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Enabling Technologies for 5G Air-Interface with Emphasis on Spectral Efficiency in the Presence of Very Large Number of Links

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Abstract— **The spectral efficiency enhancement for 5G air interface represents a technical challenge. In addition to the higher capacity requirement, 5G system will also address massive connectivity demand for 5G applications, such as IoT. A straightforward re-design of OFDM based LTE by using different radio parameter set cannot meet the challenges from the diverse 5G usage scenarios. In this paper, we present 5G radio access technologies by exploiting inter-block non-orthogonality and Intra-block non-orthogonality. The inter-block non-orthogonality is achieved by block filtering of OFDM sub-block, and the Intra-block non-orthogonality is achieved by Sparse Code Multiple Access based on optimized sequence design. Such a framework can unify the large numbers of radio links for very diverse services and also provides increased spectral efficiency. In particular, when combined with emerging polar codes, we can further increase the spectral efficiency for smaller packets and support excessive number of connection links. Several design details for this novel air-interface will be presented.**

Keywords*— *Software defined flexible air-interface; Dual layer non-orthogonal radio interface; Filtered-OFDM (f-OFDM); Sparse Code Multiple Access (SCMA); Polar code; Spectrum efficiency

I. INTRODUCTION

There are a number of significant challenging requirements for the future of 5G systems that drive the 5G air interface design. These challenges include support for:

1. Diverse traffic characteristics including diverse Quality of Service (QoS) requirements, packet sizes and traffic patterns from a wide variety of applications,
2. Massive traffic growth created by the massive number of connected mobile devices (including an increasing number of machine-type devices),
3. Densification and heterogeneity of network radio access points,
4. Diversity of device types, both end-user equipment (UE) and machine-type equipment, and
5. Exploitation of more spectrums across a wide range of frequency bands that include licensed and unlicensed assignments.

The diverse scenarios and services envisioned for 5G networks are illustrated in the “5G HyperService Cube”as shown in Figure 1[1]. This illustration shows the wide range of services mapped onto their various parameters of throughput, delay and density of links along each axis of the cube. Throughput, for example, may range from 10^3 kbit/s/Km^2 for high speed train service to 10^9 kbit/s/Km^2 for multi-user telepresence. The link connection density may range from hundreds per Km^2 for wireless cloud office environments to millions for smart sensors. The delay (latency) constraint may range from a few milliseconds for real-time social gaming to hundreds of seconds for shipping and logistics services. The 5G air interface is designed to have the flexibility required to meet the wide-ranging requirements in terms of throughput, delay and number of links (link density).

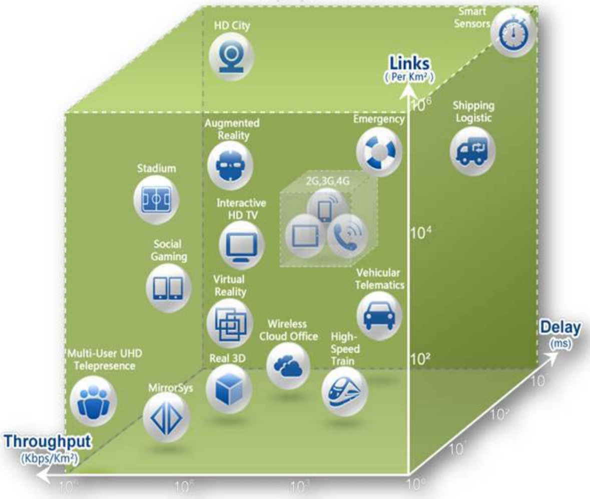

Figure1: 5G service and scenario requirements (“5G HyperService Cube”).

Although the air interface design must be flexible to include the current suite of services, the flexibility of the future system must also incorporate features to provide a major contribution to the performance improvement over the current generation of wireless networks (e.g. LTE Release 12).It is expected that the 5G system design will support three orders of magnitude higher capacity per km^2, a hundred times higher data rate, latency of less than 1 ms across the radio access link, a hundred times more connections (links) and three orders of magnitude lower energy consumption than the current generation of wireless network. Although these performance targets do not need to be met simultaneously, they provide the basis for the Gbit/s user experience for 5G networks.

Three major objectives can be established for the design of the 5G air interface:

- The 5G air interface should be adaptable to provide support for the increasingly diverse set of traffic characteristics from new and existing services, applications, devices and users.
- The 5G air interface should be scalable to handle massive connectivity and to deliver massive capacity efficiently.
- The 5G air interface should be capable of flexible and efficient use of all available spectrums in licensed and unlicensed bands.

II. SOFTWARE DEFINED FLEXIBLE AIR INTERFACE

In order to address the challenges and meet the design objectives outlined above, new design principles applicable to the air interface should be established. The old paradigm for design of air interfaces was based on a cell-centric architecture with physical devices (i.e. individual UE) connected to discrete physical cells. In contrast, the 5G air interface is designed with "UE-centric" architecture from the ground up, where wireless devices are serviced by a dynamic group of access points. Previous air interface designs adopted a one-size-fits-all strategy that focused on the requirements of one dominant application using the mobile broadband service. In order to support diverse services, applications, devices and users in 5G, a service-oriented approach is taken in which the adaptive air interface components are combined to satisfy the diverse needs of different traffic sources in the local deployment. Another important change in design principles is from the existing "per-node" based signal processing to centralize joint signal processing. As a result, mechanisms to proactively reduce and eliminate interference (i.e. create an interference free connection) are realizable. In the 5G air interface, channel measurement will rely more on the network. That is, instead of relying on the UE reporting its measurements to each network node, the network will be more involved in measuring and monitoring the channel conditions of a device. With these paradigm shifts, the new 5G air interface design will be better able to address the challenges of diversity of traffic, massive connectivity and provide the flexibility to accommodate many segments of spectrum with a variety of regulation.

In what follows, we present a dual layer non-orthogonal radio interface technology that will enable the software defined flexible air-interface. With such a dual layered non-orthogonal air-interface structure, an air-interface supporting much higher spectral efficiency and much larger number connectivity can be enabled for 5G. More specifically, dual layer non-orthogonality is realized by filtered-OFDM (f-OFDM) waveform and Sparse Code Multiple Access (SCMA). *First*, the filtered-OFDM is the foundational feature to enable the Software-Defined Air-Interface which allows network to adapt the waveform to fit the specific requirements in specific usage scenario. Such an adaptability comes from the ability of filtered-OFDM to isolate (localize) the radio resource and create an ideal framework for integrate the diverse radio parameter-driven radio connectivity (including waveform, coding-modulation, frame structure numerology and access protocol); *Second*, the SCMA technology introduces additional code dimension in addition to the time-frequency dimensions defined in the LTE technology. Such a code dimension not only introduces non-orthogonal dimensionality, i.e. increase the connectivity for multiple-access links but also increases spectral efficiency. More importantly, with specific sparse code structure, we can explore new features for the transmitter and receiver based on non-linear signal process techniques. For example, at transmitter side the SCMA allows zero PAPR transmission for small-size packet, a critical requirement for device battery saving. SCMA also allows up to 10 times increase of median and low data rate MTC links due to excessive dimensionality as compared to orthogonal dimensionality. At the receiver side the structured sparse code allows fast blind-detection as compared to the LTE technology. Such fast blind detection capability will enable grant-free type of access protocol, and therefore drastically reduces signaling overhead (up to 400%). Combining with new UE centric ID and new machine states, SCMA can enable no-cell access which virtualizes the networks nodes in conjunction of radio resources into a virtualized hyper-cell. Such UE centric architecture can drastically simplify the access protocol especially in the presence of large amount of heterogeneous networks nodes; whilst the traditional Cell-ID based access architecture will become a bottleneck in such a scenario [2].

III. DUAL-LAYRED NON-ORTHOGONAL FRAMEWORK

The structure of new air-interface consist of two major building blocks, the f-OFDM waveform and SCMA multiple access. The hierarchical constructions are as follows: (see Figure 2)

A. Inter-block Non-Orthgonality

Chunk-wise filtered OFDM waveform is used to construct flexible f-OFDM time-frequency blocks where each f-OFDM block contains flexibly reconfigurable radio parameters. The f-OFDM blocks can be grouped into a radio frame to form a TTI unit, and such a TTI unit size can be variable based on the application needs and can be re-configurable as well. With inter-block non-orthogonality:

- Each f-OFDM block is isolated to other f-OFDM blocks.
- Each f-OFDM block is non-orthogonal to other f-OFDM blocks.
- Each f-OFDM block radio resource can be defined to tailor to each application and scenario.
- Each f-OFDM block can be redefined with different numerology of radio parameters.
- Each f-OFDM block can be asynchronous to other f-OFDM blocks.
- Each f-OFDM block can be redefined with other non-OFDM waveform and co-exist with the rest f-OFDM blocks.

B. Intra-block Non-Orthgonality

The intra-block non-orthogonality is represented by code space dimensionality introduced by SCMA.,

- Each SCMA code space is non-orthogonal, therefore increase the access dimensionality.

- Each SCMA code space, in particular the code book can be optimized with respect to different requirements and usage scenarios.
- Each SCMA code space, in particular, the code book can be jointly optimized with modulation constellation and FEC.
- Each SCMA code space with ensemble code book can be detected with a blind-receiver.
- Each SCMA code space can be mapped on same transmission node, or a group of transmission nodes.
- Each SCMA code space resource can be used for contention-based-access scheme or scheduled-based-access scheme.

In addition, the SCMA code space can be used for control plane design.

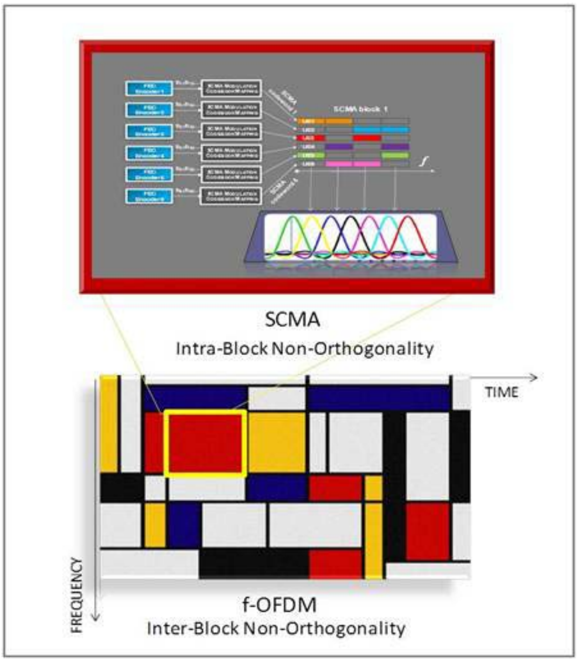

Figure2: Dual Layer Non-Orthogonality

IV. Filtered-OFDM (f-OFDM)

While OFDM remains a fundamental waveform of choice in the 5G air interface, it has limitations for some applications. These limitations include the high spectral side lobes (which may necessitate the need for guard bands), the need for time synchronization to maintain uplink orthogonality and the inability to combine flexible OFDM parameters for diverse applications. To this end, *filtered OFDM*[3] is an attractive configuration to facilitate operation of flexible waveforms. In filtered OFDM, a sub-band digital filter is applied to shape the spectrum of a portion of the OFDM signal. In this way, spectrum localization can be attained between sub-bands. Orthogonality of subcarriers is maintained within each sub-band. This facilitates the co-existence of different waveforms with different OFDM parameters as shown in Figure 3.

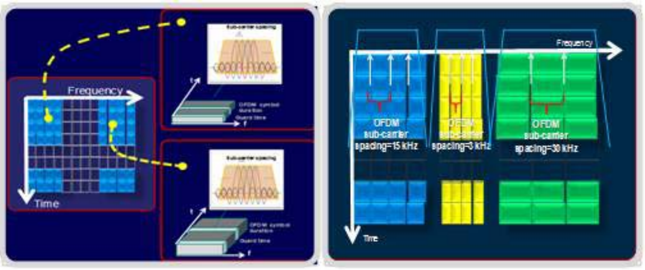

Figure 3: f-OFDM Blocks with flexible waveform parameters

Filtered OFDM is one element of fundamental waveform technology incorporated in software defined air-interface to better support different waveforms, multiple access schemes and frame structures based on the user's application scenarios and service requirements simultaneously. An example application is shown in Figure 3 in which two different transmission time interval (TTI) lengths and CP lengths (left figure) and three different sub-carrier spacings (right figure) are simultaneously supported in the system. Different user applications with diverse requirements can be supported with the individually best experience in the unified air interface. In this example, low latency applications are carried with the short TTI waveform while less latency sensitive traffic is carried with the longer TTI length. Without the ability of filtered OFDM to create optimized sub-environments for each service, common (and hence less-efficient) waveform parameters would have been configured for the entire system in order to span the diverse application requirements. As another example, a long cyclic prefix (CP) is typically chosen for a broadcast service while wide sub-carrier spacing (and hence shorter symbol duration) is typically chosen to support high mobility (e.g. high-speed train) and low cost devices. A compromise between these parameter extremes will result in a less efficient system. However, with Filtered OFDM enabling multiple parameter configurations, software defined air-interface is able to provide a more optimum parameter choice for each service group and hence better overall system efficiency.

Due to the spectrally localized sub-band filters mentioned earlier, there is less cross-talk between sub-bands. Therefore, filtered OFDM can enable asynchronous multiple access on the uplink at the sub-band level which is beneficial for different types of devices with various synchronization requirements.

V. Sparse Code Multiple Access (SCMA)

SCMA[4] is a non-orthogonal waveform that achieves improved spectral efficiency through a multi-dimensional constellation. This waveform facilitates a new multiple access scheme in which sparse codewords of multiple layers of UEs are overlaid in code and power domains and carried over shared time-frequency resources. Typically, the multiplexing of multiple devices may become overloaded if the number of overlaid layers is more than the length of the multiplexed codewords. However, with SCMA, overloading is tolerable with moderate complexity of detection thanks to the reduced size of the SCMA multi-dimensional constellation and the sparseness of SCMA codewords[5]. In SCMA, coded bits are directly mapped to multi-dimensional sparse codewords selected from layer-specific SCMA codebooks. The complexity of detection is controlled through two major factors. One is the sparseness level of codewords, and the second is the use of multi-dimensional constellations with a low number of projection points per dimension. An example of device multiplexing with a low projection codebook and the resulting constellation mapping is shown in Figure 4. A device's encoded bits are first mapped to a codeword from a codebook. In the example, a codeword of length 4 is used. The low projection codebook has a reduced constellation (from 4 points to 3 points). Furthermore, each point (e.g. "00") has non-zero component only in one tone. A codebook with one non-zero component is a zero-PAPR codebook.

Furthermore, a blind multi-UE reception technique can be applied to detect device activities and the information carried by them simultaneously [6]. With such blind detection capability, grant-free multiple-access can be supported. Due to these benefits, SCMA is a technology suitable for supporting massive connectivity.

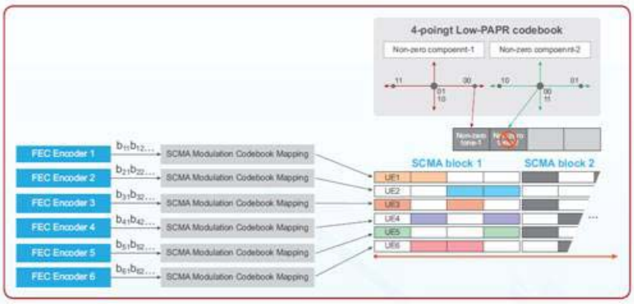

Figure 4 SCMA multiplexing and low projection codebook constellations

VI. OVERALL AIR-INTERFACE DESIGN

With LTE, a global full-band computing of a homogeneous FFT transformation irrespective to the underline of variety of applications has to be applied. Such a single FFT based computing (one-size-fit all physical layer) becomes the bottleneck for the emerging 5G application, especially the massive MTC and mission critical MTC. The proposed dual-layer non-orthogonal air-interface framework departs from the classical LTE OFDM structure to allow localization of each f-OFDM block radio resource. The dual-layer non-orthogonal construct enables the radio resource flexibility and adaptability and ultimately, with virtualize air-interface, the radio resource design will be capable to tailor into the application and scenario.

With f-OFDM, different waveform constructs appropriate for different UE applications, date rates and overage ranges can co-exist.

- The f-ODFM can fully adaptive in terms of the adaptive structure on radio parameters such as TTI, symbol size, sub-carrier spacing, CP length, Pilot density and frame structure numerology.
- The f-OFDM can be easily extended into massive MIMO applications due to orthogonal sub-carriers
- The f-OFDM can be easily ultra-extended into narrow-band waveforms due to super isolation of f-OFDM filter design.
- The f-OFDM achieves better latency than TDM arrangement for OFDM-A (ala LTE)
- The f-OFDM can achieve asynchronous access with use of larger CP (whilst in Filter Bank Multiple Access case, there is a time-domain tail overhead)

For the SCMA construct, a fully optimized code space will allow to optimize the ultimate time-frequency-spatial-code-power domain dimensionality with a sophisticated codebook design and receiver design, since SCMA is the enabler for the spectral efficiency and large number connectivity links

- The SCMA brings the extra code domain dimensionality in addition to power domain.
- The SCMA enables grant-free access and to enable the power saving and reduce the signalling overhead significantly.
- The SCMA in combination with narrow band waveform can achieve asynchronous access.
- The SCMA optimize the open-loop operation, therefore simplify the schedule
- SCMA is robust to the high speed mobility

VII. SUMMARY AND CONCLUSIONS

The dual-layer non-orthogonal air-interface is presented, the specific features associated with f-OFDM and SCMA are discussed. The unique advantages for f-OFDM and SCMA are:

A. Higher Spectral Efficiency

Both f-OFDM and SCMA increase the spectral efficiency as compared with LTE OFDM technology. For f-OFDM case, it is because of the ability to optimize radio parameters to service specific applications. For SCMA case, it is because of the ability to utilize the excess dimensional codebook.

B. Lower Laency

Both f-OFDM and SCMA reduce the latency as compared with LTE-OFDM. For f-OFDM case, it is due to the capability to support different TTIs simultaneously. For SCMA case, it is because of the blind detection of codebook and grant-free access.

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