing. We can see that the OFDM signal again is very sensitive to guard-band spacing. The LTE signals also suffers large ICI from OFDM signals due to the large out-of-band spectral leakage. However, the FBMC signals show good backward compatibility with the LTE signals due the sharp band-edge with more than 40-dB side-lobe attenuation. The quasi-gapless carrier aggregation spectrum with 8 broadband FMBC signals and three narrowband LTE signals is shown in Fig. 11(b).

The average EVMs of three LTE-bands in downlink and uplink case are shown in Fig. 12(a) and (b). More results of UL LTE bands with or without carrier aggregation are also shown in Fig. 12(b). To study the impact of inter-RAT asynchronous aggregation with other broadband OFDM or FBMC signals, the down and up-link LTE signals have same RF power before modulation. Quasi-gapless and asynchronous aggregation are performed here. Results confirm that FBMC has no impact on the LTE UL signals in due to the large suppression of out-of-band emission. However, OFDM induces large penalty to the LTE UL signals. There is a large EVM floor for LTE signals when they are quasi-gapless aggregated with OFDM. Fig. 12(c) shows the EVMs of UL LTE, FBMC and OFDM signals versus the power difference. All results confirm that FBMC has better performances in quasi-gapless inter-RAT asynchronous aggregation compared with OFDM.

V. CONCLUSION

We propose and experimentally demonstrate the full-duplex asynchronous quasi-gapless (only 1 sub-carrier spacing) carrier-aggregation scheme for MMW ROF inter-/intra-RAT in next generation 5G mobile-data-network based on the FBMC. Fourteen broadband FBMC signals are aggregated with only 1-subcarrier guard-band in the 60-GHz MMW down-link. In the up-link, quasi-gapless asynchronous inter-RAT CA between 60-GHz MMW and 4G-LTE signals are also demonstrated. The results of LTE signals with FBMC signals under coexisting condition also show that the FBMC-based new RAT is backward compatible with existing LTE systems in the Het-Nets. System performances assessment of FBMC and OFDM under different operation condition are studied. Compared with OFDM-based signals with large guard-bands, FBMC achieves higher spectral-efficiency with better EVM performance at less received power and smaller guard-bands.

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