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Radio Interface Evolution Towards 5G and Enhanced Local Area Communications

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ABSTRACT The exponential growth of mobile data in macronetworks has driven the evolution of communications systems toward spectrally efficient, energy efficient, and fast local area communications. It is a well-known fact that the best way to increase capacity in a unit area is to introduce smaller cells. Local area communications are currently mainly driven by the IEEE 802.11 WLAN family being cheap and energy efficient with a low number of users per access point. For the future high user density scenarios, following the 802.11 HEW study group, the 802.11ax project has been initiated to improve the WLAN system performance. The 3GPP LTE-advanced (LTE-A) also includes new methods for pico and femto cell's interference management functionalities for small cell communications. The main problem with LTE-A is, however, that the physical layer numerology is still optimized for macrocells and not for local area communications. Furthermore, the overall complexity and the overheads of the control plane and reference symbols are too large for spectrally and energy efficient local area communications. In this paper, we provide first an overview of WLAN 802.11ac and LTE/LTE-A, discuss the pros and cons of both technology areas, and then derive a new flexible TDD-based radio interface parametrization for 5G local area communications combining the best practices of both WiFi and LTE-A technologies. We justify the system design based on local area propagation characteristics and expected traffic distributions and derive targets for future local area concepts. We concentrate on initial physical layer design and discuss how it maps to higher layer improvements. This paper shows that the new design can significantly reduce the latency of the system, and offer increased sleeping opportunities on both base station and user equipment sides leading to enhanced power savings. In addition, through careful design of the control overhead, we are able to improve the channel utilization when compared with LTE-A.

INDEX TERMS 802.11ac, 802.11ax, 5G, energy efficiency, flexible TDD, green radio, HEW SG, low latency, local area, WLAN, LTE/LTE-advanced, small cell networks.

I. INTRODUCTION

As discussed in [1]–[3], we can expect the mobile data traffic to grow by a factor of 1000× by the year 2020. Supporting this kind of traffic growth in wireless communication networks is not possible by relying on a single solution [4]. Several improvements and modifications to existing systems, new concepts and breakthroughs are required to tackle the problem of exponential growth of mobile data traffic. Possible solutions are, e.g., off-loading traffic to local area (LA) cells, new frequency bands, new physical layer designs, massive multiple-input multiple-output (MIMO) schemes [5], self-organizing networks (SONs), etc. All of these solution candidates have to be studied to achieve the exhaustive throughput targets that the projected growth demands. There are several current initiatives focusing on 5G related research considering the aforementioned solutions. One example is the EU-funded FP7 project METIS [6], in which the target is to explore mobile and wireless enablers for the 2020 information society.

From all the possibilities to improve the spectral efficiency, going toward increased density of small LA cells or small cell networks (SCNs), is seen as the most effective candidate for boosting the network spectral efficiency [2], [7]. The small LA cells may or may not be controlled by the macro base stations, and we describe them as coordinated or uncoordinated cells, respectively. Assuming uncontrolled LA cells, the corresponding evolved Node B (eNB) or AP would most likely be owned by the end user.

In this article, we will introduce a new radio interface entitled 5G flexible time division duplex (TDD) based local area (5GETLA). The 5GETLA physical layer numerology is designed for dense LA cells using the existing tools to achieve the 5G design targets. Already in [1], the need for clearly reduced frame and transmit time interval (TTI) durations when compared to LTE were pointed out. We introduce a physical layer numerology that reduces the symbol and frame durations by a factor of 10 and discuss the effects on energy efficiency (EE), spectral efficiency (SE) and latency, by which we mean the physical layer round-trip time (RTT) from transmitting a packet to receiving an acknowledgment (ACK) to that packet. From now on, we will refer to the network elements of the new 5GETLA system as local area base stations (LABSs) as the access points used with 5GETLA. We chose to refer to them as BS because we see 5GETLA as an extension of current 3GPP LTE evolution with best aspects of WiFi adapted to the numerology. We refer to LTE capable access nodes as base stations (BSs) or eNBs.

In general, we see the outcomes of this paper and research as possible trends in 3GPP cellular evolution in the coming years. Furthermore, we have put substantial efforts in the presentation to describe the current 3GPP mobile cellular and IEEE WLAN 802.11 related technologies, and in particular their limitations towards enhanced LA communications in the future. We particularly feel that the selected thorough presentation style is in order and justified to deeply elaborate the current state-of-the-art 3GPP cellular radio and IEEE WLAN radio solutions and in particular their certain limitations from future LA communications perspective with very challenging latency, EE and device population targets. We also believe that presentation style like this will best catalyze technical discussion crossing the borders of 3GPP mobile cellular and IEEE WLAN communities, which is one purpose of this article. The main purpose of this article is to elaborate the fundamental design principles we have used to define a new candidate for 5G small cell networks physical layer. The idea is to present the concepts at early stage and not a finalized product. Also, because the design is currently evolving and the system level simulator implementation is an ongoing process, we have left the more detailed interference, latency, and throughput analysis and simulations for future research. As the technical discussion in some parts build on a variety of abbreviations, we have collected the main abbreviations to Table 1 to enhance the readability of the article.

TABLE 1. Main abbreviations used in this article.

5GETLA	5G flexible time-division duplex local area
AP	Access point
ARQ	Automatic repeat request
BS	Base station
BSS	Basic service set
CBDCH	Contention based data channel
CP	Cyclic prefix
CSMA/CA	Carrier sense multiple access with collision avoidance
D2D	Device-to-device
DCF	Distributed collision function
DL	Downlink
DLCCH	Downlink control channel
DLCRS	Downlink common reference symbol
DLCSIRS	Downlink channel state information reference symbol
DLDCH	Downlink data channel
DLDMRS	Downlink demodulation reference symbol
DRX	Discontinuous reception
DLSCH	Downlink shared channel
EE	Energy efficiency
eNB	Evolved Node B
FDD	Frequency division duplexing
FFT	Fast Fourier transform
GI	Guard interval
HARQ	Hybrid automatic repeat request
IC	Interference cancellation
LA	Local Area
LABS	Local area base station
LTE	Long term evolution
LTE-A	LTE-Advanced
MAC	Medium access control
MCS	Modulation and coding scheme
MIMO	Multiple-input multiple-output
OBSS	Overlapping basic service set
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
QoE	Quality of experience
QoS	Quality of service
RACH	Random access channel
RAS	Random access sequence
RB	Resource block
RTT	Round-trip time
SCN	Small cell network
SE	Spectral efficiency
SIFS	Short interframe space
SON	Self-organizing networks
STA	Station
TDD	Time division duplexing
TTI	Transmit time interval
UE	User Equipment
UL	Uplink
ULCCH	Uplink control channel
ULCRS	Uplink common reference symbol
ULCSIRS	Uplink channel state information reference symbol
ULDCH	Uplink data channel
ULDMRS	Uplink demodulation reference symbol
ULSCH	Uplink shared channel
WLAN	Refers to IEEE WLAN 802.11ac, unless stated otherwise

This article is organized as follows. In Section II, we discuss the design targets of 5G and future LA communications in more detail. Then, in Section III we briefly describe the existing solutions, WLAN and TDD LTE-A, for local area communications and discuss their pros and cons shortly. In Section IV the LA channels, environment assumptions, and data traffic models are discussed in detail. After these, based on existing solutions and LA environment, we propose a new numerology and radio interface design for future LA system, called 5GETLA, in Section V, and discuss its physical layer and system level aspects in detail. Finally, in Section VII, conclusions on the new system design are given and future research aspects are provided.

II. INITIAL DESIGN TARGETS AND CONSIDERATIONS FOR 5G LOCAL AREA COMMUNICATIONS

Good general discussion and direction for 5G communication technology research are available, see [8]–[12] and references therein. Stemming from these articles, we believe that the network densification with flexible TDD based new radio interface is a tractable technology solution to boost the network spectral efficiency in particular in those areas and locations where the user-density is high. In this section, we will provide an overview of our design targets and initial assumptions when starting to derive the new radio interface.

A. IMPROVED SPECTRAL EFFICIENCY

To achieve high spectral efficiency in LA cell with high user density and/or traffic load, the system has to be synchronized and scheduled. The 2nd, 3rd and 4th generation of mobile cellular macro networks have shown that the only way to efficiently serve large device populations per cell is to have synchronized and scheduled wireless access. Furthermore, the poor performance of WLAN networks under heavy load or high user density exemplifies why asynchronous and unscheduled medium access, especially carrier sense multiple access with collisions avoidance (CSMA/CA) used by the distributed coordination function (DCF) in WLAN medium access, does not work in the scenarios expected for 5G communications.

In 5G, we want to support larger number of devices per unit area. We know that the number of devices generating the traffic will continue to increase. It is more and more common for each user to have augmented reality glasses, smart phone, tablet, laptop, and possibly other devices constantly updating their status and transceiving data over wireless communications link. Especially the signaling load on existing mobile networks [12] can become exhaustive with large quantities of small packets and more efficient designs are needed to support increasing number of devices asynchronously updating their status. Therefore, it is important to improve the $bps/Hz/J/km^2$ performance of the system and *include the energy used for signaling in the evaluations*.

The peak data rates of the existing solutions are sufficient for most of the end users, but the problem is the achieved throughput of these systems. It does not help if the theoretical capacity is Gbps if only a small fraction of this can be delivered to the end user. For example, in a typical 802.11ac basic service set (BSS), the throughput dramatically drops as the number of APs which operate on the same channel in the vicinity of each other increases. In an LTE small cell, the throughput experienced by a few users is unnecessarily limited by the amount of control and signaling information designed to support hundreds of users in a macro cell. A better measure for the system performance is thus the achieved throughput above the MAC layer, and not the peak data rates. In addition, the design presented in this article is for centimeter-wave communications and we see that the very high peak data rates will be provided by the millimeter-wave communications in 5G networks [13].

B. REDUCED LATENCY

One significant factor affecting quality of service (QoS) and quality of experience (QoE) is the latency of the physical layer. As an example, the physical layer latencies in LTE femto cells when compared to WLAN BSSs in low user density scenarios are significantly larger, approximately 2-40 times larger (see Table 16). The measured latencies on top of MAC layer, including physical layer latencies and queuing latencies are of great importance, but are typically dominated by the physical layer design. Of course, bad scheduler design can destroy the gains of a good physical layer design. Especially the latency of packets that contain critical information for the higher layer protocols, for example transmission control protocol (TCP) acknowledgment (ACK) packets, should be minimized. For this reason the association and retransmissions should be very fast when compared to the higher layer timers. Also, possibility to transmit contention based data (CBD) is important. With CBD we mean that a UE could send a packet to a best-effort CBD channel (CBDCH) without first requesting UL allocation from the LABS. If the packet does not go through, e.g., because of inter-cell interference, the LABS should be able to detect a transmission and allocate resources for the UE to retransmit the desired packet. Therefore, if we introduce a CBDCH for low and medium loads, the average delay for transmitting small packets can be significantly reduced. As the traffic saturates towards full buffer scenario, the best option is to disable CBDCH allocation and use those resources for scheduling requests and scheduled data transmissions. In addition to QoS and QoE requirements, future wireless services and especially industry applications [14] require very low latency service with RTT below 1ms. CBDCH is one possible way to achieve this target in the 5GETLA physical layer design.

The WLAN 802.11 standard [15] enables a fast RTT, thanks to minimal $16\mu s$ between received packet and transmission of ACK, known as short interframe space (SIFS). Note that $16\mu s$ SIFS is used in channels around 5 GHz carrier. At 2.4GHz carrier, 802.11n uses $10\mu s$ SIFS time. Thus, at 5GHz, the minimum RTT is $120\mu s$ (transmitting one symbol of data, SIFS, receiving ACK with one data symbol, and SIFS, including the physical layer headers) and maximum is approximately 6ms. In LTE-A, the uplink RTT is typically 13ms due to system design [1]. This implies that the delay characteristics of the current technologies are far from sufficient, especially with high device population, when considering the typical 1ms latency target set for 5G wireless communications.

C. ENHANCED ENERGY EFFICIENCY

One of the main motivators for 5G systems is the reduced power consumption per transmitted and received bit, or in other words the energy efficiency of the system, that has been widely addressed for example in [16]–[18]. As we increase the amount of data that we transmit and receive daily, we do not want to increase the amount of used energy in the same manner. In other words, as a design parameter, we want to improve the $bps/Hz/J$ performance of the communications system.

With reduced symbol durations, we enable different sleeping modes from very short micro sleep (less than 1 ms) to long sleep periods (e.g. 100 ms) with improved energy saving possibilities due to reduced duty cycle. The key to achieving the energy saving potential depends on the speed of resource allocation, usage of contention based channel and different packet buffering schemes possibly used in the mobile device. Achieving full gain from the micro sleep modes also requires improvements on the hardware to be able to reduce the switch off and on times of different components, e.g., stabilizing times of oscillators. The system has to be designed to include also long sleep modes in which the LABS would wake up with certain time periodicity, e.g. 100 ms as a rule-of-thumb, and transmit a synchronization frame to allow possible new devices to associate. Depending on the time periodicity of the synchronization frame we can fine tune the power saving capability during long sleep modes. If we assume that the frame length would be 0.5 ms and the time periodicity of 100 ms, this kind of setup could facilitate power savings up to 99.5%. This could lead to energy efficiency that would allow us to keep LABSs always on (but in long sleep mode if no UEs to serve), allowing UEs to access LABS capacity with average delay of approximately 50 ms in any time and place.

For small cell environments, where the users can be expected to mainly stream video or browse through websites [19], the UL and DL traffic contains bursts with inter-arrival times that are significantly longer than the 0.5 ms frame length. When looking at the traffic over all users per cell, the average number of active users per 0.5ms can thus be expected to be relatively low. Therefore, it is crucial for the 5G LA enhancement to be able to adapt the DL-UL allocation per frame basis. Number of users served per frame may be relatively low (e.g. max 5 users per frame) as long as the frame is kept short enough.

D. WAVEFORM DESIGN AND FREQUENCY BANDS

On the waveform side, we know from WLAN that cyclic prefix (CP) of order 400 ns works well in LA communications as long as the timing synchronization accuracy is sufficient [20, Ch. 5], and it can be used as a reference point for CP design. We also want to minimize the RTT, so the orthogonal frequency division modulation (OFDM) symbol and frame duration should be as small as possible. The CP length limits the OFDM symbol duration, because we want to keep the CP overhead around 5%. The frame duration should be such that the RTT would be less than 1 ms. Another lesson learned from WLAN is that OFDM in uplink (UL) and downlink (DL) is a good solution for LA communications. This simplifies the radio interface design and allows us to use orthogonal frequency division multiple access (OFDMA) in both, DL and UL. OFDMA also enables more sophisticated interference avoidance functionalities than the basic OFDM used in WLAN.

In this article, we do not consider new nonorthogonal waveforms (see [12] and references there in). It is true that the sporadic, low rate information generated in UL or in sensor networks can benefit from the new waveforms. Supporting large quantities of asynchronous small packet traffic is vital for new 5G macro layer, especially when acting as a collector node for vast number of low power sensors or when the macro layer acts as a control layer as presented in [9]. We will concentrate on pushing the OFDM numerology to the limits to improve the spectral efficiency while simultaneously improving the energy efficiency and RTT latency. We do not see sporadic traffic as a severe problem in our low latency physical layer design for small cells, but we prepare for it by including the CBDCH in our frame design to allow small packets to be transmitted in the UL with minimal latency.

One of the main problem arises from the inter-cell interference if the macro and LA cells operate on the same frequency band. Several methods trying to minimize the inter-cell interference have been standardized and studied for LTE-A [21], but the simplest method would be using separate, preferable higher frequency band for local area communications [9]. The new 5GETLA radio interface that we discuss in this article could be introduced e.g. in the E-UTRA operating bands 42 (3400 MHz - 3600 MHz) and 43 (3600 MHz - 3800 MHz) [22, Table 5.5-1], that are defined for TDD duplex based mode for LTE-A. Together, these two bands allow 400 MHz of continuous spectrum for LA communications. In addition, introducing a new system to this dedicated band would not cause any problems with backward compatibility. This topic was pointed out also in [9] and our 5GETLA design can be thought as a candidate solution for the phantom cell physical layer. On the other hand, our higher level frame design does allow smooth coexistence between 5GETLA and LTE (see Section VI-B for more details). If we include to the design an assumption of a control connection between an eNB and multiple LABS, there is obstacle why inter-cell interference could not be handled in the case of intra-band deployment. We have left the studies related to centrally controlled 5GETLA network topology as a future topic.

More generally, we do not necessarily have to settle only for frequencies below 10 GHz. For example, in [23] an introduction to millimeter-wave communications on 3-300 GHz is discussed and in [24] the possibility of using 28 and 38 GHz carriers for 5G mobile communications is studied based on channel measurements in the respective frequencies. New, high carrier frequency solutions, commonly referred as millimeter-wave mobile communications, provide larger system bandwidths from higher frequencies. The throughput of the system can be significantly increased by the increase of the bandwidth, but achieving this requires advances in the hardware implementations and in controlling the beamforming required for reliable, high rate links.

When further increasing the used carrier frequencies we also have to consider the complexity increase caused by massive MIMO setups required for reliable links. These millimeter-wave solutions provide very high throughput and are especially interesting for local area communications because of the high path and penetration losses [24]. In addition, the outdoor measurement performed in [25] indicated that 99 percent of the measured RMS delays were less or equal to 129 ns with 25-dBi directional antennas in the transmitter and receiver. These values indicate that the new numerology we introduce in this paper is directly applicable to millimeter-wave mobile communications. As the knowledge of the millimeter-wave channels accumulates, we can easily modify the 5GETLA frame design to include the finer details for enhanced performance. Also, the high level frame architecture presented in [23] is very similar to the 5GETLA frame architecture that we will discuss in Section VI-B. In addition, in [26] and [27] similar dynamic TDD based frame designs supporting centimeter-wave (3-30 GHz) communications have also been recently reported and in [28] and [29] a dynamic TDD radio interface using single carrier waveform for millimeter-wave (30-300 GHz) communications was proposed, indicating the importance and timeliness of this work.

E. LOCAL AREA TRAFFIC AND ENVIRONMENT

Due to the burst-like nature of the traffic [30], [31], we propose to concentrate on the flexible TDD as was proposed also in [9]. This allows us to dynamically adjust the DL-UL ratio per frame per cell. Thus, the system is agile to adapt to the traffic demand changes in DL-UL directions and may serve small amount of user equipments (UEs) with higher efficiency than fixed TDD frame structures [32]–[34]. We also believe that in fast flexible TDD frame structure the number of served UEs per frame per LABS should be minimized to keep the amount of control data as small as possible. This is because we have minimized the frame duration, the proportional signaling overhead of scheduling large number of users per frame would become excessive. A few UEs may be served per frame to achieve a small frequency multiplexing gain or desired time alignment for inter-cell interference control. Furthermore, fast frame structure combined with LA channels and slow mobility allows us to reduce the amount of reference symbols used for channel estimation per frame. If the frame structure is fast enough it is sufficient to estimate the channel only once per frame.

To conclude, the future 5G local area enhancement should be fast, energy efficient, scalable, tolerate high user density and traffic load, agile with respect to DL-UL allocation, and provide superior $bps/Hz/J/km^2$ performance metrics when compared to current LTE-A or WLAN solutions. Dynamic and fast radio interface design seeking solutions to these requirements is described in this article.

III. BASIC PARAMETRIZATION OF EXISTING SYSTEMS

In this section, we will provide an overview of the main parameters and pros and cons of existing system solutions for LA communications. First we discuss WLAN based on the WLAN 802.11ac [35], and then 3GPP LTE-A [36]. We do not try to give thorough description of either of the systems, but we only pick the most relevant details that we use as a basis for comparison in Section V.

A. WLAN WITH EMPHASIS ON THE IEEE WLAN 802.11AC

IEEE 802.11 standard [15] is an excellent example of a physical layer design fitted for the LA environment. Because of this, combined with simple and distributed channel access mechanism and cheap hardware implementations, it has been the de facto standard for LA communications for over ten years. The latest amendment 802.11ac [35] for WLAN physical layer provides significant improvement in the peak data rates achieving over 1 Gbps throughput over single link and over 6 Gbps in the DL MU-MIMO communications. We refer to [35] when we discuss about WLAN, unless stated otherwise. In [20], an excellent, easy-to-read introduction to IEEE 802.11 WLAN physical layer and medium access control (MAC) layer is provided, and is recommended as a background information for anyone new to these topics.

TABLE 2. Main OFDM symbol timing and PPDU header related parameters for WLAN 802.11ac for 80 MHz bandwidth.

Parameter	Value
N_{FFT}: FFT size for 80 MHz band	256
N_{SD}: Number of data carriers	234
N_{SP}: Number of pilot carriers	8
Δf_{sc}: subcarrier spacing	312.5 kHz
T_{DFT}: DFT/IDFT duration	3.2 μs
T_{GI}: Guard interval duration	0.8 μs
T_{GIs}: Short guard interval duration	0.4 μs
T_{SymL}: Long OFDM symbol duration	4 μs
T_{SymS}: Short OFDM symbol duration	3.6 μs
$T_{SIFS@5GHz}$: SIFS time at 5 GHz carrier	16 μs
PPDU header field	
T_{L-STF}: Non-HT short training field duration	8 μs
T_{L-LTF}: Non-HT long training field duration	8 μs
T_{L-SIG}: Non-HT signal field duration	4 μs
$T_{VHT-SIG-A}$: VHT signal A field duration	8 μs
$T_{VHT-STF}$: VHT short training field duration	4 μs
$T_{VHT-LTF}$: Duration of each VHT-LTF symbol	4 μs
$T_{VHT-SIG-B}$: VHT signal B field duration	4 μs

The WLAN 802.11ac OFDM PHY [35, Table 22-5] defines an 256-sample FFT over an 80 MHz channel. The most physical layer related parameters are rewritten in Table 2. For the 80 MHz channel the standard defines 234 data carriers and 8 pilot carriers leading to 242 active subcarriers around the DC component. This leads to bandwidth utilization factor $\alpha_{WLAN80MHz} = 242/256 = 0.9453125$.

The WLAN frame structure (defined as VHT physical layer protocol data unit (PPDU) in [35]) is shown in Fig. 1,

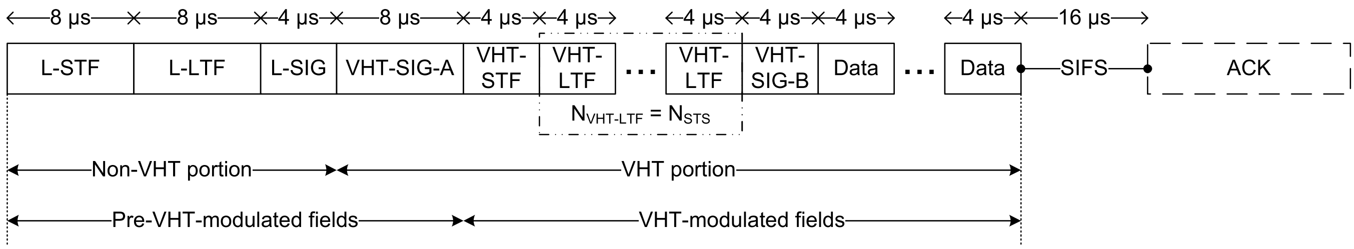

FIGURE 1. VHT-PPDU frame format including SIFS time and possible ACK packet (see [35, Clause 22.3.7]).

including SIFS time and possible ACK packet. The number of VHT-LTF symbols depends on the number of spatial streams, N_{STS}, per PPDU. We notice that each frame has an overhead of $T_{PPDU-Preamble} = 4*[9+N_{STS}]$ μs, where N_{STS} is the total number of space-time streams (STS) in a frame. The short OFDM symbol duration presented in Table 2 is used only for data symbols, and not for symbols in the PPDU header. If we consider a basic scheme in which only one STS is transmitted, the combined overhead of synchronization channel, pilot channel and control channel is 40 μs. It seems short, but it is obvious that WLAN is not efficient for transmitting very short data packets. On the other hand, as the length of the data field increases so does the SE of the WLAN system. Therefore, in [15], operation modes like aggregated medium access control (MAC) service data unit (A-MSDU) [15, Subclause 9.11] and aggregated MAC protocol data unit (A-MPDU) [15, Subclause 9.12] are defined. These methods aggregate MAC layer packets to generate larger physical layer service data units (PSDUs), that map to larger PPDUs, which increases the efficiency of the system.

Especially good in the WLAN physical layer design is that the ACK is transmitted only 16 μs after the end of the received data packet (in 5 GHz carrier). This leads to a very short RTT in a WLAN BSS if ACK is transmitted. But, if the PPDU detection fails and no ACK is transmitted then the delay between initial transmission and retransmission depends on the traffic load, number of users and interference conditions of the BSS. In the worst case, the time between initial transmission and retransmission may be too long for higher layer protocols (e.g. TCP) whose delay counters exceed allowed thresholds and the higher layer connection is terminated. This leads to reconnection at higher layer which generate significant amount of excess data traffic and further decrease the cell throughput.

Users in the BSS edge will encounter significant problems because the used MCS is small, thus the transmitted packet duration increases leading to increased probability of PPDU collision from intra-cell or inter-cell transmission (inter-cell transmission is typically considered to be overlapping BSS (OBSS) related problem in WLAN terminology), leading to high probability of packet failures. Therefore, the contention time increases and the channel access delay increases significantly. Users close to AP may use higher MCS and are typically less likely to suffer from inter-cell interference, leading to higher throughput and smaller average contention time than cell edge users. Due to CSMA/CA protocol, the throughput of all users crashes at certain traffic load/number of users because the data packets or RTS/CTS packets collide with very high probability when the stations (STAs) compete for common resources. More detailed analysis for CSMA/CA and DCF can be found, i.e., in [37]–[39] and on enhanced distributed channel access in [40].

On the other hand, as we will see in Table 16, in WLAN high MCS transmissions with small data packets leads to very low spectral efficiency due to physical layer overheads. Therefore, large buffers are required to store higher layer packets to be aggregated before transmission to improve the spectral efficiency. This leads to increased implementation complexity and increased end-to-end latency, both of which are not desired for 5G communications.

B. 3GPP LTE-A TDD MODE

Although we concentrate in this section to the basic parametrization of the LTE, we should not forget that our target is to compare the pico or femto cells with WLAN BSSs and 5GETLA. In [41], an intuitive wrap-up of the past, present and future of the femto cells is provided, discussing the problems and potential of femto cells. It also provides an extensive list of references for further studying this topic. For readers not familiar with LTE system, we recommend to read [42], which is an excellent introduction to the LTE technology.

LTE-A supports two different frame structures, type 1 for FDD mode and type 2 for TDD mode [21]. In this article, we are more interested in the type 2 frame structure and introduce the main parametrization based on type 2. For more details, the overall description of LTE is described in [21] and detailed physical layer definition is given in [36].

The basic numerology for LTE-A in 20 MHz system bandwidth is given in Table 3. The basic transmission unit is the radio frame. Each radio frame is divided into two half-frames, which are divided into 5 subframes. Each subframe contains 2 slots. We assume that normal cyclic prefix (CP) length and subcarrier spacing $\Delta f_{sc} = 15$ kHz are used. In TDD LTE there exists DL-UL configurations with 5 ms and 10 ms DL-UL switch-point periodicity. In case of 5 ms DL-UL switch-point periodicity, the special subframe exists in both

TABLE 3. Main parameters for 3GPP LTE-A physical layer for 20 MHz carrier bandwidth.

Parameter	Value
T_{frame}: Frame duration	10 ms
$T_{subframe}$: Subframe duration	1 ms
T_{slot}: Slot duration	0.5 ms
N_{FFT}: FFT size	2048
Δf_{sc}: subcarrier spacing	15 kHz
F_s: Sampling frequency	30.72 MHz
T_s: Sampling time	32.6 ns ($1/F_s$)
T_{DFT}: DFT/IDFT duration	66.7 μs ($2048T_s$)
$T_{CP,L}$: Cyclic prefix duration for the first symbol	5.2 μs ($160T_s$)
$T_{CP,S}$: Cyclic prefix duration for other symbols	4.7 μs ($144T_s$)
N_{sym}: Number of OFDM symbols per slot	7
$T_{Sym,symL}$: First OFDM symbol duration	71.9 μs ($2208T_s$)
$T_{Sym,symS}$: Other OFDM symbol durations	71.4 μs ($2192T_s$)

half-frames, and in the case of 10 ms periodicity the special subframe exists in the first half-frame only. The special subframe contains the downlink pilot time slot (DwPTS), guard period (GP), and uplink pilot time slot (ULPTS). The size of the GP defines the maximum cell size supported by TDD LTE. The LTE Release 11 supports seven different DL-UL configurations for the TDD frame, from which four are with 5 ms periodicity and three are with 10 ms periodicity [36, Table 4.2-2], as shown in Table 4. Especially those DL-UL configurations in which the traffic is heavily DL oriented, as configuration 5 in Table 4, it is obvious that the minimum latency for UL ACK is significant and may exceed the duration of the radio frame.

From Table 3, we notice that with the given parametrization the symbol duration in LTE is approximately 66.7 μs. This is approximately seventeen times longer symbol duration than in WLAN. The shorter CP is 4.7 μs, which is approximately twelve times longer than the short GI used in WLAN and even longer than the duration of long OFDM symbol in WLAN. These differences are explained by the fact that LTE is designed for macro cells, taking into consideration long distances and high velocities. Therefore, *using LTE physical layer numerology directly for LA communications is not meaningful or at least cannot be seen optimized for LA scenarios. This is one of the fundamental motivating factors behind this article.*

In addition, in LTE TDD the reconfiguration time is limited to 640 ms [32], [43] in order to successfully notify all UEs of the upcoming change. This limitation on the time dynamics of the LTE TDD has been shown in several sources, see [32]–[34], to limit the performance gains achievable for the dynamic TDD. Typically the outcome is that the faster time dynamics the system supports, the higher throughput gains are achievable with low or medium traffic loads. This is one of the key insights why we are trying to minimize the frame duration and support per frame DL-UL allocation adaptation in 5GETLA, as will be discussed in Section V. Currently, there is also significant research effort in 3GPP to study the effect of allocating DL and UL resources more flexibly, i.e., by scheduling a normal UL transmit time interval (TTI) to DL. This is possible in Release 12 [21] through TDD Enhanced Interference Management and Traffic Adaptation (eIMTA), which allows adaptation of UL-DL configuration via L1 signaling.

Furthermore, in LTE [21] the layer 2 is split into three separate sublayers: Medium Access Control (MAC), Radio Link Control (RLC) and Packet Data Convergence Protocol (PDCP). In addition to these layer 2 protocols, LTE radio interface consists of Radio Resource Control (RRC) protocol which in co-operation with layer 2 protocols supports, e.g., flexible radio resour ce configuration, QoS, network controlled mobility, lossless in-sequence data delivery, and header compression, to mention some of the functionalities that are not perhaps necessary in low complexity "best effort" LA networks. We assume that the macro network is always present to provide ubiquitous coverage and UEs may always fall back to the macro connectivity (if LA communications terminate unexpectedly) or even maintain simultaneous connectivity to the macro network by means of dual connectivity.

IV. LOCAL AREA CHANNEL ENVIRONMENT AND EXPECTED TRAFFIC DISTRIBUTIONS

In this section, we review the most commonly used channel models for LA communications and discuss the possibilities that the low mobility of UEs provide. In addition, further comments on the expected traffic on the LA cells are given.

TABLE 4. Possible DL-UL configurations for LTE TDD frame type 2. Here D, U, and S correspond to downlink, uplink, and special subframe, respectively.

DL-UL configuration	DL-UL switch-point periodicity	Subframe number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

TABLE 5. Main parameters related to WLAN 802.11 TGn channel models.

Channel Model	B	C	D	E
RMS delay spread [ns]	15	30	50	100
Coherence bandwidth [MHz] with 50% correlation	18.4	9.2	5.5	2.76
Max. excess delay [ns]	80	200	390	730
Min. reference symbol interval [MHz]	12.5	5	2.56	1.37

A. PROPAGATION SCENARIOS AND REFERENCE SYMBOL DENSITY

LA channel models have been extensively measured over the past years. Most commonly used models rely on WLAN channel models [44], [45] or on WINNER channel models [46], and references there in. In addition, several other sources, like [47], show that indoor LA environments typically experience channels with root-mean-squared (RMS) delay spread well below 400 ns and often also the maximum delay component is inside this time value. This indicates that a good starting point for CP length for LA communications is 400 ns, as used in WLAN as short GI for data field symbols. Note that we could have designed the 5GETLA frame structure to have longer CP and support larger cells, but one of the main points of new design is to optimize the physical layer for *ultra-dense small cells* to significantly boost the area capacity. Macro layer designs for 5G are their own area of interest, see [12] and references there in.

In Tables 5 and 6, we have collected the main parameters of the most interesting channel models related to LA communications, representing the main parameters for WLAN and WINNER channels, respectively. Here the presented RMS delay spread and maximum excess delay values/fractals are based on tapped delay line models [44] for WLAN channels and measurement data [46] for WINNER channels. For the amplitude coherence bandwidth we have assumed exponentially decaying channel impulse response with Rayleigh fading. Based on [47], the coherence bandwidth is given as

$$B_{coh} = \sqrt{\frac{1 - R_f^2}{R_f^2 4\pi^2 \tau_{RMS}^2}}, \tag{1}$$

where R_f is the desired amplitude correlation, τ_{RMS} is the RMS delay spread of the channel, and B_{coh} is the frequency response amplitude correlation. Assuming Jakes spectrum, the time domain correlation function is defined as

$$R_t = J_0(2\pi f_{doppler,max} t_{coh}), \tag{2}$$

where $J_0(\cdot)$ is a zeroth order Bessel function of the first kind, R_t is the time correlation value, $f_{doppler,max}$ is the maximum Doppler frequency and t_{coh} is the desired coherence time. The given coherence times are obtained by plotting the time correlation with 10μs accuracy and rounding to the closest value above desired correlation value. The presented minimum pilot symbol intervals in Tables 5 - 7 should allow us to acquire all essential information about the channel impulse response. However, because typically majority of the channel's energy is concentrated in the beginning of the impulse response, using even larger pilot intervals in the frequency domain could be acceptable.

From Tables 5 and 6, we notice that typically reference symbol (RS) interval in the order of 2 MHz is sufficient to estimate the channel in LA environment. Still, for optimized performance, we propose that the LABS could adapt its downlink common reference symbol (DLCRS) interval in the frequency domain based on the measurement reports it collects from the associated UEs. The frequency band carrying control information should always use at least predefined maximum interval for DLCRSs. By increasing the spread (reducing CRSs) we can limit the distance at which the UEs are capable of decoding the control channel, instead of changing the transmission power. This in effect causes so called controlled cell breathing phenomenon, in which the LABS can control the cell range. Limiting the DLCRS power would have similar kind of effect on the cell range. If the maximum transmission power is limited, we change the signal-to-interference-and-noise ratio (SINR) distributions in the cells and reduce the area where highest modulation and coding schemes (MCSs) are supported. As indicated in [48], not limiting the LABS transmission power as we decrease the cell size allows us to faster empty the transmission buffers of all users, thus reducing the time the potential interferers are active. In other words, limiting LABS transmission power as we shrink the LA cells does not directly map to improved performance. Cell breathing is a well known effect especially in code division multiple access (CDMA) based networks [49], [50]. It has also been studied in WLAN systems [51], [52], to limit the number of STAs connected to a congested AP. In [53], an interesting concept was presented

TABLE 6. WINNER local area channel model parameters. A1 corresponds to indoor office/residential, B3 to large indoor hall, A2 to indoor to outdoor, and B4 to outdoor to indoor propagation scenarios.

Channel model	A1 (LOS)	A1 (NLOS)	B3 (LOS)	B3 (NLOS)	A2	B4
RMS delay spread 50%/90% fractals [ns]	26.1/47.3	25.2/44.6	26.5/40.9	39.3/47.2	21.4/65.5	45.4/109
Coherence bandwidth [MHz] with 50% correlation (50%/90% RMS delay fractals)	10.6/5.83	10.9/6.18	10.4/6.74	7.01/5.84	12.9/4.21	6.07/2.53
Max. excess delay 50%/90% fractals [ns]	180/377	146/252	125/175	175/250	175/362	239/487
Min. reference symbol interval [MHz] (50%/90% max. delay fractals)	5.56/2.65	6.85/3.97	8.0/5.71	5.71/4.0	5.71/2.76	4.18/2.05

TABLE 7. Mobility related parameters for local area channels for 3.5 GHz and 5.0 GHz carriers.

Carrier frequency [GHz]	3.5		5.0	
Velocity [km/h]	3	30	3	30
Coherence time [ms] (50%/90% correlation)	24.9 /10.5	2.48 /1.05	17.4 /7.30	1.74 /0.73
Max. Doppler frequency [Hz]	9.8	97.5	13.9	139.4
Min. reference symbol interval in time [ms]	51.3	5.13	35.9	3.59

related to limiting the number of users per renewable energy powered low-power BS by using cell breathing. The main idea was to maximize the usage of renewable energy and to minimize the usage of the on-grid energy while preserving the outage targets.

Another important parameter for RSs is the required update interval. Because we are discussing LA communications with expected cell range less than 50 m, we assume that the associated users will not move with high velocity ($v_{UE} < 30$km/h). Also, typically users in home or lecture hall environment move by walking and often spend long durations in fixed positions when using data intensive applications. Therefore, we propose that the system should be designed to support only low mobility users to minimize the RS overhead. High mobility users should be served by the macro BS to avoid unnecessary handovers and to provide better QoE for the end users. Alternative solution is the phantom cell concept presented in [9], where macro BS has full control over small cells and dictates the handovers for high mobility users. Then it could be possible to predict the location of the user at certain time instant and in extreme case transmit packet per small cell as the user moves through dense small cell network (SCN).

Based on some simple analysis on the time correlation properties with low mobility (3km/h) and maximum desired operating mobility (30km/h), presented in Table 7, we notice that even in the worst case with 5 GHz carrier the update interval in time can be less or equal to 3ms. Thus, if the frame duration in time for enhanced LA system is less than or equal to 1ms, it is sufficient to estimate the channel in the beginning of every third frame for reliable transmission. In practice, the estimation would probably be updated per frame, so this allows us to filter channel estimates over few consecutive frames. In addition, because the DLCRSs are available in each frame, after a long sleep duration, it is sufficient for UE to wake up one or two frames before scheduled status update, in order to resynchronize to the desired LABS.

B. TRAFFIC MODEL CONSIDERATIONS FOR LOCAL AREA COMMUNICATIONS

As mentioned in [19], the expected traffic in future wireless mobile communications will be mainly caused by video streaming (66.5%) and web/data (24.9%) already in 2017 and most of the traffic is generated by portable devices. In addition, already with the current level of social media and other applications constantly updating their status and active mobile users uploading status updates, photos and videos to the cloud services the amount of UL traffic, especially small packet traffic, has increased significantly and there is no saying what will be the "killer app" of the 5G networks.

As shown in [30], [31], and [54], the traffic will be very bursty with inter-arrival times larger than 10ms for more than 70% of all the measured data bursts. Having an inter-arrival time larger than 10ms between most of the data bursts indicates that if our physical layer is fast enough, it can serve multiple UEs between data bursts. In other words, fast physical layer allows transmitting a single data burst fast to the UE and allows this UE to sleep between data bursts. For example, due to the enhanced duty cycle, the active time can be 0.5ms and sleep time almost 9.5ms in every 10ms between data bursts, facilitating 95% sleeping possibilities. The sleep duration can be adapted on the fly on the LABS based on the histogram of detected inter-arrival times for data bursts for certain UE.

In LTE-A, the per UE power savings are achieved by discontinuous reception (DRX), where the UE wakes up in the beginning of a DRX cycle and listens the physical downlink control channel (PDCCH) for resource allocation (see [55]). The short DRX option allows UE to sleep a predefined time in shorter cycles after there has been a resource allocation for that UE, which improves the performance if bursty data arrival is assumed. In [56], it was shown that the use of DRX is always a tradeoff between power consumption and delay. In 5GETLA, we can adapt the sleep times per UE based on the measured traffic, which is not possible in LTE-A, and due to significantly faster radio interface we can sleep between packet arrivals without increase in the experienced delay. In WLAN, STAs typically listen to each and every frame transmitted in the channel. In the case of SU-MIMO transmission, it is possible to detect already from the VHT-SIG-A1 if the packet is meant for us [35], otherwise the confirmation is achieved in the beginning of the MAC layer packet detection. This can be used to reduce the on times, but typically the transmission durations are very short in WLAN due to the balance between packet error probability and retransmission cost, and therefore the achievable energy saving through sleeping in typical operation is not significant. Especially in a high traffic cell, the fraction of packets actually meant for the STA of interest can be very small, and unnecessary detection procedures are constantly required. In [15], the use of traffic indicator maps (TIMs) is defined to allow STAs to sleep between beacons and to wake up to read TIMs in the case AP has packets buffered for the STA. The downsides of using TIM for energy saving are increased latency in both DL and UL, increased beacon overhead which further increases the problem of beacon congestion in dense WLAN deployments, and the non-tunable operation and timing of the service.

A large fraction of the packets generated in the UL with web browsing, video streaming, skype, and browsing Facebook has been shown to be relatively short, with almost 80% of the UL data packets being less than 66 bytes long [54]. This indicates that there is a need for a CBDCH in the

5GETLA frame design, that allows UEs to transmit short data packets without asking for resource allocation. This would further reduce the latency in low and medium load scenarios and could significantly improve the QoS and QoE as the delays for short higher layer control packets are minimized. In addition, energy savings are achieved because the CBDCH would reduce the Tx/Rx activity times as UEs can avoid the time needed for resource allocation. The current LTE-A specification does not support this kind of unscheduled data transmission and in WLAN the overhead in transmitting these kinds of short packets can be up to 96% (assuming single OFDM symbol long data field with single spatial stream). In addition, the CBDCH provides means to support large quantities of asynchronous, low rate packet data typically generated in sensor networks or in certain industy applications.

As a final remark we want to emphasize the results of [48], which clearly indicate that the simulations for the 5G dense SCNs should not be made based on full buffer traffic, but mainly based on finite buffer traffic with fine tuned parametrization based on measured models for video streaming, web browsing and VoIP calls.

V. NEW RADIO INTERFACE FOR 5GETLA COMMUNICATIONS

When starting to design the new radio interface for enhanced 5G local area communications, we deploy the frame structure of LTE and OFDM symbol durations from WLAN as a starting points and seek for new symbol and frame durations that enable dynamic operation and short latencies, high EE and SE. For simplicity, we concentrate in this article on the single-input single-output (SISO) scheme. The MIMO support for 5GETLA is discussed in more detail in [57]. We assume that MIMO functionalities, beamforming, sectorization, etc. bring at least similar throughput performance gains as seen in LTE or WLAN 802.11ac. Due to the reciprocity of the TDD channel and very slowly changing channel with respect to the frame duration, we can expect even better MIMO and beamforming gains in 5GETLA than in macro FDD LTE.

The effect of antenna sectorization was considered already in [58], where the possible path of 4G was evaluated and FDD and TDD approaches were discussed. The advantages of TDD systems presented there, like channel reciprocity, dynamic traffic allocation, higher frequency diversity, unpaired frequency band allocation and lower hardware costs have not changed, as have not the main solutions proposed for intercell interference: synchronization, sectorization and time slot grouping (similar to our DL-Only and UL-Only sections in the beginning and end of each 5GETLA frame, respectively). On the contrary, our proposal for using flexible TDD for LA communications reduces the challenges related to DL/UL transition guard times, switching delays in MAC and (H)ARQ, and outdated CSIT, which were pointed out in [58].

The main target in this article is to define a completely new frame structure, including DLCRSs, downlink control channel (DLCCH), and DL data channel (DLDCH). The frame will also contain transition symbols for DL-UL and UL-DL transmission direction transition, UL control channel (ULCCH) and UL data channel (ULDCH), random access channel (RACH) for association and scheduling requests, and a variable sized CBDCH for small packet transmission with very low latency in low and medium traffic load scenarios.

TABLE 8. Main parameters for defining new radio interface.

Parameter	Value
F_B: Base frequency	30.72 MHz
F_s: Sampling frequency	92.16 MHz
T_s: Sample time	$1/F_s$
Δf_{sc}: subcarrier spacing	180 kHz
B_s: System bandwidth	100 MHz
α_{new}: Bandwidth utilization factor	0.9
T_{frame}: Frame duration	0.5 ms
T_{slot}: Slot duration	0.1 ms

A. PHYSICAL LAYER DESIGN CONSIDERATIONS

We start the physical layer design for 5GETLA by searching for proper FFT size and symbol time given the target slot and frame duration. The main assumptions behind the forthcoming numerology are provided in Table 8. We have chosen to use integer multiple of LTE sampling frequency as the sampling frequency of our new numerology. We believe that we should consider bandwidths significantly larger than 20 MHz for 5G LA communications and have chosen to study 100 MHz bandwidth. The frame duration 0.5 ms is chosen to clearly improve the RTT when compared to LTE-A and to achieve latencies below 1 ms. We have also divided the frame into 5 slots, each having duration of 0.1 ms. The slot based frame design allows us to do DL-UL allocation either by per slot or per OFDM symbol accuracy. We propose that DL-UL allocation should be redefined per frame basis and done with OFDM symbol time granularity. Per OFDM symbol accuracy improves the efficiency of the system but will slightly increase the amount of control bits needed to signal the DL-UL switch time.

In Table 9, we compare different options for FFT size with the given sampling rate F_s in 100 MHz system bandwidth. We use the first row of parameters from Table 9 as our reference design. We notice that with FFT size $N_{FFT} = 512$ and by allocating 17 symbols per slot, we obtain OFDM symbol times $T_{symL} = 544T_s \approx 5.90\ \mu$s and $T_{symS} = 542Ts \approx 5.88\ \mu$s, for the first (long) OFDM symbol and for the other symbols (short) in each slot, respectively. The symbol duration is now somewhat longer than in WLAN but *less than one-tenth of the LTE symbol duration*. The CP duration with the chosen numerology is now slightly shorter than the short CP in WLAN. Based on our survey on LA channel models, this CP length should still be adequate and combined with HARQ there should not be significant problems. In addition,

TABLE 9. Possible FFT-sizes, symbol times, CP lengths and other parameters for fitting new radio interface numerology to a 0.1 ms slot time.

N_{FFT}	T_{FFT} [μs]	Δf_{SC} [kHz]	$N_{active\ SC}$	$N_{symbols\ per\ slot}$	$T_{CP,L}$ [ns (samples)]	$T_{CP,S}$ [ns (samples)]	CP overhead [%]
512	5.56	180	500	17	347 (32)	326 (30)	5.6
512	5.56	180	500	16	694 (64)	-	11.1
1024	11.11	90	1000	8	1389 (128)	-	11.1
2048	22.22	45	2000	4	2.778 (256)	-	11.1

TABLE 10. Possible resource block sizes for new numerology assuming FFT size 512 and 17 data symbols per 0.1 ms slot.

N_{RB}	$N_{SC\ per\ RB}$	Min. allocation per RB BPSK,R=1/2 [bits]	Max. allocation per RB 256-QAM,R=5/6 [bits]
5	100	850	11333
10	50	425	5666
25	20	170	2266

a robust mode with longer CP, either using the same FFT size with only 16 symbols per slot or possibly $N_{FFT} = 1024$ can also be defined. Then the cyclic prefix duration is doubled or quadrupled, respectively. The longer cyclic prefix mode may also be useful in interference cancellation in the LA system (possibly enabling decoding and canceling signals from many transmission points), but this topic needs to be studied with further elaboration.

When operating in a low mobility LA environment with frames of duration 0.5 ms, it is obvious that the channel characteristics do not change during the frame. In addition, based on Tables 5 and 6, we know that the correlation bandwidth expected is rather large, so achieving significant frequency domain multiplexing gain by allocating several users per frame is difficult. In Table 10, we present different sized resource blocks (RBs), where resource block is defined as the smallest continuous frequency segment allocated per user. Notice that the actual allocation size in data bits per RB depends on the DL-UL allocation (time duration of DL and UL sections). In Table 11, we show an example of the achievable SNR gains over different sized allocations with different sized RBs. The results are obtained for WLAN 802.11ac channel model D in non-line of sight (NLOS) conditions, using carrier frequency $f_c = 2.4$ GHz and UE velocity 3 km/h. The results are averaged over 1000 channel realizations with time duration of 200 ms and time granularity of 0.5 ms. The FFT size used is 512 from which 500 SCs are active, corresponding to 90 MHz system bandwidth. We have evaluated the gain as the difference between average SNR over the full active bandwidth (90 MHz) and the best allocated resources. This example corresponds to allocating resources for one UE from the full bandwidth. The comparison is done for linear average and for geometric average (average of dB values). The first row of results indicates the maximum achievable gain if ideal SC wise allocation would be used. There is a clear trend of decreasing gain as the allocation size increases. The explanation is that as we allocate wider bandwidth for certain user we also have to include more SCs from which larger fraction has relatively smaller gains.

As seen from Table 11, there is only 2.6 dB loss in linear average between ideal SC wise allocation and using resource block size of $N_{SC\ per\ RB} = 100$ SC, assuming that we allocate 100 SC per user. Therefore, we propose to allocate from one to five users per frame with RBs of size 100 SC. This minimizes the overhead caused by signaling the used frequency allocations, because each user has a continuous frequency allocation of 18 MHz. Alternative solution would be to use RB of size 10 SCs and allocate each user 10 RBs. This scheme would lose in the best case only 0.6 dB to ideal SC wise allocation in the linear average SNR. The gain compared to RB of size 100 SCs is clear, but the signaling overhead would be ten times larger and also reporting overhead related to measured SINR distributions or interference statistics would be ten times larger. A good option is be to define multi-

TABLE 11. Achievable gain in average SNR (linear/geometric) per allocation versus the average SNR over system bandwidth with different RB sizes on WLAN 802.11ac channel D, carrier frequency $f_c = 2.4$ GHz, and UE velocity 3 km/h.

SNR gain (linear/geometric) [dB]	Total Allocation Size				
	10 SC/ 1.8 MHz	20 SC/ 3.6 MHz	25 SC/ 4.5 MHz	50 SC/ 9 MHz	100 SC / 18 MHz
Ideal per SC allocation	6.6/8.97	6.05/8.41	5.84/8.19	5.08/7.39	4.1/6.32
RB of size 10 SCs	5.72/7.79	5.26/7.29	-/-	4.42/6.34	3.55/5.33
RB of size 20 SCs	-/-	4.37/5.9	-/-	-/-	2.99/4.24
RB of size 25 SCs	-/-	-/-	3.91/5.24	3.43/4.67	2.78/3.87
RB of size 50 SCs	-/-	-/-	-/-	2.6/3.36	2.14/2.82
RB of size 100 SCs	-/-	-/-	-/-	-/-	1.52/1.91

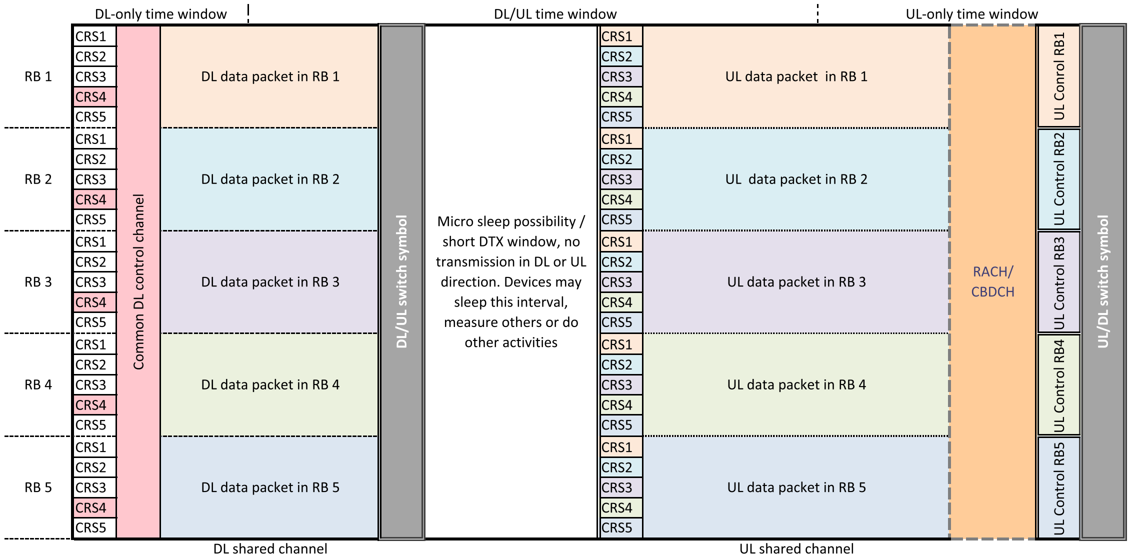

FIGURE 2. Frame structure example for the 5GETLA system.

ple control frame structures facilitating the use of different frequency domain scheduling accuracies depending on the environment.

Furthermore, because the frame duration is very short with respect to the channel time correlation, we can choose and keep certain frequency scheduling per user over several frames without additional signaling. The number of frames that certain scheduling is valid depends on the UE mobility and may be a design parameter (defined in a specification) or a system parameter (LABSs adjust). The effect of this kind of semi-persistent scheduling is open for further studies. Also, with the given parametrization it is possible to support 30 km/h mobility up to 60 GHz carrier or up to 200 km/h mobility at 10 GHz carrier, if we only consider the channel coherence time as a limiting factor. This provides additional tolerance for our design and enables easy extension to centimeter-wave carrier frequencies at 3-30 GHz.

B. 5GETLA FRAME DESIGN

1) DOWNLINK SECTION

Each frame starts with a DL-only time window, which starts with a DLCRS followed by the DLCCH, where both of the aforementioned entities occupy one OFDM symbol. In Fig. 2, example structure for proposed 5GETLA frame is provided. We propose that the used DLCRS would be spread in the frequency over the whole channel bandwidth based on certain reuse factor for the DLCRS. This allows LABSs to choose their DLCRS location based on the measured interference (if LABSs may hear each other) or then the network controller may choose best frequency slot for each LABS. This improves the simultaneous detection of multiple closest cells in UEs and provides channel measurement information over the full active band for UEs and for LABSs overhearing each other, assuming that LABSs have the possibility to occasionally measure the DLCRS and DLCCH of other LABSs.

In Fig. 2, the proposed DLCCH is shown as the first symbol after the DLCRS. If we assume that the control channel uses QPSK modulation and coding rate $R = 1/3$, we can fit 333 information bits in the single control channel packet. This is then divided for UE identifiers, block ACKs (BACKs) for the uplink data channel (ULDCH) of the previous frame, resource allocation, DL-UL allocation, MIMO mode, etc. An example of the possible content for the DL control packet is given in Table 12. Other parameters, that are assumed to change relatively slow with respect to the frame time (for example number of transmitter/receiver chains, total transmission power, etc.), can be transmitted in separate master information block (MIB), e.g., once in a 100ms. The timing of DL and UL BACKs are shown in Fig. 3. Each DLCCH contains BACKs for the ULDCH of the previous frame and each uplink control channel (ULCCH) contains BACKs for the DLDCH of the current frame. This kind of strict timing setup allows us to achieve physical layer RTT which is always smaller than the frame duration.

In Fig. 3 it is also shown how the computational burden shifts from LABS to UEs and vice versa as the DL-UL allocation changes. In frame k in Fig. 3, there are four UL slots (assuming slot based scheduling) which causes largest computational burden on the LABS. Then again in frame $k+1$ there are four DL slots, which shifts the computational load to UEs because they have to generate DL BACKs by the end of the frame. The existence of the DL-UL switch symbol and RACH/CBDCH channel in the UL section before ULCCH provides in minimum two short symbol durations of excess time for UEs to decode and detect DL packets. The LABS has currently more time to detect the transmitted UL packets due to UL-DL switch symbol and DLCRS, but LABS also has to schedule UEs for the next frame based on received information in the ULCCH so one can realize the challenges followed by these strict timing requirements.

TABLE 12. **Example content for the DL control field.**

Control field attribute	Bits/RB	Bits	Definition
Control field type	-	4	Defines control field type (reserved for future use)
RS Tx power	-	3	Defines the used RS Tx power used for cell breathing and for path loss evaluation in the UEs
DL end index	-	7	Last active OFDM symbol in DL
UL start index	-	7	First active OFDM symbol in UL
CRC	-	12	Cyclic redundancy check for DL control field
UL BACK indicator	16	80	Block ACK for all CWs transmitted in previous UL data packet per RB
UL CBD channel ACK	-	2	ACK for CBD channel for responding to possible CBD packets. Indicates also possible collision or successful detection of multiple packets
Detected RACH sequence index	-	30	Indicator for up to 5 simultaneously detected RACH sequences. Each LABS has a DLCRS that is associated with a set of RACH sequences used to identify associated and new users
Retransmission redundancy version	-	2	Redundancy version for retransmissions
UE/Group ID	15	75	Per RB, UE or Group ID used for scheduling to associated users, CBD packets with request for data allocation or for RACH indications. Group IDs used for DL/UL MU-MIMO transmissions
UEs per RB	2	10	Number of UEs served in DL/UL MU-MIMO per RB
STS per RB per UE	8	40	Number of space-time-streams (STS) per RB per UE (assumed max. 4 UEs served by max. 4 STS per RB)
DL MCS	4	20	DL modulation and coding scheme (MCS) per RB (same for all users in DL MU-MIMO)
UL MCS	4	20	UL modulation and coding sheme (MCS) per RB (same for all users in UL MU-MIMO)
Channel codec	2	10	Used channel coding per RB
Use SFBC	1	5	Indicator for using space-frequency block codes (SFBC) per RB
Time to sleep	-	4	Counter in frames or Master Frames to the start of the LABS network sleep
Sleep duration	-	2	Indicator for sleep duration. Values could indicate relatively long sleep durations, for example long frame duration, till next MIB or that sleeping pattern is distributed in the MIB. Indicating sleeping periods of a few frames are not seen important due to the good energy efficiency of the LABS

Because flexible TDD is used, we propose that the first slot or appropriate time window in the beginning of the frame should always be used only for DL transmission and last slot or appropriate time window in the end of the frame only for UL transmission. Even with OFDM symbol based DL-UL allocation division, we should fix certain number of symbols from the beginning of each frame for different RSs and for DLCCH. Fixing the direction of transmission in first and last slot protects them from DL-UL inter-cell interference (see Fig. 4). Therefore, they are perfect for transmitting critical system information, like control information, retransmissions, etc. or for serving cell edge clients. Optimizing the DL-UL allocation and DL-UL inter-cell interference between cells is an open problem for flexible TDD and an active research topic. For 5G LA communications, we believe that the *solution has to be based on decentralized cooperative DL-UL allocation*. One example solution achieving good performance with low rate signaling information exchange between BSs is presented in [59].

The DLCCH is followed by the downlink shared channel (DLSCH), which may contain the downlink data channel (DLDCH) and possibly downlink channel state information reference symbols (DLCSIRS) or downlink demodulation reference symbols (DLDMRS), as discussed in [57]. The DLCSIRSs are used for channel estimation to define precoders for MIMO transmission and DLDMRSs are used to estimate the effective channel with precoding. The DL section of a frame ends with the DL-UL switch symbol.

2) UPLINK SECTION

The UL section starts with ULCRS after the DL-UL switch symbol and possible idle period in the middle of the frame, as shown in Fig. 2. It is then followed by the uplink shared channel (ULSCH), which may contain the ULDCH and uplink channel state information reference symbols (ULCSIRS) or uplink demodulation reference symbols (ULDMRS). After the ULSCH is the combined RACH/CBDCH, in which random access sequences (RASs) are transmitted and possibly CBD packets, depending on the allocation size. If only one or two OFDM symbols are allocated for RACH/CBDCH, it is used only for random access. If the allocation is three or more OFDM symbols, then UEs are allowed to transmit also CBD packets in the channel. Each CBD packet has its own dedicated ULCRS to allow detection. The CBD packets have only one or a few allowed, robust MCS modes to ease blind detection. The RASs transmitted in the RACH are maximum length (≤ 542 samples) sequences with good correlation properties. These sequences are then divided to LABSs based on the DLCRS. Inside each LABS, the RASs are divided into two sets; one set for associated UEs and one set for UEs initiating an association process. This division allows LABS scheduler to know something about the forthcoming process following the RAS reception. In addition, distributing UEs with different RAS and RACH symbol index allows LABS to identify certain number of UEs directly based on the detected RAS. The random access sequences transmitted by UEs initiating an association are always transmitted in the same OFDM symbol. Furthermore, if the ULCCH would be located to be before RACH/CBDCH, the UL-DL switch symbol in the end of the frame would efficiently take care of propagation delays for RACH sequences transmitted without timing alignment (TA). If the ULCCH is located after RACH

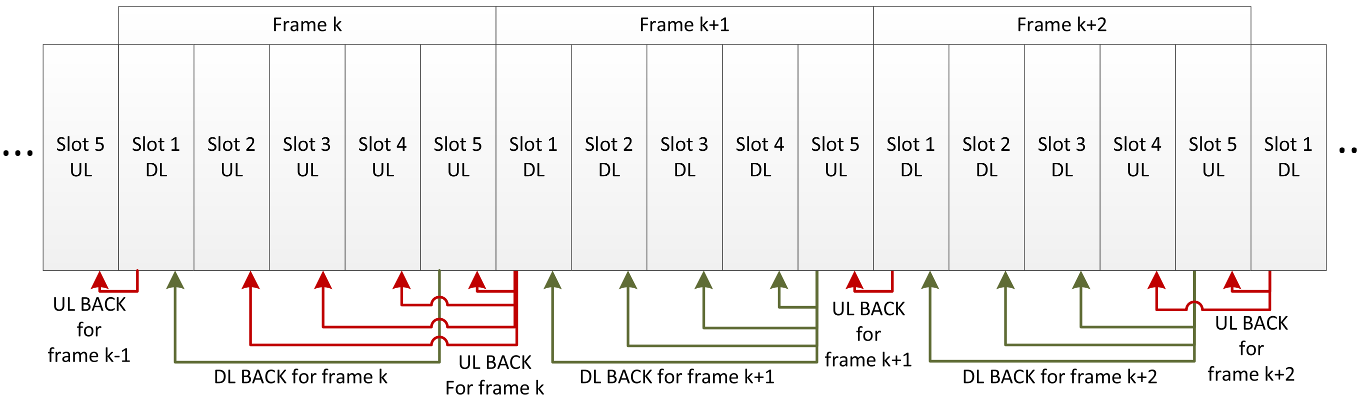

FIGURE 3. Time dependency example for the block ACK transmission with 5GETLA frame structure.

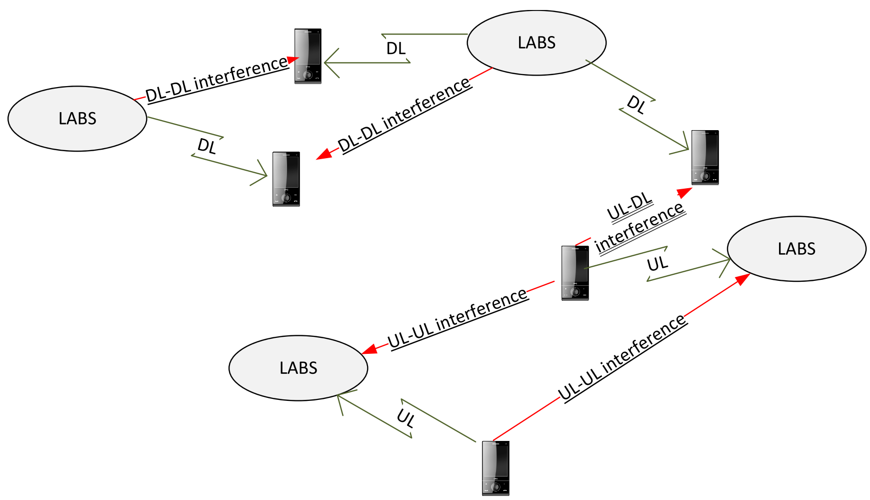

FIGURE 4. Interference types encountered in flexible TDD based networks.

channel, advanced signal processing is required to ensure the detection of ULCCHs.

The ULCCH is located in the end of the UL-only time window. This reduces the probability of destructive inter-cell interference on top of UL control fields and allows UEs to have more processing time to detect the DL transmission before generating the DL block ACKs (BACKs). The possible content of the UL control fields is described in Table 13. The UL control field is mainly for DL BACK, sleep indicators, buffer status, and possible robust feedback field. The ULCCH is followed by the UL-DL switch symbol which ends the 5GETLA frame. Having an empty symbol in the end of the frame eases the frame synchronization detection and provides LABS additional time to detect UL transmissions and schedule next transmissions.

3) ADDITIONAL DETAILS ON THE FRAME DESIGN

If we define that we always fill the frame with DL traffic starting from the first symbol and continuing in order toward the last symbol, we can derive collision probabilities per symbol if we have information on the traffic distributions. Also, based on the spatial location of the served UEs, we can decide what kind of DL-UL allocation we should use. We will discuss this topic further in Section VI.

TABLE 13. Example content for the per RB UL control field.

Control field attribute	Bits	Definition
DL BACK	16	DL block ACK. Max. 16 CWs per DL data allocation assumed
Sleep indicator	1	indicates that UE intends to sleep
Sleep duration	8	Number of frames that the UE intends to sleep (not reading frame headers)
UL important feedback type	8	UL control field may contain critical feedback information that UE wants to protect by the robust MCS, e.g, buffer status and indication for time critical higher layer data (like TCP ACK)
Important feedback	33	Possible extension for UL control. Contains the information defined by UE by UL important feedback type

In Fig. 2, we have also indicated how the idle in the middle of the frame can be used for micro sleep among LABS and active UEs. Especially the possibility to allow LABS micro, short and long sleep periods may be the most significant driver for energy savings in 5GETLA system. In [60], for reference, the effect of macro cell discontinuous transmission (DTX) was studied and they showed that 90% energy savings were possible based on a traffic measured from a typical European city. In addition to power saving possibilities, the micro sleep allows us to reduce the inter-cell interference on top of the center most OFDM symbols among the LA cells. Depending on the DL and UL time window definitions (which can be adjusted by each LABS based on the traffic and measurements on interference distributions), we can save up to 93% in the power consumption in low traffic cells with this kind of setup (assuming device has to be awake for 6 symbols per frame, DLCRS + DLCCH + DLDCH + ULCRS + ULCCH + ULDCH). Those UEs that wake up to read the control channel but do not find any transmission indicated for them may continue sleeping immediately after DLCCH. In this case the energy saving potentiality is up to 97%, as we can sleep 83 symbols out of 85.

To make the best of low latency frame design for 5G LA communications, the synchronization should be as fast as possible. The separate synchronization channel is discussed in Section VI-B, that is the main methods for UEs to detect and synchronize to LABSs. As a secondary synchronization method we propose to use the DLCRS. For this reason the DLCRS per LABS should a) identify the LABS with required accuracy (operator, access level, etc.) and b) have also good correlation properties. The first requirement allows devices to look only LABSs belonging to their operator or which are open for access independent of the operator. The second requirement would allow UEs to find and synchronize to the active cell without separate synchronization channel. Because the DLCRS is repeated with periodicity of 0.5 ms, it allows fast synchronization if the sequence is properly defined. A good candidate for the common reference sequence is the Zadoff-Chu sequence [61]. These sequences have good circular correlation properties and they have constant amplitude characteristics, making them applicable for both synchronization and channel estimation.

One important possibility for a TDD based system is the channel reciprocity. The transceiver hardware is not reciprocal, but can be calibrated with signal processing based solutions [62]. By the reciprocal nature of the wireless channel, the distortion experienced by the packet does not depend on which entity is transmitting and which receiving (LABS or UE). In our fast TDD design the channel reciprocity could be used for, e.g., DL beamforming transmission based on only received UL CSI-RSs and in scheduling of a new user as the RACH sequence is spread over the whole system bandwidth. For this reason in Fig. 2, the RACH extends over the whole system bandwidth. This provides LABS an initial channel estimate over the whole system bandwidth that can be used for scheduling decision. Transmitting RACH sequences and data on the CBDCH on top of each others is possible, because LABS can detect long RACH sequences with high probability and can perform interference cancellation to detect data from the CBDCH. Therefore, the data packets transmitted on the CBDCH should use some robust MCS, e.g. QPSK with $R = 1/2$ coding, for reliable detection. In addition, using predefined, robust MCS for the CBD channel eases the blind detection in the LABS side and alleviates detection of multiple simultaneous CBD packets if enhanced interference cancellation techniques are used.

In Table 14, we present some of the most important physical layer parameters that affect the systems performance in LA communications. We compare WLAN, LTE-A and 5GETLA in terms of these parameters and provide a short reasoning why we have chosen certain value for 5GETLA.

C. PERFORMANCE COMPARISON BETWEEN 5GETLA, WLAN 802.11AC, AND LTE-A

In Table 16, the different overheads present in each of the wireless communication systems are given for an example where one physical layer packet of size 50000 bits is transmitted. We present the overheads for two different modulation and coding schemes (MCSs), MCS0 and MCS9 taken from the 802.11ac specification [35], corresponding to BPSK with coding rate $R = 1/2$ and 256-QAM with coding rate $R = 5/6$, respectively. The results shown for WLAN include overheads caused by SIFS time and ACK packet. Therefore, for example, synchronization overhead contains twice the L-STF and VHT-STF fields. Note that we consider also the ACK payload as overhead.

We use the same MCSs for LTE-A and 5GETLA for comparison. We assume that we operate with system bandwidth of 100 MHz, which allows 802.11ac to use 80 MHz channel bandwidth, and LTE-A and 5GETLA full 100 MHz channel bandwidth. For LTE-A comparison, we have chosen TDD frame type with UL-DL configuration 5 (see Table 4), which has 10 ms DL-UL switch-point periodicity and maximum allocation for DL resources (8 DL, 1 UL, and 1 special subframe per radio frame).

For LTE-A, channel estimation overhead is defined only based on antenna port 0 RSs causing loss of four resource elements (REs) per slot. Note that in typical LTE-A BS there are at least two transmitting antennas, so the overhead in real LTE-A transmission would be bigger. Also, we chose to have only CRS pilots because minimum allocation with demodulation reference symbols (DM-RS) with single antenna port would cause larger overhead [64]. For WLAN, channel estimation overhead contains L-LTF, and VHT-LTF symbols and pilot carrier overheads. In 5GETLA, one OFDM symbol in reserved for DLCRS and ULCRS.

For LTE-A, the synchronization overhead is based on primary synchronization signal (PSS) and secondary synchronization signal (SSS), repeated twice in a radio frame. For WLAN, synchronization overhead contains L-STF and VHT-STF symbols. For 5GETLA, synchronization overhead is 0.1%, because separate synchronization channel is assumed, which is repeated every 100 ms. The synchronization channel is transmitted in a special frame

TABLE 14. Parameter comparison between 5GETLA and existing systems and short explanation why the parameter value is chosen.

Parameter	WLAN 802.11ac (80MHz)	LTE-A (100MHz)	5GETLA (100MHz)	Reasoning
FFT size	256	8192	512	Smaller FFT size improves robustness against frequency error and makes the system faster, leading to improved power saving possibilities and reduced latencies
CP/GI duration	400/800 ns	4.69/5.21 μs	326/347 ns	In local area environment with cell radius less than 50 m, it is very unlikely that CP longer than 400 ns is required. If so, new numerology may include a robust mode with increased CP duration for outdoor small cell operation
Frame duration	variable	10 ms	0.5 ms	Shorter frame duration allows 5GETLA to faster adapt its DL-UL allocation, leading to more agile flexible TDD service than LTE-A. In WLAN the frame duration depends on the PSDU size, which is typically made as large as possible to minimize the overhead caused by the PPDU preamble. The maximum duration for a PPDU is limited to 5.484 ms in 802.11ac
RTT	$\geq$120 μs & <6 ms	$\approx$ 10ms	<1 ms	One of the main drawbacks of using LTE in local area communications is the inbuilt latency (long RTT). In WLAN, we get response after a 16 μs SIFS time. In 5GETLA, the RTT is a compromise between control overhead and frame duration, but still always below 1 ms with current numerology, which is sufficient for most of 5G targets
RS interval in time	Start of each packet	$\approx$ 210 μs	DL:$\approx$0.5 ms, UL:$\approx$0.1 - 0.9 ms	Because the mobility in local area environment is very slow, we can easily allow DL/UL channel estimate updates only once per frame, or once per Long Frame ($T_{Long\ Frame}$ = 10ms)
RS interval in frequency	Every active carrier, except pilot carriers in VHT-LTF	90 kHz	1.8 MHz/ 0.9 MHz	Due to the short channel spread environment, for which 5GETLA is designed, it is sufficient to sample the channel in frequency domain with granularity of 2 MHz. Using 1.8 MHz (every tenth SC) sampling, we can achieve spectral reuse of factor 10 for the DLCRS transmitted in the beginning of each frame. For ULCRS we have assumed spectral frequency reuse equal to five (the number of RBs) is used to provide denser RS grid to allow the use of channel reciprocity for DL beamforming [63]
Synchronization interval	Start of each packet	40 ms	0.5 ms / 100 ms	The DLCRS sequence repeated in the beginning of each frame may be also used for synchronization, if properly designed. Through time averaging, UEs can quickly detect the LABS and synchronize to them based only on the DLCRS. In 5GETLA, we have assumed that the synchronization frame is transmitted every 100 ms
Control/ scheduling complexity	low	high	low	Following the ideology of WLANs very simple MAC, we have decided to limit the number of users per frame to 1-5 (4-20 with MU-MIMO support). This is sufficient to achieve some frequency domain scheduling gain and due to very fast frame structure, the average waiting time even in densely populated networks is very small. Furthermore, concentrating on frequency domain scheduling and noting long time correlation, the scheduling of users can be easily forecasted several ms to the future

containing also the MIB element. For more details, see Section VI-B.

For LTE-A, the control overhead contains one OFDM symbol reserved for physical control format indicator channel (PCFICH), physical downlink control channel (PDCCH),and physical hybrid ARQ indicator channel (PHICH), and 288 REs per radio frame allocated for physical broadcast channel (PBCH). For WLAN we include L-SIG, VHT-SIG-A, and VHT-SIG-B to the control overhead. With 5GETLA, we have included one OFDM symbol for DLCCH and for ULCCH per frame.

For LTE-A and 5GETLA one OFDM symbol is assumed to be used as a switching time from DL-to-UL or UL-to-DL. For LTE-A, we have assumed that the DL ACK is transmitted in the first UL slot available, noting the 3ms processing time requirement.

Examining now the results in Table 16, it is surprising to see how WLAN with MCS9, despite of poor channel utilization factor, can provide RTT 15-50 times faster than LTE-A. The 5GETLA system design achieves faster transmission times than WLAN but slightly loses on the RTT time due to the limitations of scheduled frame design. In Table 16, the channel utilization factor gives the fraction of the frequency-time resources used to transmit user data vs. the total used frequency-time resources. Thus, it measures how efficiently the system uses frequency and time resources for transmitting information. The channel utilization factor for LTE-A and 5GETLA is larger than for WLAN with both MCS, especially

TABLE 15. Example numerology related to transmitting 50 kbit packet throuhg each system assuming SISO scheme.

Parameter		WLAN 802.11ac (80MHz)	LTE-A (100MHz)	5GETLA (100MHz)
Bandwidth utilization factor		0.914	0.9	0.9
CP overhead (short/long)		0.111/0.2	0.066/0.072	0.055/0.059
Packet size		50000 bits		
MCS0	Data Tx duration (min/max)	1.581 ms	2/4 ms	1.27 ms
	Channel estimation overhead	0.0667	0.048	0.0235
	Synchronization overhead	0.0145	0.00034	0.001
	Control overhead	0.0193	0.072	0.0235
	SIFS+ACK overhead	0.0477	-	-
	DL-UL and UL-DL switch overhead	-	0.0143	0.0235
	Total overhead	0.316	0.278	0.214
	Channel utilization factor	0.684	0.722	0.786
	RTT (min/max)	1.66 ms	4/13 ms	1.5 ms
MCS9	Data Tx duration	0.159 ms	1 ms	0.1 ms
	Channel estimation overhead	0.145	0.048	0.0235
	Synchronization overhead	0.102	0.00034	0.001
	Control overhead	0.137	0.072	0.0235
	SIFS+ACK overhead	0.323	-	-
	DL-UL and UL-DL switch overhead	-	0.0143	0.0235
	Total overhead	0.785	0.278	0.214
	Channel utilization factor	0.215	0.722	0.786
	RTT (min/max)	0.234 ms	4/10 ms	0.5 ms

TABLE 16. Example content for the dl packet header field.

Packet header attribute	Bits	Definition
UL feedback type	10	UL data packet feedback may contain CQI measurements, interference statistics, etc.
UL feedback size	10	Feedback size in octets
Min. frame count to resource allocation	4	AP tells UE how many frames it may sleep before looking for resource allocation on the same RB, based on expected traffic on AP
Min. frame count type	1	Indicates if the frame count is linearly or exponentially increasing. Exponential increase allows larder delays between data allocations
Power control	2	LABS may command UEs to increase or reduce Tx power for improving the system capacity
Initiate measurement	1	Orders UE to start measuring metrics defined by measurement type
Measurement type	5	Indicator for the measurement type requested from the UE
Timing advance	6	Timing advance correction value for the UE. Initial value is defined based on the delay of the RACH indicator, and from there on this value is used to constantly adapt timing advance

with MCS9. If the transmitted packet would have been larger, the WLAN channel utilization factor could exceed both, LTE-A and 5GETLA, due to improved spectral efficiency as discussed earlier. Note that LTE-A and 5GETLA systems can serve also other users during the RTT time, where as WLAN can serve only one user. The proposed numerology for 5GETLA achieves 0.5ms RTT, which is only 2 times larger than with WLAN system.

Furthermore, if we assume that we would transmit 50 packets of size 50 kbits, which can be for the same user or for multiple users, we obtain clearer differences due to the improved spectral efficiency of 5GETLA. Even if we assume that WLAN could always transmit immediately after SIFS time (impossible in practice, although possible for short time periods if TXOP used in the AP [15, Clause 9.19]), it would take approximately 83 ms if all packets were transmitted with MCS 0, and 11.72 ms if all packets were transmitted with MCS 9. With LTE-A, it would take approximately 70-80 ms with MCS 0 and 8-20 ms with MCS 9. Finally, with 5GETLA, it would take only 63.5 ms with MCS 0 and 5 ms with MCS 9. As we aim for higher user densities, this simple example shows how 5GETLA can, in theory, significantly improve the throughput and latencies of the system, especially with small and medium sized physical layer packets. Furthermore, we were able to transmit information more than two times faster than ideal WLAN with no contention delay or collisions.

VI. SYSTEM LEVEL CONSIDERATIONS FOR 5GETLA

In this section, we discuss the benefits of new 5GETLA physical layer numerology design in general and from the higher layer perspective. Also, we try to indicate how the proposed flexible TDD design helps us achieving significant energy savings and how the reduced frame duration allows us to easily incorporate 5GETLA to existing LTE networks even when using the same operation frequency.

A. FLEXIBLE TDD

First of all, the flexible DL-UL allocation with OFDM symbol time resolution minimizes the non-useful active time of wireless radio chains, as LABS may push DL or UL packets through as fast as possible by modifying DL-UL allocation per frame. This means significant power savings for all devices in the network and also maximizes the time that LABS may spend in micro/short sleep modes. As shown in [65], for LTE pico cell power consumption, being able to sleep due to short inactivity periods in the time domain provides significantly better power saving possibilities than fractionally used frequency band.

In addition, flexible TDD allows LABS to serve users at different distance with different DL/UL allocation. In Fig. 5 we have depicted an example of how UEs at different distances may be scheduled to have different DL/UL allocations. In addition, we have considered the possibility to reduce the maximum Tx power per UE link *if it does not reduce the link throughput* (cause smaller MCS). Therefore, when the user penetration is sufficiently high, we can always select users with the similar pathloss for scheduling with certain DL/UL allocation.

Frames which include data for cell edge users are special cases. It would be in SINR sense optimal to allocate DL data only in slot 1 and UL data only in slot 5, but this would cause significant capacity loss in the system. Basically, we have two options for scheduling data in cases when we serve cell edge users. These are elaborated below.

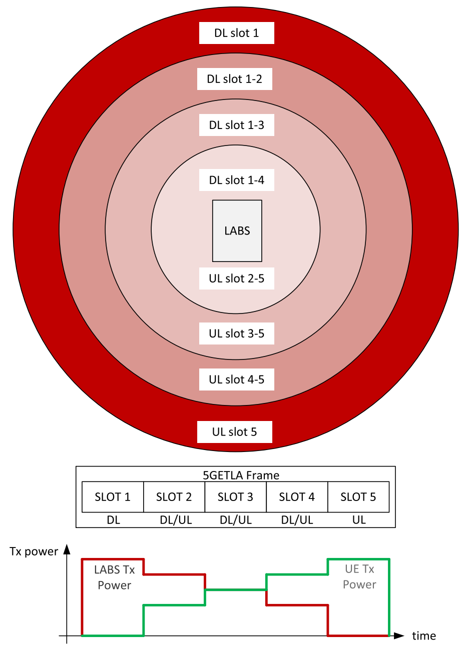

FIGURE 5. Example of the targeted transmission range per slot for DL and UL direction and used transmission power per slot.

First option is to choose any DL/UL allocation based on the cell edge users buffer status reports and accept that the middle OFDM symbols have higher probability to be lost due to inter-cell interference. If the system is designed in such a manner that the cell edge is defined as the distance where the lowest MCS barely works, then we cannot improve the collision probability. On the other hand, if the system is designed so that cell edge is defined based on some medium MCS achieving desired throughput for the cell edge users, we can use lower MCS for middle symbols which we suspect to suffer from inter-cell interference based on the interference statistics we have collected. This way, we could increase robustness for the middle symbols even for cell edge users and enable IC functionalities for symbols/slots under inter-cell interference. This would require an MCS indicator for which OFDM symbols/slots are assumed to be in risk for collision and use the robust MCS.

The other option is to have also time domain allocation in the scheduler, making it possible to allocate different resource blocks in different slots for different users. This could improve the scheduling gains achievable in semi-constant interference conditions, but the price would be constant increase in the control overhead. One solution is an optional mode, in which the scheduling is done only in the time domain. This would make the Tx and Rx times even shorter and ease the scheduling with respect to the UE distance from the BS. This way we would lose the frequency scheduling gain but could improve the experienced

SINR distributions. What is actually the optimal approach in hyper-dense SCN using flexible TDD in terms of overhead, scheduling flexibility, and achieved SINR distribution is still an open research topic. In any case, controlling the scheduling overhead is a critical design parameter as we aim to significantly reduce the scheduling interval and at the same time reduce the control plane overhead.

We believe that the best choice is to design the system to have cell edge based on reasonable throughput that is achieved with some medium MCS. This allows us to improve the robustness in the cell edge by keeping the lowest MCSs reserved for robust transmission, possibly combined with IC capabilities. In addition, if we are targeting high system level throughput design we have to ensure that the cell edge users have sufficient throughput, because the cell edge users are the ones that destroy system efficiency. Obviously, other low rate communications and parameter optimization could be performed based on principles of SON if the LABSs are so close that they can exchange information with the lowest MCS. Other lower rate over-the-air control channels are also possible, especially if implemented on different frequency band.

B. HIGHER LEVEL FRAME DESIGN AND CO-EXISTENCE WITH THE OVERLAY LTE-A NETWORK

The very short frame duration of 5GETLA allows us to significantly reduce the layer 2 RTT. This should significantly improve the reliability and operation of the higher layer protocols as the important packets do not have to wait tens or hundreds of milliseconds to be transmitted or retransmitted. Especially, the generally used transmission control protocol of the internet protocol (TCP/IP) [66] is sensitive to large variations in the experienced delays on receiving TCP segments. Missing part of a single TCP packet due to bad channel environment or interference burst can cause different timers to experience timeout and shift the TCP protocol to congestion avoidance mode. In the worst case, the TCP connection is assumed lost and a new connection establishment is required. In addition, the very short frame duration allows us to simplify the layer 2 control. For example, we can serve less UEs simultaneously and have simplified per UE HARQ processing when compared to LTE (optionally could even be only ARQ as in WLAN) which could lead to relaxed memory requirements as the number of simultaneous HARQ processes is reduced. It should be remembered that the complexity of the 5GETLA HARQ process should be compared to LTE-A with five 20 MHz channels, each channel having normal amount of parallel HARQ processes. Still, time distributed service in 5GETLA requires that the HARQ process states for multiple UEs are stored over certain time window, as new connections may be opened while pausing the transmission to certain UEs due to RACH indicators asking for association. Depending on the device class (similar to LTE device classes), we can define how many UEs the LABS can simultaneously support. Of course, scheduling algorithms should be defined to minimize the time spent on transmitting a MAC layer packet for certain UE or otherwise we lose the main target of the fast physical layer design.

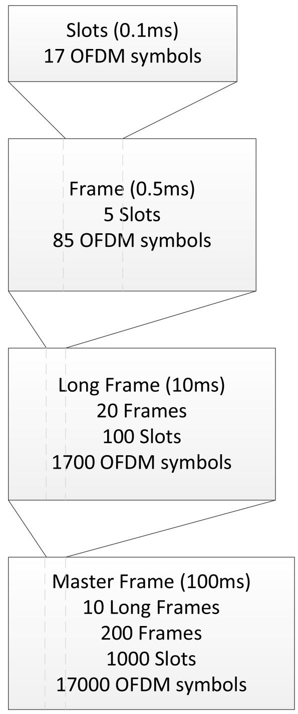

FIGURE 6. Frame hierarchy design example for the 5GETLA.

For interoperability with LTE and for higher energy saving potentiality we define two new higher level frame structures for 5GETLA, the long frame with duration of 10 ms and master frame with duration of 100 ms, as illustrated in Fig. 6. Now, because 5GETLA frame time duration corresponds to LTE slot and 5GETLA long frame duration corresponds to LTE radio frame, the intra frequency utilization of these two systems is facilitated. With the given numerology, we can fit two 5GETLA frames into a single LTE TTI. In a simple co-existence scheme the eNB schedules UL TTIs for the 5GETLA LABS, which can then use these time instances to transceive information in the LA cell. Also, because the 5GETLA RB allocation is now comparable to 20 MHz LTE channel, we can allow operation in a 5GETLA RB in the same frequency by muting one or more LTE subframes. Supporting partial allocation of the 100 MHz system bandwidth requires minor modifications to the DLCRS, DLCCH, ULCRS, and RAS definitions and could be implemented as an complementary operational mode.

We believe that with very high probability in most locations where 5GETLA system is used there will be an LTE-A macro coverage available. In addition, thanks to simultaneous connection to macro network there is no need for idle-state in the local area network. The devices are either in active state, reading control headers with predefined periodicity and connecting LABS only through RACH or CBD channels, or offline. The macro layer works as the backoff layer, providing the required service probability if the 5GETLA network is not available. This assumption is similar to the phantom cell concept introduced in [9], although we do not state that the control plane should be covered by LTE-A network. Defining an operation mode in which 5GETLA LABSs are connected to eNB with dedicated links and are responsible only of the UEs data layer is possible and could be desired in certain cases.

The master frame is defined based on the desired energy savings in the network sleep mode and based on the desired average synchronization/cell detection latency. We have chosen master frame duration of 100 ms, which corresponds to a typical beacon interval in WLAN networks. In each master frame one special synchronization frame is transmitted, containing synchronization channel and 5GETLA MIB. The 5GETLA MIB contains parameters that change slowly with respect to the master frame time, e.g., cell ID/SSID, is the cell public or private, total transmission power, number of active antenna chains, cell contention level, neighbor list, etc. In our design, the information contained in 5GETLA MIB is not required for starting association process through sending a RACH indicator to any LABS, but it contains information that reduces the amount of unnecessary association trials and can also be used to exchange information between LABS that overhear each others. During the association process, all other relevant information is exchanged through the data channel. The goal is to minimize the overhead caused by broadcast information, that does not change in time or changes with low probability or time periodicity. Broadcast information blocks such as system information blocks (SIBs) defined in LTE should not be used in 5GETLA. We believe that the LA system should provide high throughput data access and e.g. emergency information should anyway be received through overlay macro network or transmitted through dedicated user data in DLDCH to all users connected to a LABS. If UEs want to receive additional information from the operator or respective entity, they can request available information from the LABS through the data channel. The synchronization frame contains also synchronization channel, which has duration of 0.1ms (one slot) and contains multiple copies of the DLCRS to achieve high detection probability. The special synchronization frame would then be used in long sleep modes, in which LABS wakes up once per master frame and transmits synchronization channel and MIB and waits for a RACH indicator. If no response is detected, LABS sleeps another 99.5ms and tries again. If a RACH indicator is detected, the LABS has to wake up fast to be fully operational in the next frame. As a simple example, if the detection probability of the RACH indicator sequence is only 90%, in the next try it is already 99%, then 99.9% and so on. For this detection probability the expected detection time is still only ≈ 60 ms, assuming that the LABS wakes up every 100 ms to listen for RACH sequences.

C. ENERGY SAVINGS THROUGH VARIABLE SLEEPING PERIODS

Defining two different higher level frame structures also allows us to design short and long sleep cycles similar to LTE short and long discontinuous reception (DRX). In short sleep cycle UE would wake up every 10 ms (or less) to check for scheduled data. This level of sleep interval does not significantly affect the user experience but allows the UEs receivers to be active less than 5% of the time. In the long sleep mode, which would be the normal mode in which associated UEs are, the UE wakes up once per 100 ms to listen for scheduled DL transmission. In the case of UL activity, UE can be defined to wake up immediately to send small packet in CBD channel or to send a RACH indicator, or to wait for the next scheduled frame in which it will listen for DL allocation. These modes allow UEs to achieve significant energy savings with different average latency levels. In latency critical applications, UE would disable short and long sleep modes and utilize only micro sleep possibilities. By micro sleep we mean sleeping less than a frame duration, either during inactivity period in the middle of the frame or due to not detecting any scheduled data in DLCCH and not having anything to transmit in the UL.

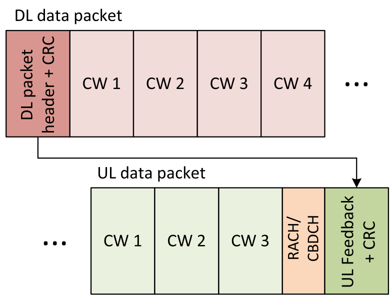

FIGURE 7. Example of the data packet structures inside one resource block including multiple code words (CWs), which are the retransmitted elements in the HARQ process. Also, how the DL packet header defines the feedback type and size used in the UL is illustrated.

One significant improvement achieved by using a synchronized system for LA communications when compared to WLAN is the better support for long sleep durations for both UEs and LABSs. By informing all associated UEs of the coming sleep period with long frame or master frame duration, the scheduled system allows better QoS than WLAN. In addition, the sleep modes may be used with higher user densities than in WLAN. LABS can decide the sleep duration based on the recent traffic activity/distributions.

In Fig. 7 and related Table 16 we show an example how the DL data packet header further defines the UL feedback type and indicates the served UE the maximum sleep time before next resource allocation. The DL data packet header is used to convey all the information related to the active link that is not required for the detection of the packet or does not have to be broadcasted for all UEs. The target is to divide the control into two layers, to the broadcasted DLCCH and to the per UE DL packet header. This allows us to reduce the broadcasted information and provides additional flexibility in defining different sized DL packet headers to support advanced reporting and parametrization. The sleep command in the DL packet header allows UEs to initiate sleep mode as soon as the BACK has been received in the next DLCCH.

During inactivity periods, the LABS can also decide to sleep over a short or long cycle. LABS has to inform all associated UEs of the coming sleeping cycle(s) and this takes 100ms if all the UEs wake to listen once per master frame. There is no system design limit how complex sleeping pattern the LABS chooses to perform. One example is to broadcast a bitmap with given time resolution of the future sleeping pattern of the LABS in the MIB. Note that LABS sleeping reduces the DL-DL interference (see Fig. 4) especially on DLCCH and DLDMRS and DLCSIRS. Automated sleeping may provide significant improvement on the system performance and is open for further studies. Also, in the 3GPP community the possibility to switch small cells on/off has gained interest recently. In [67], a large set of simulation results in different scenarios with different cell on-to-off and off-to-on times are presented. As a summary, these results indicate that large gains are available for energy efficiency (measured as active subframe ratio) and also for user-perceived throughput when compared to baseline where small cells are always on. The gains are generally larger for faster on-off and off-on switching times. In WLAN, the AP sleeping is not well supported and the continuous transmission of beacons by all APs, even those with no STAs in the BSS, causes significant congestion in the radio channel, increasing interference on dense deployments and reducing achievable throughput in those BSSs where active STAs are located.

D. CONTENTION BASED DATA CHANNEL

When considering the benefits of CBDCH, an example for the significant gains obtained by it can be seen if we consider the LTE uplink, which is fully scheduled. If we assume that we would have a relatively small packet to send in UL, for example 100 bytes, then we could just send it in 5GETLA in low or medium traffic load scenarios through CBDCH and receive an ACK for it in less than 0.5ms. Then again, in LTE UL we have to send scheduling request through physical layer uplink control channel (PUCCH), which takes 1ms. Then we have 3ms processing time in the eNB after which during the next 1ms we get the DL grant. Then we have 3ms processing time for the UE after which we can transmit the UL packet during the next 1ms. Then, again 3ms processing time waiting before we get the HARQ feedback. In total, 13 ms RTT and in the worst case, we may not fit the full UL packet to the scheduled UL allocation. Therefore, providing a CBDCH with sufficient resources for low and medium traffic load scenarios may provide significant latency gains for the short packets, that dominate the UL traffic [30], [31], [54]. Also, the simplicity and low latency of WLAN systems shows the potential of contention based access for low and medium loads. Signaling is important to achieve collision free channel for large data chunks, but in the case of small sporadic packets the signaling easily becomes unnecessary overhead. Instead of sacrificing energy and time-frequency resources for signaling the forthcoming short packet it is probably more energy efficient to directly transmit the small packet with robust MCs. For CBD data the average success time is important metric. For example, if there is a 70% probability to get the packet through per frame, the average time spent to achieve 99.9% reliability is ≈ 0.462 ms, assuming that there is average delay of 0.25 ms to the first transmission trial. It should also be clear that if the traffic is saturated in the cell, corresponding to the full buffer scenario, there is no point in reserving valuable resources for the CBDCH. In this case all UL traffic would be fully scheduled by the LABS. This increases the minimum achievable latency, but also increases the system capacity. This is a topic that has achieved relatively small amount of attention and additional research for future enhancements is required. With the proposed frame design for 5GETLA, assuming association indication at the end of first frame, RACH ACK and UL allocation in the next frame and UL ACK in the beginning of third frame would mean that the UL packet can be transmitted with 1 ms delay from the RACH indicator to the UL ACK.

E. CHANNEL QUALITY INDICATORS AND INTERFERENCE STATISTICS

As discussed in the Section IV-A, the frame duration is short when compared to the channel correlation times. This means that the channel quality indicator (CQI) reporting interval may be once in a long frame. Indicators related to interference conditions should be based on longer term statistics, e.g. time and power distributions and not trying to present the instantaneous interference conditions, because it is impossible. Furthermore, frequency domain allocation (chosen RBs) are valid over several frames which may be used to reduce the scheduling overhead.

As mentioned, it is impossible to predict the exact instantaneous per UE SINR environment due to bursty nature of the traffic generated by the interfering UEs in a flexible TDD based network. Therefore, we should not waste any resources on these kinds of methods but rather design the system to tolerate collisions and measure, collect, and report most relevant parameters and distributions related to the experienced interference during a certain time window. This topic requires more analysis as we have more information on the expected traffic protocols and their traffic distributions and on the expected user densities.

F. COMMENTS ON FULL-DUPLEX AND D2D

The 5GETLA system design supports naturally full duplex communications that has been recently shown to be viable solution for WLAN communications [68]. Especially LABSs could improve the throughput by adapting full duplex communications for the center slots in the frame because it would allow the LABS to transmit and receive information at the same time, in the same frequency, and in the same spatial location. Full duplex could be first introduced for LABSs and later on possibly for UEs. The only requirement for full duplex is to define per UE different DL-UL allocation and possibly overlapping RBs, again requiring a new control frame with modified fields to provide the full gains of full duplex operation. In this case, the control overhead would probably increase. Depending on the scenario, full duplex systems probably require also more signaling overhead, so the actual benefits of full duplex remains to be solved. In addition, full duplex can be used to detect changes in the local interference environment during the transmission and this way allow simultaneous adaptation.

In addition to the prementioned benefits, 5GETLA allows the use of system controlled and ac hoc low power device-to-device (D2D) links. In the system controlled D2D links, LABS orders two or more UEs in the close proximity of each others to directly connect each other using transmission powers and time and frequency slots defined by the LABS. The benefit of system controlled D2D links is that LABS may use spatial multiplexing by beamforming or physical antenna sectorization to direct its own DL-UL links to different part of the cell, as non-disruptive location as possible, as the D2D link is active in some other part of the cell. System controlled D2D links could also be used to order UEs from different cells to exchange measurement information for cooperated optimization of system parameters. In addition, for 5G networks different levels of caching are considered [69] to ease the traffic loads in the backhaul network. Enabling D2D communications between devices which can share content from their local cache may provide significant improvements in the experienced delays.

Low power ad hoc D2D links could also be enabled by UEs that detect a known UE in the close proximity. UE wanting to establish D2D link would start to act as a low power, low class LABS and could directly connect the desired UEs nearby. By using low power connection the range and interference area are reduced. Still, with distances less than 10 meters and by using low transmission power like 10 dBm combined with MIMO transmission significant throughput is achieved and exchanging information should be fast and easy, as long as we note that the reliability of low power ad hoc connection can not be guaranteed to be on the same level as with system controlled D2D links.

VII. CONCLUSIONS AND DISCUSSIONS

In this article, we have first provided an overview of the current WLAN and LTE-A radio interface parametrizations. Then, motivated by the short-comings of these existing systems, we have introduced a new physical layer numerology called 5GETLA, a future enhancement for 5G local area communications using flexible TDD and OFDMA that can improve the QoS and QoE when compared to WLAN and significantly reduce the latency when compared to LTE-A, and improve the spectral efficiency when compared to either wireless access scheme.

We have indicated that significant energy savings are possible due to reduced duty cycle in the proposed 5GETLA system. Especially, the different sleep modes for LABSs can significantly reduce the energy consumption of 5GETLA system compared to LTE-A and WLAN, and allow LABSs to sleep with average cell access delay half of the master frame duration. Reduced energy consumption allows higher LABS density when compared to current solutions. The careful design of location of DL and UL RSs allows LABSs and UEs to sleep maximal fraction of the frame for enhanced energy conservation.

The design, in which we aim to minimize the active times of Tx and Rx chains by minimizing symbol and frame durations, allows us to greatly enhance the system energy efficiency, but also leads to clear reduction in the physical layer latencies. Reducing physical layer latency to 0.5 ms allows us to achieve 10-26 times faster RTT when compared to LTE-A. In addition, the user QoE can be expected to improve significantly as we can provide high throughput with low latency. With 5GETLA design, the radio interface becomes more transparent for the higher layers and delays are mainly generated by buffering on the trunk network side and in the higher protocol layers of 5GETLA devices.

To further reduce average energy consumption and latency, the per frame DL-UL allocation adaptation enabled by the flexible TDD was used and control structure supporting this functionality was designed. Control overhead has been carefully considered to avoid spectral efficiency decrease due to the shortened frame duration. Also, the scheduler complexity can be relaxed by scheduling only a few users in frequency domain and possibly fixing the frequency allocations for several frames. Furthermore, the selected flexible TDD design allows us to predict the probabilities of collisions with certain DL-UL allocations. We believe that going from interference avoidance to system design in which inter-cell interference is allowed but we minimize the probability of destructive interference (loss of packets) will eventually lead to better throughput with significantly lower signaling overhead. In addition, we believe that some level of cooperation between neighboring small cells is required to locally optimize the DL-UL inter-cell interference.

As discussed in Section VI, in high load scenario the 5GETLA performance depends mainly on the scheduler design and the number of available degrees of freedom, affected by, e.g., sectorization, LABS cooperation, MIMO mode, etc. For saturated scenario, corresponding to traditional full buffer approach, the optimal solution is to fix the DL-UL allocation based on the average traffic demand as is done in the macro layer.

In 5GETLA system design we incorporate the accumulated knowledge we have collected from small cells, LA channel environment, and traffic distributions to optimize the radio interface and provided guidelines for future designs to achieve energy efficient LA radio interface. Special care has been given for latency and energy saving possibilities in which both LABSs and UEs are capable to sleep various time intervals. WLAN and LTE-A are both excellent pieces of engineering and do well in the environments to which they are designed. But, by combining the best of both worlds, we can design substantially better LA system that could be part of the solution to provide high QoS and high throughput for high user density and traffic loads. In other words, 5GETLA is an essential part of the solution for future 5G LA communications and the 1000× data challenge. Thus, the fast 5GETLA frame structure introduced in this article for future LA communications is not just another radio interface, it is the solution dictated by the environment in which we operate and enables the highest efficiency in high user density and traffic loads.

The finalized future solutions and system architectures are eventually results of thousands of engineering work-years. One purpose of this article is to catalyze the technical and scientific discussions and work towards future enhanced local area connectivity solutions with better optimized radio interface to small cell communications, compared to current 3GPP LTE/LTE-A which is still stemming from macro cells and large mobility.

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