Multi-Carrier Waveform Based Flexible Inter-Operator Spectrum Sharing for 5G Systems

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Abstract—**This paper presents a multi-carrier waveform based inter-operator spectrum sharing concept for 5G mobile and wireless communication systems. The proposed concept considers the flexible air-interface being developed for 5G and can support coordinated inter-operator spectrum sharing in various scenarios, including mutual renting, spectrum spot market, co-primary sharing, licensed shared access (LSA), secondary horizontal sharing etc. Compared to state-of-the-arts, the proposed concept has much broader applicability and less restrictions on infrastructure conditions, including radio access network (RAN) sharing, inter-operator synchronization and fast inter-operator signaling. Furthermore, the proposed concept allows high flexibility both in spectrum allocation and adaptation of the transmission signals to support the large variety of devices expected in 5G scenarios. The key elements of the proposed concept includes the determination of a common subcarrier grid, a two-stage allocation procedure, fragmented spectrum usage, usage of "out-of-fragment radiation masks", and adaptation of multi-carrier waveforms. Preliminary results have shown that the proposed concept allows efficient and flexible fragmented spectrum usage, with robustness against inter-operator synchronization mismatch.**

I. INTRODUCTION

Conventionally, the spectrum allocation and licensing for mobile broadband (MBB) has been done in an exclusive manner, i.e. each operator obtains a certain amount of spectrum for exclusive usage. Such exclusive spectrum licensing has the advantages of guarantee of Quality of Service (QoS), inherent interference avoidance, and high degree of market certainty for creating adequate investment and innovation incentives. However, the demand on wireless traffic is growing explosively, with the expected increase to 1000 fold by 2020 [1]. Correspondingly, huge amount of spectrum will be required in future 5G wireless communication systems, causing the problem of "spectrum shortage" [2], i.e., there will be not enough spectrum bands, especially in the range below 6 GHz, to be allocated exclusively to the different operators. Even if there are enough spectrum bands for exclusive allocation, the mobile operators will face the pressure of the high spectrum cost [3]. Considering that the mobile operators' revenues are going into saturation [4], the reduction of spectrum cost is desired. Furthermore, exclusive spectrum allocation suffers from low flexibility and low scalability. It often leads to spectrum underutilization in a lot of locations and/or periods of time, and hence, low efficiency of spectrum usage. Therefore, spectrum sharing becomes a necessary and important complementary tool to exclusive spectrum usage for fulfilling the large spectrum requirements in 5G systems [5]. On the one hand, mobile operators may have to share the spectrum with other communication or non-communication systems. On the other hand, mobile operators may have to share certain amount of spectrum with each other. Actually, both sharing cases can occur simultaneously, e.g. several operators share a band with another service, e.g., the radar service [6], in a primary-secondary manner, while they share this band with each other on an equal basis.

In this paper, the spectrum sharing between operators, i.e., inter-operator spectrum sharing, is addressed, which can occur in different scenarios. One example is the LSA scenario [7], where the frequency band of an incumbent user (e.g. radar service) is temporarily licensed to multiple operators in a certain location and for a certain time period for shared usage. Another example is the co-primary sharing, which means that the regulator licenses a spectrum band to multiple operators, without fixed boundaries between the spectrum bands of the different operators. These operators should coordinate their spectrum usage according to mutual agreement and certain sharing rules. Further examples include mutual renting [5], spectrum spot market [8], and secondary horizontal sharing, e.g., in the TV white space (TVWS) bands.

No matter under which scenario the inter-operator spectrum sharing occurs, we focus on the case that the sharing is done in a coordinated manner. This implies that the opportunistic approaches based on spectrum sensing is not considered. Furthermore, if the spectrum is also shared with other services, we assume that the sharing with other services is already managed by a higher level approach, e.g. the geo-location data base (GLDB) approach or the LSA-approach. Accordingly, we can summarize the inter-operator spectrum sharing as follows: Multiple operators obtain a certain spectrum band for shared usage in a certain time period. This spectrum band can be contiguous or non-contiguous, while the usage right can be primary, secondary or even unlicensed. Note that by the term "operator", we are not limited to national operators. Local network operators (LNO) [9] can also participate in the spectrum sharing.

When sharing the spectrum, different operators can generate interference to each other. Therefore, the key technical challenge can be formulated as follows: Given an available spectrum band for sharing (contiguous or non-contiguous), how can the operators manage the mutual interference while achieving high efficiency of spectrum usage and still having the flexibilities to adapt their transmissions individually?

There are already a number of works addressing the above challenge for inter-operator spectrum sharing [3, 10–17]. In [3,

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10], schemes based on the principle "sharing as a last resort" are proposed. In [11], inter-operator infrastructure sharing was considered and the principle of "always connected to the best base station (BS)" was applied. In [12], two further principles are introduced: 1) "Always connected to the least loaded BS" considering inter-operator roaming; 2) "Sharing as a secondary user". The commonality of the schemes in [10–12] is that time division multiple access (TDMA) is used to coordinate the spectrum usage of different operators, i.e., different operators use different time slots in a common super-frame. In contrast, [3] uses frequency division multiple access (FDMA) with fixed width frequency channels. Although the above schemes have achieved certain performance gain, they are lack of flexibility and are restricted in the usage efficiency of the shared spectrum. In [13, 16], orthogonal frequency division multiple access (OFDMA) based schemes were proposed for operators without RAN sharing. In these schemes, different operators have a common spectrum pool and are allocated orthogonal subcarrier sets. While [16] considers centralized resource allocation (across multiple operators) to maximize the throughput, [13] considers both centralized and distributed resource allocation from a game theoretic perspective. Similar OFDMA-based schemes have also been developed under active inter-operator RAN sharing [14, 17]. Such RAN sharing schemes have even been realized in parts of the current mobile networks. In [15], different operators even use overlapping (i.e. non-orthogonal) subcarriers and apply transmit beamforming technologies to manage inter-operator interference. Such OFDMA-based schemes are more flexible and efficient than the TDMA- or FDMA-based schemes. However, such OFDMA-based schemes require very accurate synchronization (especially frequency synchronization) between the networks of different operators. As illustrated in Fig. 1, with accurate inter-operator synchronization, the OFDM subcarriers of one operator lie in the zeros of the signal spectrum of the other operator. Therefore, there is no mutual interference between operators, when different operators use different subcarriers. But if there is synchronization mismatch (i.e. a carrier frequency offset, CFO) between operators, the mutual interference will be very large, due to the high spectral sidelobe of OFDM signals, resulting in low signal-to-interference ratio (SIR) of the transmitted signals and low spectral efficiency. Nowadays, the networks of different operators are mostly not synchronized to each other. Accurate inter-operator synchronization is only realized in downlink when different operators share the RAN or costly GPS modules are used in BS's [18]. However, for BS's with cost constraints, e.g., the small cell BS's, for indoor BS's, as well as for the uplink[1], inter-operator synchronization is still very challenging, especially when it comes to frequencies above 6 GHz. Therefore, the applicability of the OFDMA-based schemes is restricted. Moreover, for operators without collocated BS's, the joint subframe level scheduling of [16] requires very rapid and frequent information exchange between BS's of different operators. Such information exchange requires inter-operator backhaul with considerable capacity, which is not always available in practice. Also, the operators may rather want to carry out the resource scheduling independently of each other, or at least partially independently. Finally, the OFDMA-based schemes require all operators to use an identical signal frame structure with alignment in time. However, as predicted in [1], 5G systems have to adopt a large variety of devices (including devices for machine-to-machine communication) and use cases, which require different and flexible frame structures [19]. Thus, the OFDMA-based schemes can not fulfill such 5G requirement.

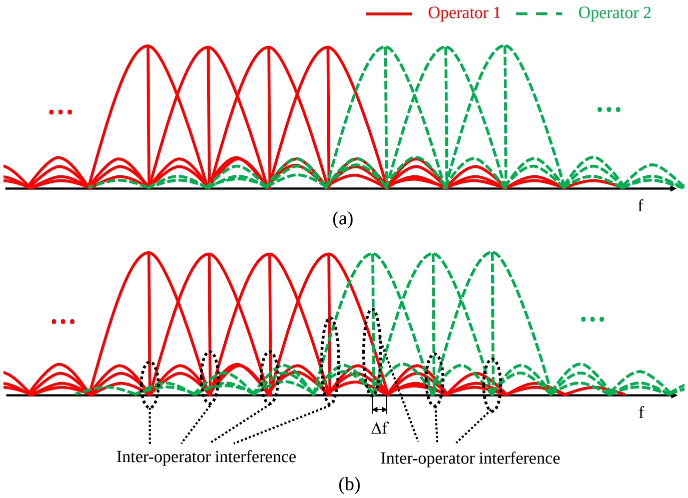

Fig. 1. Illustration of inter-operator interference due to frequency offset Δf.

In this paper, we propose a multi-carrier waveform based inter-operator spectrum sharing concept, which is a strong extension of the OFDMA-based schemes and has much broader applicability and much less restrictions on infrastructure conditions, e.g., RAN-sharing, inter-operator synchronization and fast inter-operator signaling. On the one hand, the proposed concept considers the new air-interface being developed for 5G [19], which will probably use filter bank based multi-carrier (FBMC) type waveforms[2] and allow flexible adaptation of the waveform (e.g. prototype filter, subcarrier spacing) as well as the frame structure according to the traffic type and propagation environment etc. [19]. On the other hand, backward compatibility is considered, e.g., for OFDM waveforms. Furthermore, it can support inter-operator spectrum sharing different sharing scenarios. The key elements of the proposed concept include the determination of a common subcarrier grid, a two-stage allocation procedure, fragmented spectrum usage, usage of "out-of-fragment radiation masks", and adaptation of multi-carrier waveforms and frame structure. Compared to the state-of-the-art schemes mentioned above, the proposed concept provides the following advantages:

- This concept can support operators with and without RAN-sharing, as well as with and without accurate mutual synchronization. One example is that a subset of the operators share the RAN or have accurate mutual synchronization, while the other not;
- Operators with independent network deployments can easily apply this concept to access the shared spectrum;

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[1] For the uplink, even accurate synchronization between the UT's of one operator is challenging.

[2] Also called "OFDM/OQAM".

- The allocation of the spectrum resource to each operator is very flexible. Each operator can dynamically obtain multiple non-contiguous fragments from the shared spectrum;
- The shared spectrum can be used very efficiently and effectively, even if it is non-contiguous and very fragmented (e.g., when parts of the available spectrum are still occupied by a higher priority service like public safety service);
- Each operator has high flexibility to adjust its signal- and frame structure, e.g. to adjust the waveform characteristics and transmission time interval (TTI) size according to use case, traffic type and propagation environment, etc. [19]. Such adjustment is done independently from other operators.
- With the proposed two stage spectrum allocation procedure, each operator can schedule frequency resources to its users independently from the other operators;
- Applicability to operators with and without the same air-interface;
- Backward compatibility with the conventional OFDMA-based schemes mentioned above, e.g., [13, 15, 16], is provided;
- Applicability both for downlink and uplink.

This paper is organized as follows: Sec. II describes the system setup. Sec. III describes the determination of a common subcarrier grid for multiple operators. Sec. IV presents the two-stage spectrum allocation procedure. Sec. V and VI describe the adaptation of signals and spectrum fragments, respectively. Sec. VII explains the operation considering shared RAN or accurate inter-operator synchronization. Sec. VIII talks about the usage of waveforms. Sec. IX shows the preliminary simulation results. Sec. X concludes this paper.

II. SYSTEM SETUP

Fig. 2 shows the system setup of the proposed concept, with two or three operators as examples. The actual number of operators is not limited. As shown, two or more operators share a frequency band. This means that the BS's of different operators transmit signals in the same frequency band to their user terminals (UT), or receive signals in the same frequency band from their UT's. The sharing of the frequency band is done in a coordinated manner. The coordination is done via a spectrum manager, which can be either a separate entity in the network (e.g. managed by a third party) or just a virtual entity which is implemented in a distributed manner in the BS's. As shown in Fig. 2 (b), in the system setup, a subset of the operators or even all operators may share the RAN, meaning that the BS's of the corresponding operators share the site as well as the BS hardware. The BS hardware can be shared either partially (e.g. only the antenna, and/or certain processing units) or completely (e.g. in the case of virtual mobile operators). Furthermore, some of the operators, including those with shared RAN, may have accurate mutual synchronization, while others not. Finally, although using the same frequency band, different operators transmit signals in orthogonal sets of frequency resources (e.g. subcarriers or subchannels).

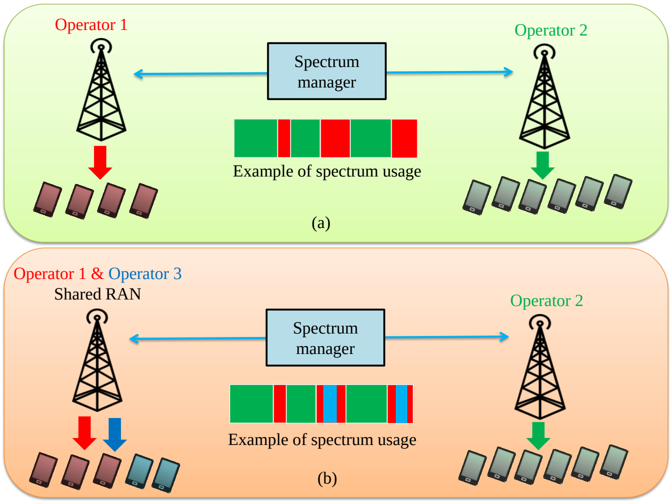

Fig. 2. System setup of the considered inter-operator spectrum sharing concept. Larger number of operators sharing the spectrum is possible. Furthermore, more BS's per operator is also possible.

Fig. 3 illustrates the spectrum sharing related functional units of the system setup described above. Generally, the whole system consists of a spectrum manager and the BS's of different operators. The spectrum manager has the information about the available shared spectrum. Such information can be obtained from the regulatory body, a GLDB or a LSA repository, etc. Furthermore, the spectrum manager is responsible for calculating the common subcarrier grid, partitioning the shared spectrum, determining the out-of-fragment radiation masks and allocating the spectrum fragments to different operators. Each operator can have one or more BS's involved in the spectrum sharing procedure. Each BS has three relevant functional units. The first functional unit is responsible for sending spectrum sharing related information, e.g. traffic demand, to the spectrum manager. The second functional unit is responsible for adaptation of the transmission waveform and signal structure. The third functional unit is responsible for scheduling the frequency resources to the UT's. Note that in Fig. 3, the downlink case is shown. However, for the uplink, the only difference to the downlink case is that the physical layer (PHY) is not in the BS's but in the UT's. When two or more operators share a RAN, they can either be treated as separated operators or as one "virtual" overall operator using the BS. If they are treated as separated operators, each operator will have the above three functional units. If they are treated as one "virtual" overall operator, they can share some of the functional units, but need to extend their functionalities and even need additional functional units to coordinate the resource allocation and operations among them.

III. THE COMMON SUBCARRIER GRID

The proposed concept requires that all operators sharing the spectrum use multi-carrier waveform, while different operators can use different air-interfaces. The used air-interface should provide certain degree of flexibility, e.g. flexible size of DFT (discrete Fourier transform) and scalable bandwidth. Furthermore, the air-interface should be able to be configured

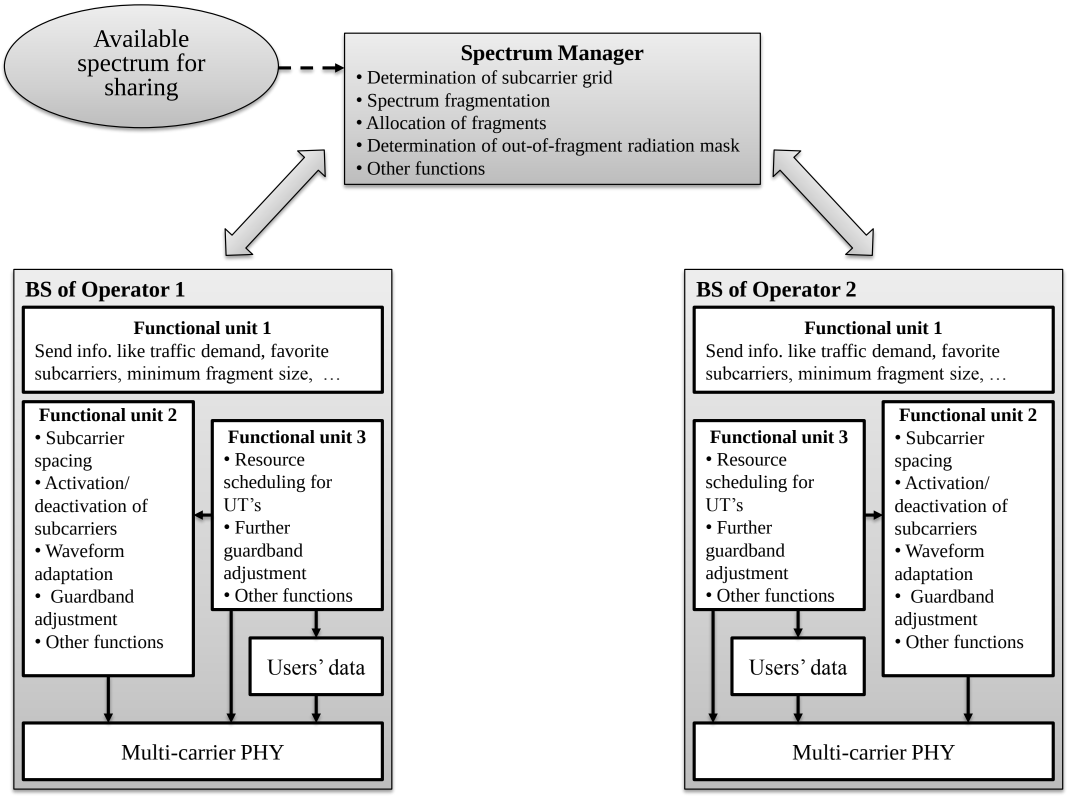

Fig. 3. Illustration of functional units and their interactions related to this invention (downlink as example). PHY: Physical layer.

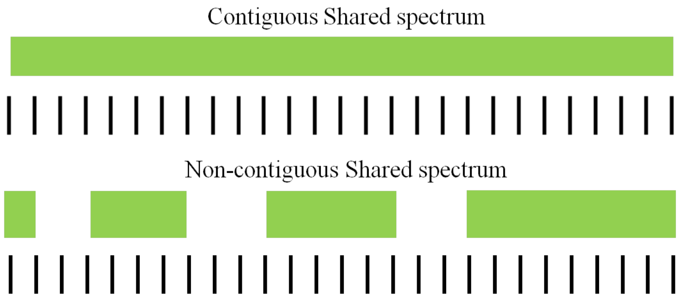

Fig. 4. Illustration of the subcarrier grid.

to support different frequency ranges, e.g., including the spectrum above 6 GHz.

Prior to the shared spectrum usage, the spectrum manager determines a common "subcarrier grid". The subcarrier grid contains the maximum total number of subcarriers, i.e., the sum of the active subcarrier numbers of all operators who are sharing this spectrum, and the minimum subcarrier spacing. Note that different operators do not use the same subcarriers. The structure of the subcarrier grid can be determined according to the size, structure (e.g. smallest band of non-contiguous shared spectrum) and channel propagation characteristics (e.g. the channel coherence bandwidth) of the shared spectrum, as well as other parameters e.g. expected UT number, tolerance against CFO and Doppler effect, etc. Also, the air-interface configurations supported by the different operators should be considered. If the shared spectrum is non-contiguous, the subcarrier grid should cover all parts of the shared spectrum. Fig. 4 illustrates the "subcarrier grids" for contiguous and non-contiguous spectrum fragments.

As will be described later, the spectrum will be partitioned into fragments. The size of such spectrum fragment must be integer multiple of the subcarrier spacing of this subcarrier grid. Furthermore, the allocated fragment to each operator will be indicated by an index set of subcarriers in this subcarrier grid. Each operator is only allowed to transmit signal on the subcarriers of this subcarrier grid. But the actual subcarrier spacing can be different but must be integer multiple of the subcarrier spacing of this subcarrier grid.

IV. THE TWO-STAGE SPECTRUM ALLOCATION PROCEDURE

After the common subcarrier grid is determined, the spectrum allocation procedure can be started. Instead of scheduling the frequency resource directly to the UT's [16], we propose a two-stage approach to perform the allocation of the shared spectrum resource. The first stage is a medium or long term procedure, where the shared spectrum is partitioned and allocated to different operators. The second stage is a short term procedure, where each operator allocate the frequency resources to the UT's.

Stage 1 - Medium term/long term inter-operator spectrum allocation: In this stage, each operator sends necessary information, e.g., the traffic demand, the favorate subcarriers in the subcarrier grid (e.g. based on channel quality information, CQI) and the wished minimum fragment size etc., to the spectrum manager. The actual content of such information would depend on the sharing agreement or a standardized sharing framework. After gathering such information, the spectrum manager partitions the shared spectrum into a number of fragments and allocates these fragments to the operators. Each operator obtains a different set of such fragments, which should have no overlap with the sets of the other operators. Such partitioning and allocation is done according to the size and structure of the shared spectrum, the requirements of the operators, as well as the sharing policy. The spectrum partitioning and fragment allocation in this stage is done periodically in medium term (e.g. every 500 ms) or long term (e.g. every several second). But if the inter-operator backhaul capacity or the capacity between the connections of the BS's and the spectrum manager is high, this procedure can be carried out with even shorter period (e.g. every 10 ms). After the spectrum partitioning and fragment allocation, the spectrum manager sends to each operator the information about the allocated fragments (e.g. starting and ending subcarrier indices in the subcarrier grid for each fragment). Alternatively, the spectrum manager can broadcast the whole spectrum fragment allocation map to all operators. The spectrum manager will also send information about out-of-fragment radiation masks, which will be described later.

Stage 2 - Short term per-operator resource allocation to UTs: From the allocated spectrum fragments, each operator allocates the frequency resource to its UT's, in terms of certain number of subchannels or subcarriers. Generally, the operators can perform such resource allocation independently from each other. Alternatively, the operators can also have certain degree of cooperation, e.g., exchanging relevant information for further reduction mutual interference.

V. OUT-OF-FRAGMENT RADIATION MASK AND SIGNAL ADAPTATION

As mentioned above, in the first spectrum allocation stage, the spectrum fragment size should be integer multiple of the subcarrier spacing of the subcarrier grid. Each operator transmits signal in the allocated spectrum fragments by activating and deactivating subcarriers of the signal, i.e., only the subcarriers within the allocated spectrum fragments are activated, while others not. Since different operators do not necessarily have accurate mutual synchronization, the "out-of-fragment" radiation power of the signals of each operator has to be taken into account, which causes interference to the other operators. For this purpose, an out-of-fragment radiation mask is generated by the spectrum manager for each spectrum fragment and distributed to the operators. Such masks are determined based on the sharing policy or framework, and regulates the maximum power spectral density (PSD) of the transmitted signal outside the allocated fragments. Each operator must reserve certain guardbands at the edges of the spectrum fragments and adapt their signal waveform to meet such out-of-fragment radiation masks and manage the inter-operator interference. Note that in the simplest case, such out-of-fragment radiation masks are identical for all fragments and all operators. Alternatively, such masks can be adjusted according to the actual situation, e.g., the SIR requirements of each operator or the different transmit power of the BS's of different operators.

In order to meet the out-of-fragment radiation mask, each operator can adjust both guardband and signal waveform. The adjustment of the signal waveform is aimed to adjust the spectral sidelobe level of the signal. For OFDM waveforms, adjustment of the raised cosine (RC) windowing [20], low-pass filtering [21], or the side-lobe reduction techniques like insertion of cancellation carriers (CC) [22], subcarrier weighting [23], multiple choice sequence (MCS) [24], adaptive symbol transition (AST) [25] and EVM-constrained precoding [26], etc., can be applied. For FBMC waveforms, the pulse shape of the prototype filters can be adjusted, including, e.g., the IOTA pulse with different α parameters [27] or the PHYDYAS pulse [28, 29].

As long as the out-of-fragment radiation masks are met and the air-interface is sufficiently flexible [19], each operator has the following further degree of freedom to adapt its signal structure:

- Adaptation of the subcarrier spacing, as integer multiple of the subcarrier spacing in the subcarrier grid;
- Structure of the signal frames, e.g. the TTI size, since the signal frame of different operators need neither to have identical structures nor to be aligned in time (compared to [16]). This provides the operators high degree of freedom to adjust the signal frames independently of each other, e.g., to support different types of services.

As mentioned in Sec. I, when two operators have accurate mutual synchronization, their subcarriers in downlink transmission can be accurately orthogonalized. Therefore, if these two operators are allocated neighboring spectrum fragments, no out-of-fragment radiation mask need to be established between such fragments. In other words, no guardband has to be reserved between these neighboring fragments. The practical operation relating to this issue will be described in more detail in Sec. VII.

Fig. 5 illustrates the concept of out-of-fragment radiation mask.

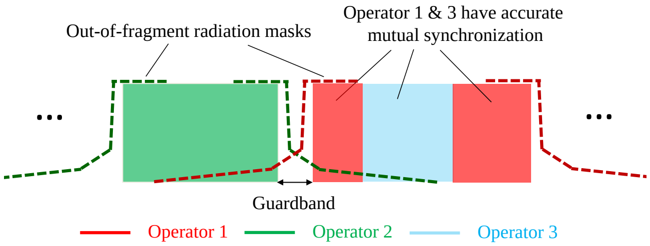

Fig. 5. Illustration of out-of-fragment radiation masks.

VI. FLEXIBLE FRAGMENT SIZE AND FRAGMENT DISTRIBUTION

The spectrum manager determines the total amount of spectrum for each operator according to the sharing policy and certain current parameters, e.g., the traffic demand of each operator. One example of such policy could be that the amount of each operator scales with its traffic demand under fairness constraints. Afterwards, the spectrum manager partitions the shared spectrum into orthogonal sets of fragments. Each fragment set will be allocated to one operator, fulfilling the determined spectrum amount for this operator. In this procedure, both the fragment size and the distribution of the fragments for each operator can be flexibly adjusted.

Adjustment of the fragment size: Generally, if no accurate inter-operator synchronization is available, the larger the spectrum fragments, the higher the overall spectral efficiency (as will be seen in the simulation results in Sec. IX). The reason is that the larger such fragments, the stronger the decay of the out-of-band radiation of the signals of the other operators, and therefore, the lower the overall interference power[3]. In contrast, the smaller the fragments, the more evenly the fragments of an operator can be distributed over the spectrum, and thus the higher the frequency diversity. Also, the smaller the fragment, the more efficient the exploitation of non-contiguous shared spectrum, and the more operators can share even small fragmented spectrum. Therefore, in the first spectrum allocation stage, each operator can claim a minimum fragment size to the spectrum manager so that inter-operator interference can be controlled below a certain level and the guardband overhead can be below a certain value. Afterwards, the spectrum manager adjusts the actual size of the fragments, on the one hand, to meet the minimum fragment size requirements of different operators as well as possible, and on the other hand, to exploit frequency diversity, non-contiguous spectrum and small available portion of spectrum (e.g. due to large operator number). This will motivate the development of intelligent algorithm in the spectrum manager to determine the fragment size;

Adjustment of the fragment distribution over the whole shared spectrum: The spectrum manager also adjusts the distribution of the spectrum fragments for each operator, e.g. according to the information about favorable subcarriers that is provided by the operators, as well as some fairness constraints. Such adjustment can achieve a tradeoff between frequency diversity, multi-user diversity, interference reduction, non-contiguous band exploitation, and complexity etc.

VII. OPERATIONS FOR OPERATORS WITH ACCURATE MUTUAL SYNCHRONIZATION OR SHARED RAN

As mentioned in Sec. V, the availability of accurate mutual synchronization will determine whether the out-of-fragment radiation mask between neighboring fragments of different operators is established. In practice, the information about such mutual synchronization can be either prestored in the spectrum manager or sent by the BS's to the spectrum manager. In the first spectrum allocation stage, the spectrum manager will take such information into account when partitioning the shared spectrum and allocating the spectrum fragments. Specifically, the spectrum manager should allocate neighboring fragments to operators with accurate mutual synchronization so that the overall required guardbands can be reduced.

The operators sharing a RAN actively can either join the spectrum sharing procedure individually or jointly as an overall "virtual" operator. In the latter option, functional unit 1 collects the information from all operators sharing the RAN, aggregates such information and then sends it to the spectrum manager. Afterwards, the spectrum manager sends the spectrum fragment allocation information to this BS. Based on such information, an additional functional unit can allocate the resource of the allocated spectrum fragments to different operators sharing the RAN. Finally, these operators adjust their signal waveform, frame structure and guardband, and allocate the frequency resource to their UT's independently. Alternatively, the operators sharing this RAN can also allocate the frequency resource to their UT's jointly as described in [13, 16].

Furthermore, under further mutual cooperation and agreement, operators having accurate mutual synchronization can even apply the non-orthogonal sharing schemes like that in [15].

VIII. USAGE OF MULTI-CARRIER WAVEFORM

In general, the proposed concept is compatible with any multi-carrier waveform. However, in the general case that not all operators have accurate mutual synchronization, the lower the spectral sidelobe of the waveform, the less the required guardband (for a given out-of-fragment radiation mask) and thus, the more efficient a spectrum fragment can be used. For an operator with a certain traffic demand, this means also that the less amount of spectrum is used, which may scale with the spectrum usage cost. Therefore, operators are motivated to use multi-carrier waveforms that have inherently low spectral sidelobe, like the FBMC waveform and the Generalized Frequency Division Multiplexing (GFDM) waveform [30]. In addition to low spectral sidelobe, FBMC provides high flexibility for the air-interface [27–29] and is seen as a promising candidate for 5G systems [19]. Nevertheless, some operators can still use OFDM waveform, probably combined with the sidelobe reduction techniques described in [20, 22, 25, 26] etc.

IX. PRELIMINARY SIMULATION RESULTS

In our preliminary simulation, we implemented the scenario where two operators share a contiguous spectrum band of 40 MHz bandwidth. We observe the downlink in a cellular network with either FBMC or OFDM as the transmission waveform (typical examples of multi-carrier waveforms). The two operators use the same waveform and obtain orthogonal sets of active subcarriers for transmission. The total number of subcarriers in the subcarrier grid is 2048, resulting in a subcarrier spacing of about 19.5 kHz. For simplicity, the subcarrier spacing of each operator remains the same as that in the subcarrier grid. Furthermore, even distribution of spectrum fragments over the shared spectrum is assumed, where the fragment size excludes the guardband size. For

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[3] Actually, the increase of fragment size will increase the out-of-fragment radiation. However, as shown in Sec. IX, this is not the dominant factor for the overall spectral efficiency.

the FBMC signals, the PHYDYAS pulse is used [28, 29]. For OFDM, the cyclic prefix (CP) of length-144 is used. Moreover, both rectangular window and RC-window [20] in time domain are compared. For RC-window, the roll-off factor is 3.47%, resulting in 74 samples additional overhead in time domain. Furthermore, constant frequency-flat channel is used. For further simplicity, we assume each operator has only one served UT. The synchronization mismatch between both operators is modelled as follows: timing offset of 3 samples (i.e. 0.75 ns) and CFO between BS's of both operators that is 4% of subcarrier spacing (i.e. 0.78 kHz, 0.3 ppm for carrier frequency of 2.6 GHz). Again, for simplicity, noise is ignored, but a limit of 50 dB is put on the SIR to reflect the limitation on spectral efficiency caused by noise. Note that since this is just the preliminary simulation, not all aspects of the proposed concept are implemented and investigated, e.g. the adaptation of the waveform and the frame structure. This simulation mainly focuses on the effect of signal sidelobe levels, fragment size, guardband size, as well as robustness against inter-operator synchronization mismatch.

Fig. 6 shows the average spectral efficiency (averaged over bandwidth, but summed over operators) as a function of the spectrum fragment size, with different values of the guardbands. Both spectrum fragment size and guardband size are indicated in terms of the number of subcarriers. The average spectral efficiency was calculated based on the SIR using the Shannon equation. For simplicity, the CP and RC-windowing overhead of OFDM are not considered. From Fig. 6, we can see that the average spectral efficiency generally increases with the spectrum fragment size. Furthermore, the average spectral efficiency with FBMC is much higher than those with OFDM (more than 46% gain), due to much lower spectral sidelobes. Moreover, we can observe that the increase of average spectral efficiency goes to saturation as the fragment size increases. For FBMC, the saturation point is achieved with fragment size of about 70 subcarriers, while much larger fragment size (>200) is required by OFDM to achieve such saturation. This means that FBMC allows the usage of small fragment size, which leads to higher flexibility and efficiency of spectrum usage.

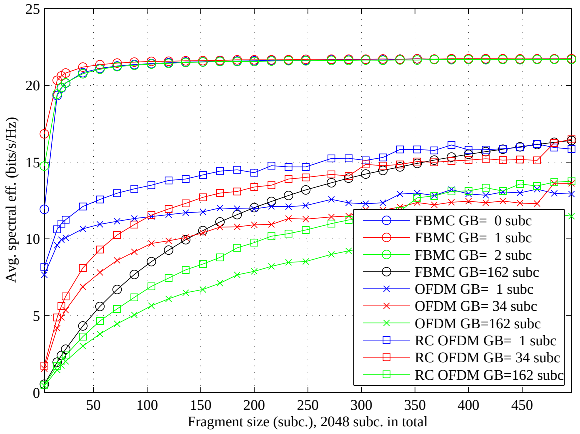

Fig. 6. Average spectral efficiency as a function of the spectrum fragment size, with different values of the guardbands.

Fig. 7 and Fig. 8 show the minimum SINR per subcarrier and the average spectral efficiency, respectively, as functions of the guardband size, with different values of the spectrum fragment sizes. According to Fig. 7, if the out-of-fragment radiation mask should assure a minimum SIR of, e.g., 40 dB, the required guardband sizes for FBMC, RC-OFDM and OFDM are 1, 27 and 400, respectively. Thus, the required guardband overhead of FBMC is much lower than RC-OFDM and OFDM. From Fig. 8, we can see that as the guardband increases, the average spectral efficiency can first increase slightly but then decreases continuously. This implies that after a certain guardband size, the guardband overhead becomes the more dominant spectral efficiency limiting factor than the inter-operator interference.

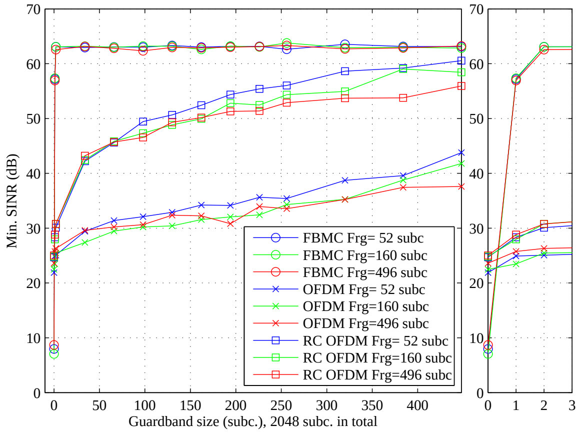

Fig. 7. Minimum SINR per subcarrier as a function of the guardband size, with different values of the spectrum fragment sizes.

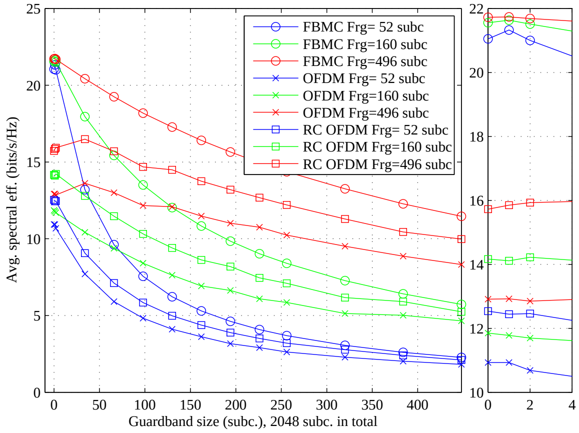

Fig. 8. Average spectral efficiency as a function of the guardband size, with different values of the spectrum fragment sizes.

Now, we compare the influence of inter-operator synchronization accuracy on different waveforms for spectrum sharing. For this purpose, the above simulation was repeated for different values of inter-operator time and frequency synchronization mismatches. Different fragment sizes and guardband sizes are used for FBMC, OFDM and RC-OFDM, as listed in table . The guardband sizes are determined based on the results in Fig. 7 and the required minimum SIR of 40 dB. Furthermore, small fragment size is used by FBMC, while large fragment sizes are used by OFDM and RC-OFDM. Actually, for OFDM, the shared 40 MHz spectrum is partitioned into two halves, each for one operator.

TABLE I
USED FRAGMENT SIZE AND GUARDBAND SIZE

Waveform	**Fragment size (excluding guardband)**	**Guardband size**
FBMC	70 subc.	1 subc.
OFDM	600 subc.	400 subc.
RC-OFDM	600 subc.	27 subc.

Fig. 9 shows the spectral efficiency gain of using FBMC against using OFDM and RC-OFDM as functions of the time and frequency synchronization mismatches. The spectral efficiency gain is defined as

$$\frac{C_{\text{FBMC}} - C_{\text{OFDM;RC–OFDM}}}{C_{\text{OFDM;RC–OFDM}}} \times 100\%,$$

where $C_{\text{FBMC;OFDM;RC–OFDM}}$ is the spectral efficiency of FBMC, OFDM or RC-OFDM, respectively. As shown, OFDM and RC-OFDM have only advantages for very small range of synchronization mismatches, i.e. time shift of $<$ 144 (CP size) and CFO under 0.2% of subcarrier spacing (e.g. 0.02 ppm for carrier frequency of 2.6 GHz). Outside this range, FBMC can always achieve much better spectral efficiency than using OFDM an RC-OFDM. The spectral efficiency gain of FBMC over OFDM and RC-OFDM can be above 150% and 60%, respectively. Note that if the CP overhead and RC windowing overhead are taken into account, the gain of FBMC will be even larger. This result motivates the usage of FBMC when no accurate inter-operator synchronization is available.

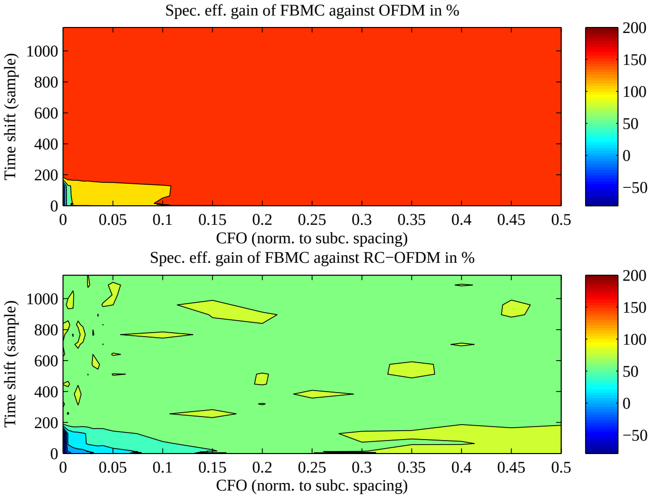

Fig. 9. Spectral efficiency gain of FBMC over OFDM and RC-OFDM as functions of the inter-operator time shift (time synchronization mismatch) and carrier frequency offset (frequency synchronization mismatch).

X. CONCLUSIONS

In this paper, a multi-carrier waveform based flexible inter-operator spectrum sharing concept is proposed for 5G mobile and wireless communication systems. Based on a common subcarrier grid, the shared spectrum can be dynamically fragmented and allocated to the operators for "in-band" sharing. By adapting waveforms regarding the out-of-fragment radiation masks, inter-operator interference can be avoided. With the proposed concept, operators with and without RAN sharing or accurate mutual synchronization can share spectrum bands. Furthermore, this concept is compatible with different multi-carrier waveforms and allows each operator to adjust its waveform and frame structure flexibly and independently. Preliminary simulation results show that when no accurate inter-operator synchronization is available, the guardband overhead and the spectrum usage efficiency are greatly depending on the sidelobe characteristics of the transmit signals. As an example, we have compared the waveforms FBMC, OFDM and RC-OFDM. We show that due to much lower sidelobes, FBMC can achieve much higher spectrum usage efficiency than that OFDM and RC-OFDM. Furthermore, with FBMC, small spectrum fragment size is allowed, which provides more flexibility for resource allocation.

Based on the proposed concept, a number of interesting future works can be identified, including

- Signaling protocol between BS's and the spectrum manager;
- Policy and algorithms for spectrum fragmentation and allocation, which consider matching of traffic load, fairness, synchronization conditions, frequency diversity, etc.;
- Waveform adaptation mechanism to avoid inter-operator interference and to enhance transmission quality;
- Extension of the proposed concept to non-orthogonal spectrum sharing, i.e. different operators can reuse the same subcarriers under interference constraints. Advanced power control and beamforming techniques will be taken into account.

REFERENCES

[1] A. Osseiran, V. Braun, T. Hidekazu, P. Marsch, H. Schotten, H. Tullberg, M. A. Uusitalo, and M. Schellmann, "The foundation of the mobile and wireless communications system for 2020 and beyond," in *Proc. IEEE Veh. Tech. Conf. (VTC'13-Spring)*, IEEE. Dresden, Germany: IEEE, 06/2013 2013.

[2] J. Chapin and W. Lehr, "Mobile broadband growth, spectrum scarcity, and sustainable competition," *The Research Conf. Commun. Info. Internet Policy (TPRC'11), Available at SSRN: http://ssrn.com/abstract=1992423*, 2011.

[3] B. Aazhang, J. Lilleberg, and G. Middleton, "Spectrum sharing in a cellular system," in *Proc. IEEE Int. Symp. Spread Spectrum Tech. Appl. (ISSSTA'04)*, 2004, pp. 355–359.

[4] A. Fehske, G. Fettweis, J. Malmodin, and G. Biczok, "The global footprint of mobile communications: The ecological and economic perspective," *IEEE Commun. Magazine*, vol. 49, no. 8, pp. 55–62, 2011.

[5] T. Irnich, J. Kronander, Y. Selen, and G. Li, "Spectrum sharing scenarios and resulting technical requirements for 5G systems," in *Proc. IEEE Int. Symp. Person. Indoor Mobile Radio Commun. (PIMRC'13)*, 2013.

[6] M. Tercero, K. Sung, and J. Zander, "Exploiting temporal secondary access opportunities in radar spectrum," *Wireless Personal Communications*, vol. 72, no. 3, pp. 1663–1674, 2013. [Online]. Available: http://dx.doi.org/10.1007/s11277-013-1127-7

[7] J. Khun-Jush, P. Bender, B. Deschamps, and M. Gundlach, "Licensed shared access as complementary approach to meet spectrum demands: Benefits for next generation cellular systems," in *ETSI Workshop Reconfig. Radio Syst.*, Cannes, France, Dec. 2012.

[8] J. Bae, E. Beigman, R. Berry, M. Honig, H. Shen, R. Vohra, and H. Zhou, "Spectrum markets for wireless services," in *Proc. IEEE Symp. Dynam. Spectrum Access Networks (DySPAN'08)*, 2008, pp. 1–10.

[9] D. H. Kang, K. W. Sung, and J. Zander, "The validity of unlicensed spectrum for future local highcapacity services," in *European Regional ITS Conference*, 2013.

[10] G. Middleton, K. Hooli, A. Tolli, and J. Lilleberg, "Inter-operator spectrum sharing in a broadband cellular network," in *Proc. IEEE Symp. Spread Spectrum Tech. Appl. (ISSSTA'06)*, 2006, pp. 376–380.

[11] M. Bennis and J. Lilleberg, "Inter base station resource sharing and improving the overall efficiency of B3G systems," in *Proc. IEEE Veh. Tech. Conf. (VTC'07-Fall)*, 2007, pp. 1494–1498.

[12] V. Heinonen, P. Pirinen, and J. Iinatti, "Capacity gains through inter-operator resource sharing in a cellular network," in *Proc. Wirel. Person. Multimedia Comm. Symp. (WPMC'08)*, 2008.

[13] H. Kamal, M. Coupechoux, and P. Godlewski, "Inter-operator spectrum sharing for cellular networks using game theory," in *Proc. IEEE Int. Symp. Person. Indoor Mobile Radio Commun. (PIMRC'09)*, 2009, pp. 425–429.

[14] A. Mihovska, F. Meucci, N. Prasad, F. Velez, and O. Cabral, "Multi-operator resource sharing scenario in the context of IMT-Advanced systems," in *Int. Workshop Cognitive Radio Advanced Spectrum Manag. (CogART'09)*, 2009, pp. 12–16.

[15] E. Karipidis, D. Gesbert, M. Haardt, K.-M. Ho, E. Jorswieck, E. Larsson, J. Li, J. Lindblom, C. Scheunert, M. Schubert, and N. Vucic, "Transmit beamforming for inter-operator spectrum sharing," in *Proc. Future Network Mobile Summit (FutureNetw), 2011*, 2011, pp. 1–8.

[16] L. Anchora, L. Badia, E. Karipidis, and M. Zorzi, "Capacity gains due to orthogonal spectrum sharing in multi-operator lte cellular networks," in *Proc. Int. Symp. Wireless Commun. Syst. (ISWCS'12)*, 2012, pp. 286–290.

[17] R. Kokku, R. Mahindra, H. Zhang, and S. Rangarajan, "Cellular wireless resource slicing for active RAN sharing," in *Proc. Int. Conf. Commun. Syst. Networks (COMSNETS'13)*, 2013, pp. 1–10.

[18] V. Jungnickel, T. Wirth, M. Schellmann, T. Haustein, and W. Zirwas, "Synchronization of cooperative base stations," in *Proc. IEEE Int. Sym. on Wirel. Comm. Sys.(ISWCS '08)*, 2008.

[19] P. Popovski and et. al., "Requirement analysis and design approaches for 5G air interface," *Deliverable D2.1 of the EU FP7 project METIS (Mobile and wireless communications Enablers for the Twenty-twenty Information Society)*, 2013.

[20] J. Luo, W. Keusgen, and A. Kortke, "Optimization of time domain windowing and guardband size for cellular ofdm systems," in *Proc. IEEE Veh. Tech. Conf. (VTC'08-Fall)*, 2008, pp. 1–5.

[21] E. P. Lawrey, "Adaptive techniques for multiuser OFDM," Ph.D. dissertation, School of Engineering, James Cook University, Dec. 2001.

[22] S. Brandes, I. Cosovic, and M. Schnell, "Reduction of out-of-band radiation in OFDM systems by insertion of cancellation carriers," *IEEE Communications Letters*, vol. 10, no. 6, pp. 420–422, June 2006.

[23] I. Cosovic, S. Brandes, and M. Schnell, "Subcarrier weighting: a method for sidelobe suppression in OFDM systems," *IEEE Communications Letters*, vol. 10, no. 6, pp. 444–446, June 2006.

[24] I. Cosovic and T. Mazzoni, "Suppression of sidelobes in OFDM systems by multiple-choice sequences," *European Trans. Telecomms.*, vol. 17, pp. 623–630, 2006.

[25] H. Mahmoud and H. Arslan, "Sidelobe suppression in OFDM-based spectrum sharing systems using adaptive symbol transition," *IEEE Communications Letters*, vol. 12, no. 2, pp. 133–135, February 2008.

[26] J. van de Beek and F. Berggren, "EVM-constrained OFDM precoding for reduction of out-of-band emission," in *Proc. IEEE Veh. Tech. Conf. (VTC'09-Fall)*, 2009, pp. 1–5.

[27] B. Le Floch, M. Alard, and C. Berrou, "Coded orthogonal frequency division multiplex," *Proceedings of the IEEE*, vol. 83, no. 6, pp. 982–996, 1995.

[28] M. Bellanger, "Physical layer for future broadband radio systems," in *Proc. IEEE Radio Wireless Symp. (RWS'10)*, 2010, pp. 436–439.

[29] Y. Medjahdi, D. Le Ruyet, D. Roviras, H. Shaiek, and R. Zakaria, "On the impact of the prototype filter on FBMC sensitivity to time asynchronism," in *Proc. IEEE Int. Symp. Wireless Commun. Syst. (ISWCS'12)*, 2012, pp. 939–943.

[30] G. Fettweis, M. Krondorf, and S. Bittner, "GFDM - generalized frequency division multiplexing," in *Proc. IEEE Veh. Tech. Conf. (VTC'09-Spring)*, 2009, pp. 1–4.