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Abstract—**In parallel with ongoing standardization of third generation partnership project (3GPP) Long Term Evolution – Advanced (LTE-A), also referred as 4G, the discussion on next generation beyond 4G (B4G) radio access technologies is already active. Purpose of B4G system, expected to be available in 2020, is to cope with the exponential increase of mobile data traffic. In this paper we analyze the feasibility of LTE-A and wireless local area network (WLAN) physical frames against B4G requirements and discuss how the B4G environment, radio channel properties and evolved component technology affect the design of the physical layer frame. We analyze the B4G physical subframe numerology including aspects such as time division duplex (TDD) switching time and cyclic prefix (CP) duration. The proposed numerology allows to design a B4G-optimized TDD physical subframe structure which further enables reaching the very tight physical layer round trip time (RTT) requirements.**

Index Terms— **Beyond 4G, TDD, OFDM, cyclic prefix, guard period, frame structure**

I. INTRODUCTION

While Long Term Evolution – Advanced (LTE-A) development continues strongly within 3GPP Release 11 and 12 standardization, the discussion on a Beyond 4G system (B4G) has also been opened recently [1][2]. The requirements for B4G radio access technology are assumed to be ~10 times better than in the current LTE-A generation. Round trip time (RTT) on the order of 0.1 – 1ms is considered as the initial RTT target for B4G systems [3]. Moreover, an approximate 10 times increase in the number of mobile subscribers with up to 100 times higher data traffic per user is expected.

The need for higher capacity requirements can be met by using more frequency spectrum, boosting the spectral efficiency and, most importantly, increasing the number of cells [2]. Since most of the data traffic is expected to be generated by indoor subscribers, the focus is in increasing the number of indoor cells (e.g. femtocells) operating on a dedicated spectrum. Indoor cells are further restricted compared to outdoor cells, with restrictions such as lower output power, higher carrier frequency and higher sensitivity to wall and floor penetration. This leads to very dense femtocell deployments with very limited coverage per cell.

There are several advantages in using TDD over frequency division duplex (FDD) when considering local area (LA) and B4G focus. The amount of available unpaired TDD spectrum is larger, radio frequency costs are smaller and TDD properties such as reciprocity and good uplink (UL)-downlink (DL) scalability can be utilized efficiently to create link-independent air-interface and access scheme. Thus, we consider TDD to be the most feasible duplexing method for B4G LA purposes and focus on half-duplex TDD for the rest of the analysis.

Orthogonal frequency division multiplexing (OFDM) [4] is the proposed modulation in B4G [2] since it enables simple one-tap equalization at the receiver, as well as straightforward extension to multiple input multiple output (MIMO) antenna techniques, good latency and cost effectiveness.

The focus of this paper is on a stand-alone indoor local area B4G system design and its impact on physical layer TDD subframe numerology. Main motivation for the physical layer TDD latency analysis and design is the tight B4G RTT target of ~1ms. Physical frame structure and related numerology are dependent not only on surrounding radio channel properties but also on component technology. The design of existing LTE-A and wireless local area network (WLAN) frames are presented and their feasibility in B4G environment is analyzed. We carefully examine how indoor LA environment, B4G radio channel properties and evolved component technology affect the B4G physical frame numerology and analyze parameters like TDD guard period (GP) and cyclic prefix (CP).

The paper is organized as follows. In Section II we briefly present main parameters affecting the OFDM TDD frame design. A brief introduction of the existing TDD LTE-A and WLAN frame structures is given in Section III. In Section IV an overview of the main characteristics of B4G local area indoor environment together with evolved component technology is presented, as well as our analysis of the new B4G related frame numerology. Section V concludes the paper.

II. CRITICAL PARAMETERS FOR OFDM BASED FRAME DESIGN

In TDD mode, the same frequency band is used for UL and DL transmission, but in different time instants. A time guard

period (GP) between a transmission direction switching should be allocated with two main goals:

1) obtaining a sufficient off power of the transmitter for avoiding power leakage in the receiver chain,

2) compensating propagation delay and delay spread towards the receiving devices before they switch to transmission mode.

The GP represents a system overhead and the effective values of the elements which determine its length should be then carefully evaluated.

The first factor affecting to the GP length, T_{GP}, is the radio channel environment. First of all, GP needs to compensate for channel delay spread, T_{CH_ds}, interpreted as the arrival time difference between the earliest significant multipath component, typically the line-of-sight component, and the last significant multipath component. In the following we consider root-mean-square (r.m.s) delay spread, meaning the standard deviation value of the delay of reflections, weighted proportional to the energy in the reflected waves. In macro-cellular mobile radio environment, delay spreads are mostly in the range from ~100ns to ~10µs whereas in indoor and micro-cellular channels the delay spread values are usually smaller and rarely exceed a few hundred nanoseconds [5]. The filter response time to delay spread in transmitter and receiver, T_{HW_filter}, needs also to be compensated by GP. In addition to the delay spread, GP needs to compensate for the propagation delay in the radio channel, T_{CH_prop}, dependent on the cell size.

In addition to the channel delays, also the hardware delays of devices need to be compensated within GP time. In a TDD device, the receiver may be interfered by the transmitter since the power amplifier has ramp-on and ramp-off delays. The one direction hardware TDD switching time, T_{HW_switch}, consists of the time required to achieve proper ON/OFF power level. It includes the rise or fall time and so called gate lag time and it needs to be considered in both the sending and receiving device. The fall time is the time needed by the device to switch from 90% to 10% nominal power (vice versa for rise time) and it is in the range of less than 1µs in the current switches. The gate lag time is the time needed to switch from the last 10% nominal power to adequate near-zero level. In the current switches the time required to go from the 10% to 2% for instance is in the order of 20~200µs.

Taking all the components presented above into account, time needed for GP can be estimated as

$$T_{GP} \approx T_{CH\_ds} + T_{CH\_prop} + T_{HW\_switch} + T_{HW\_filter}. \qquad (1)$$

In OFDM systems inter-symbol interference (ISI) and inter-carrier interference (ICI) due to time-dispersive channel propagation is prevented by allocating a cyclic prefix (CP) to each OFDMA symbol. The CP duration is designed so that it exceeds the delay spread in the environment where the system is intended to operate. In a real channel environment the power delay profile (PDP) of the received signal often follows an exponential decay function; our design criteria can be then related to the amount of remaining energy in the tail of the PDP which is tolerated to interfere with the next symbol. In addition

to delay spread, the impact of transmitter and receiver filters needs also to be taken into account in the CP design. Also, CP design is sensitive to timing errors in the cell and synchronization mismatches can move parts of the symbol data outside the CP causing ISI and ICI degradations. For instance, in cellular systems a timing advance (TA) procedure [6] ensures that the signals sent by multiple user equipments (UEs) are aligned within the CP duration at the base station, by adding a timing offset related to the specific UL propagation delay. In case such procedure is not used, the time uncertainty due to the propagation delay needs to be compensated within the CP. Since UE is synchronized to DL signal, this time uncertainty can be estimated as a two-way propagation delay. The total time needed for cyclic prefix, T_{CP}, can then be estimated as

$$T_{CP} \approx T_{CH\_ds} + 2 \cdot T_{CH\_prop} + T_{HW\_filter}. \qquad (2)$$

III. PHYSICAL FRAME STRUCTURES OF TDD LTE-A AND WLAN

The physical layer of a radio access system plays a key role when comparing different systems in terms of expected performance. Physical frame structure sets hard limits to parameters like DL/UL switching periodicity, DL/UL ratio and consequently to the physical layer RTT.

A. TDD LTE-A frame structure

3GPP LTE-A [6] standards cover both FDD and TDD modes of operation in the same set of specifications. These modes have been developed together and harmonized so that both operation modes share the same underlying framework including e.g. radio access schemes, fundamental subframe formats, configuration protocols, architecture and procedures. The main differences between them are related to physical layer and the related parameter control on medium access control (MAC) and higher layers. Physical layer differences are mandatory due to transmission direction switching operation in TDD mode. The need to support several adjustable TDD UL/DL configurations and coexistence requirement with other TDD systems has led to a few additional physical layer features exclusive to TDD mode [7]. One of the most fundamental TDD features is the specific TDD frame structure with the introduction of the special subframe.

TDD LTE-A frame, presented in Figure 1, has been built on top of the LTE frame structure type 2 [8]. Subcarrier (SC) spacing of 15kHz leading to OFDM symbol length of 66.7 µs is used. Each radio frame consists of ten subframes of 1 ms duration. DL/UL switching with certain switching timings is included in the frame structure in the form of the special subframe. There are three fields in this special subframe: DL pilot time slot (DwPTS), GP and UL pilot time slot (UpPTS). The length of each field may vary within the special subframe depending on the supported cell size and co-existence requirements with other TDD systems. Different supported special subframe configurations are presented in Table I where the lengths of different fields are given in multiples of OFDM symbols. GP time includes sum of the switching times of both

switching directions (DL-UL and UL-DL). The switching time division between these two switching points is adjusted by enhanced nodeB (eNB) with TA commands.
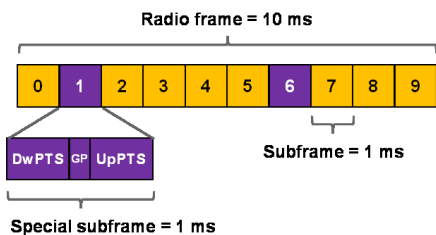

Figure 1. LTE-A TDD frame structure

TABLE I.   LTE-A TDD SPECIAL SUBFRAME CONFIGURATIONS WITH NORMAL CP

Format	DwPTS	GP	UpPTS
0	3	10	
1	9	4	
2	10	3	1
3	11	2	
4	12	1	
5	3	9	
6	9	3	
7	10	2	2
8	11	1	

Special subframes are utilized to provide support for two switching point periodicities, namely 5ms and 10ms. Subframe 1 is always assigned to be a special subframe providing 10ms switching periodicity. In addition, also subframe 6 may be assigned as special subframe leading to 5ms switching periodicity. Other subframes in the frame are regular DL or UL frames. Subframes 0 and 5 contain synchronization signal dedicating them as DL subframes whereas subframe 2 is always dedicated to be UL subframe. Regarding the rest of the subframes the UL/DL ratio is adjustable according to Table II.

TABLE II.   LTE-A TDD UL/DL ALLOCATIONS

UL/DL configuration	Switching periodicity	Subframe									
		0	1	2	3	4	5	6	7	8	9
0		D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2		D	S	U	D	D	D	S	U	D	D
3		D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5		D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

Like in FDD LTE-A mode, also the TDD radio frame structure has been optimized for wide area scenarios. This is evident in the TDD LTE-A numerology; for example, minimum CP duration of 4.7μs, minimum GP length of 1 OFDMA symbol and minimum TA adjustment value of 20.3μs. It also has to be noted that, as a result of harmonization of FDD and TDD specifications, there is not too much TDD optimization in current TDD LTE-A. In TDD mode the latency performance including delays due to hybrid ARQ (HARQ) acknowledgements (ACK) [6] is clearly worse compared to

FDD and varies according to link direction, UL/DL configuration and the subframe number, whereas in FDD mode the air-interface latency is fairly constant with comparable number of HARQ retransmissions [6]. Another issue related to the current TDD LTE radio frame structure is that UL/DL switching ratio can be adjusted only in limited manner. This was already visible in Table II where the UL activity can be adjusted only between 20% and 60% (disregarding UpPTS). Ideally UL/DL traffic adaptation should be fully dynamic without any limitation in the UL/DL ratio. Also the UL/DL switching restriction of 5ms at minimum can be seen as a hard limit for the latency in TDD LTE-A.

B. High Throughput WLAN frame structure

IEEE 802.11ac is a wireless LA standard under development providing high data throughput for 5 GHz band. Although this standard will increase the data throughput of the previous WLAN systems [9][10] by exploiting additional features such as mandatory support for 80MHz bandwidth (extendable up to 160 MHz) and increased number of spatial streams, the basic frame structure will follow closely the one presented in the IEEE 802.11n standard.

Standard OFDM symbol in 802.11n has 4μs duration, comprising of 3.2μs data part and 0.8μs guard interval (GI). In order to improve the data rate of the system, also a short GI of 0.4μs was introduced in IEEE 802.11n. GI in WLAN corresponds to CP in LTE-A systems, comprising a copy of the last 0.8μs or 0.4μs of the data part of the OFDM symbol.

The WLAN systems are based on carrier sense multiple access with collision avoidance (CSMA/CA). Basically, each station senses the medium for a period of time defined as distributed coordinated function (DCF) inter-frame space (DIFS); in case the medium is idle the station can take the ownership and begin a frame exchanging sequence. The short inter-frame space (SIFS) is inserted between successive frames. In that sense, SIFS can be considered as the minimum sensing and TDD switching time requirement defined in WLAN standard. In 802.11n, the duration of SIFS is set to 16μs. As the duration of DIFS has been defined to be SIFS + 2×SlotTime, it allows the station owning the medium to finish the transmission sequence without interruptions from the other stations. The principle of DIFS and SIFS timings is shown in Figure 2. It has to be mentioned that a mandatory ACK message has to be transmitted after SIFS before the transmission of the following data frame can begin. This increases the total latency of the WLAN system. However, in WLAN systems, the UL/DL ratio is not restricted due the frame structure, as the access points (AP) participate in CSMA/CA along with the UEs.

Figure 2. WLAN guard times

IV. B4G CHARACTERISTICS AND TDD NUMEROLOGY

In B4G scenario, we foresee a large deployment of small indoor cells working in dedicated spectrum. Optimization to

B4G specific radio channel environments together with evolving component technology will impact the design of the radio technology and the physical frame numerology, aiming to reach the tight B4G RTT requirement of ~1ms.

A. B4G radio channel properties

The primary causes of signal attenuation and fading in the radio channel are cell radius, multipath propagation and penetration losses through walls and floors. Higher carrier frequencies used in indoor environment also lead to higher pathloss values. In LA scenario, the propagation delay in the radio channel decreases drastically compared to macro cells. The size of a typical LA cell is anticipated to be around ~50m corresponding to propagation delay of about 170ns. Short propagation delay implies that precise timing control procedures ensuring the concurrent reception timings of users with different propagation delays, such as TA, are not needed. Getting rid of TA allows faster cell change and initial access.

In indoor cells multipath waves tend to arrive in clusters so that the delays between clusters are relatively large but the different paths within one cluster have quite small delay separation. Comparing to outdoor or macro cells the typical r.m.s. channel delay spreads of LA indoor channels are much shorter, typically less than 100ns for office premises and less than 50ns for home environments. As the delay spread of the channel gets smaller, the impact of the transmitter and receiver filtering to the overall length of the impulse response becomes significant. The filter response to delay spread in radio channels with small delay spread is estimated to be ~50ns.

There are also power and power spectral density restrictions in indoor cells. Output power levels should be kept low, both due to power saving and energy efficiency requirements of B4G and emission regulations.

B. Component technology enhancements

In addition to radio channel properties, the component technology development needs to be considered in the design of physical subframe structure. The lower output power requirements in B4G devices allow decreasing the time required to achieve proper OFF power level, thus decreasing the switching time. On the other hand, the sensitivity of the devices may improve in the future, and this can lead to a lower OFF power value. There is already some evidence of the rapid component evolution available, for example MASW-009590-000DIE [11], a new wireless LA network (WLAN) switch, provides already rise/fall times of 13ns and gate lag of 27ns resulting in <60ns total switching time. In [12] it has been shown that by proper device design together with optimization of semiconductor fabrication process, gate lag times less than 20ns can be achieved. Consequently, it is reasonable to believe that low gate lag switches will be broadly available in products in 2020, supporting low TDD switching times.

The digital signal processing performance is expected to increase according to Moore's law [13]. Based on this we can expect more than 10 times increase in execution speed of fast Fourier transform (FFT) compared to the current component benchmarking values [14]. This enables relatively low SC spacing even with larger B4G bandwidths.

C. B4G TDD frame numerology

When considering indoor LA scope it can be noted that the existing standards (LTE-A, WLAN) are designed for different scenarios and have legacy burden restrictions when utilizing evolving component technology. This is visible for example in LTE-A and WLAN TDD minimum switching times of 20.3μs and 16μs, respectively. B4G radio channel properties and evolved component technology allow completely different numerologies regarding, for example, GP and CP durations.

Let us first consider GP. According to formula (1), the time required for GP in B4G TDD system can be estimated as a function of reduced channel delay spread, propagation delay and evolved component parameters presented in Sections IV.A and IV.B as

$$T_{GP\_B4G} \approx T_{CH\_ds} + T_{CH\_prop} + T_{HW\_switch} + T_{HW\_filter}$$

$$= 100ns + 170ns + 60ns + 50ns = 380ns < 0.5\mu s.$$

Thus, extremely short GP is needed compared to corresponding times of LTE-A and WLAN.

CP suitable for B4G can also be estimated using the B4G channel delay spread and component parameters. Assuming that TA is not used in B4G system, the cell time uncertainty is included in the CP as a two-way maximum propagation delay. Using formula (2) we get an estimation of

$$T_{CP\_B4G} \approx T_{CH\_ds} + 2 \cdot T_{CH\_prop} + T_{HW\_filter}$$

$$= 100ns + 2 \cdot 170ns + 50ns = 490ns < 0.5\mu s.$$

Again, B4G requirement for CP is clearly much more relaxed compared for example to LTE-A CP of 4.7μs.

Figure 3 illustrates the percentual CP & GP overhead as a function of the TDD switching period quantisized with symbol resolution. For B4G, CP and GP values of 0.5μs are used assuming a subcarrier spacing of 15kHz. We also present minimum CP & GP overhead for LTE-A and WLAN as references. Standardized SC spacing of 15kHz is used in the LTE-A numerology curves. As shown in Table II, only two values for the switching point periodicity (5ms and 10 ms) are currently supported by the LTE-A standard. The solid LTE-A curve presents the overhead of the standardized CP value of 4.7μs and the minimum standardized GP requirement for LTE-A component technology, that is the minimum allowed value for TA adjustment of 20.3μs. In practice, the GP overhead is even larger. This has been illustrated with dashed LTE-A numerology curve where the standardized minimum GP value of 1 OFDMA symbol per two switching points is used. In this curve we take the average of the GP time per switching point by dividing this 1 OFDMA symbol by two. In the WLAN numerology curve, the standardized SC spacing of 312.5kHz [9] and minimum standardized GI time of 0.4μs (corresponding to CP in LTE-A systems) have been used. SIFS time of 16μs has been used as minimum TDD switching time (corresponding to GP in LTE-A system). In a real WLAN system, TDD switching time would be even longer due to

CSMA/CA related DIFS and delays due to backoff timers. It can be seen from Figure 3 that the CP&GP overhead reduction of B4G numerology is remarkable compared to both LTE-A and WLAN. Overhead for legacy systems starts to increase rapidly for TDD switching periods of less than ~1ms, whereas the suggested B4G LA numerology has very low overhead and supports switching periods of 0.5ms and even below.
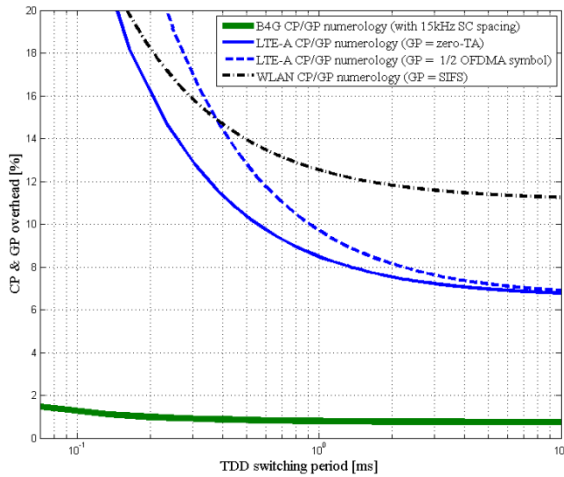

Figure 3. CP/GP overhead for B4G, LTE-A and WLAN numerology

Since GP time is a critical factor in TDD efficiency, decreased GP length will consequently allow more frequent UL/DL switching. CP overhead is in general a critical factor in OFDMA overhead, whose length reduction would enable more efficient usage of OFDMA in LA environment. These factors allow the design of a B4G optimized TDD physical subframe structure, where subframe corresponds to a minimum scheduling unit in time, that can be used to reach really low physical layer latency. The RTT is affected by subframe length and processing time. As we can see from Figure 3, B4G numerology enables remarkably smaller TDD switching period and thus smaller subframe length compared to existing standards. RTT time is also affected by the processing time that can be minimized by placing the data-associated control signaling before data and thus enabling fast and cost efficient pipeline processing in the receiver. As a conclusion, B4G numerology enables possibility for low physical layer RTT, really fast TDD switching and fully flexible UL/DL ratio. These are clear improvements compared for example to the minimum 5ms TDD switching periodicity and restricted UL/DL ratio options of LTE-A. The precise optimal subframe length depends on parameters such as practical device processing times and design of e.g. control, synchronization, reference and demodulation reference signaling. A more detailed subframe length analysis is left for further study.

V. CONCLUSIONS

Existing wireless network standards, such as LTE and WLAN, are either designed for wide area environments and/or burdened by legacy restrictions when utilizing evolving component technologies. LTE-A TDD frame is not fully optimized for TDD systems due to harmonization of LTE-A FDD and TDD modes. The B4G environment and radio channel properties, such as smaller propagation delay, lower channel delay spread and lower transmission powers, together with evolved component technology aspects such as lower TDD switching and processing times, enable usage of shorter GP and CP times compared to existing technologies. This B4G CP & GP numerology enables usage of shorter subframe length and a physical subframe structure design fully optimized for TDD. Thus, with this B4G optimized subframe structure fast TDD switching periodicity and support for fast and flexible UL/DL ratio switching can be achieved, consequently leading to very short physical layer RTT. This is a major advantage compared to the current LTE-A TDD frame structure with switching periodicity restriction of 5ms and restricted UL/DL ratio configurations; moreover, it also allows the system to overcome the obvious latency problems caused by the CSMA/CA in WLAN systems.

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