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Radio Resource Management Techniques for eMBB and mMTC services in 5G Dense Small Cell Scenarios

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***Abstract*—Research in 5G has so far been aimed towards laying out a conceptual vision and the engineering requirements. The focus is now shifting towards standardization through evaluation of potential solutions. 5G wireless communication system is expected to serve a diverse range of services with different design requirements. Dense small cells with multiple antenna nodes are believed to be key elements in meeting these challenging requirements. 5G will thus feature an adaptable air interface with carefully designed radio resource management techniques that can optimize each link according to its service requirements. This article provides an overview of key radio resource management techniques for 5G dense small cells and demonstrates how these techniques can contribute to fulfilling some of the important 5G requirements. Preliminary system level simulation results indicate that a mean throughput gain of around 63%, and up to 84% in latency reduction can be achieved utilizing the discussed resource management techniques.**

I. Introduction

The first half of this decade saw the emergence of the fifth generation of cellular technology (5G) as a concept. Research in 5G have so far been focused on laying out a conceptual vision for a 5G system, namely aimed at answering the question: "what will 5G be?" [1]. In particular, engineering requirements in terms of the data rate, latency and energy efficiency; core services like mission critical and massive machine type communication; and key enablers such as ultra-dense small cells and massive multiple-input multiple-output (MIMO) have been identified [2]. With the system requirements agreed, the focus is now shifting towards turning the vision into a functioning reality. Evaluation of potential 5G solutions for standardization is expected to begin early this year, with detailed specification submission targeted by 2020 [3].

The exponential growth of mobile data traffic is a significant, though not the only driving force behind 5G. In fact, 5G is expected to experience a proliferation in the number of emerging use cases categorized into several broad service groups such as: enhanced Mobile Broadband (eMBB) supporting an evolution of today's broadband traffic with an increased spectral efficiency, Ultra-Reliable Low Latency Communications (URLLC) where messages need to be transferred with high reliability and low latency, and massive Machine Type Communication (mMTC) catering to a large number of (generally) low-data rate, low-cost devices. In par with the use cases, the set of key performance indicators (KPIs) are also expected to be diversified. KPIs such as reliability, latency and battery lifetime will be as important as conventional metrics like the data rates [2].

Demand for radically higher data rates, increased reliability and improved energy efficiency will drive the 5G standard to adopt a number of novel disruptive technologies, primarily through a combination of gains in three frontiers: cell densification, harnessing MIMO capabilities, and moving to new frequencies above 6 GHz using both centimeter wave (cmWave) and millimeter wave (mmWave) technologies [1]. However, early 5G standards will most likely feature dense small cells operating in cmWave frequencies below 6 GHz.

Efficient radio resource management (RRM) techniques are essential for delivering the stringent 5G KPI targets. Dynamic and flexible RRM techniques offer the possibility to prioritize performance measures according to the service requirements, and hence need to be carefully designed to specifically meet some of the more critical 5G KPI requirements like low latency and high reliability. Alongside, an important aspect of 5G system design is the frame structure [4]. A flexible frame structure which can support the diverse design requirement is foreseen as an important building block of a 5G system [5].

This article provides a survey of the State of the Art in 5G frame design, followed by an overview of key RRM techniques for 5G dense small cells. The objective is to demonstrate how these techniques can contribute to fulfilling some of the important 5G requirements specific to the considered scenarios. This paper is focused on dense small cell scenarios with limited coverage operating in licensed bands for cellular systems below 6 GHz. MIMO capable nodes with at least 4×4 configuration, and equipped with interference suppression receivers are considered as a baseline. The main 5G service groups relevant for an indoor small cell deployment are eMBB and mMTC, where each can be broadly associated with one or more KPIs. This work is primarily targeted towards relevant use cases within eMBB and mMTC services; and hence, the associated KPIs of spectral efficiency, latency and energy efficiency are the main evaluation criteria considered.

The remainder of this paper is organized as follows: a comprehensive State of the Art in 5G frame design is reviewed in Section II. Section III presents spectral efficiency improving RRM techniques aimed towards eMBB services. Latency enhancement features, such as full duplex

communication, are discussed in Section IV, followed by a detailed observation on energy efficiency in Section V. Finally, Section VI concludes the paper.

II. State of the Art in 5G Frame Design

The frame structure is an essential component of a radio air interface that helps to maintain synchronisation and to manage the different types of information that need to be exchanged between the network entities. A dynamic and flexible frame structure offers the possibility to prioritize performance measures according to the service requirements. The State of the Art in 5G frame design is reviewed in this Section.

A frame structure specifically designed for 5G small cells (SC) is discussed in [4]. The focus is on outdoor cells, and the frame is designed assuming a significant part of it to be occupied by uplink reference signals which enables network controlled operations. The proposed frame structure supports flexible scheduling of uplink (UL) and downlink (DL) data within a single transmission time interval (TTI) of $167.3\mu s$, and has a combined overhead of 27.3%.

As opposed to [4], the frame structure proposed in [6] targets indoor SCs. The frame structure features a control part which is time separated by a data part. The TTI duration is set to 0.25 ms, making it attractive from a latency and round trip time (RTT) minimization point of view. All cells are assumed to be time synchronized, e.g. in a distributed manner using [7], and the same frame format to be used in both UL and DL. The selected transmission mode is Time Division Duplex (TDD), as it does not require paired spectrum as in Frequency Division Duplex (FDD) and adapts well to unbalanced traffic scenarios by allowing dynamic allocation of the transmission direction.

In the context of a wide area (WA) cellular network, [5] addressed the design of a 5G frame structure for the FDD mode. The authors propose a flexible frame design aiming at multiplexing services with different requirements. The TTI duration is set accordingly to the specific service, such that latency limited applications can benefit from shorter transmission while broadband users enjoy the benefits in terms of coding gain and reduced control overhead of longer frames. The variable TTI length is also meant to ensure sufficient UL transmit time for cell-edge users. In-resource control signaling is recognized as the enabler of such flexible design.

Table I summarizes the state-of-the-art proposals [4]–[6] along with the LTE-Advanced specification [8]. The proposal in [4] adopts a very large subcarrier spacing to further boost robustness to phase noise and achieve high time granularity for allocating the uplink reference symbols. This leads however to a significantly larger overhead despite the shorter CP. The proposal in [5] adopts a longer CP to deal with the larger delay spread in wide area; different subcarrier spacing options are also considered, to fit a 0.2 ms TTI.

TABLE I: SOTA 5G Frame Structure Numerology compared with LTE

Parameters	Outdoor SC [4]	WA FDD [5]	Indoor SC [6]	LTE-A [8]
Subcarrier spacing [kHz]	312.5	16/32	60	15
Symbol time (incl. CP) [μs]	3.2	66.66/ 33.33	17.66	71.35/ 71.87[a]
Cyclic Prefix [μs]	0.5	2.08 /4.17	1	4.69 /5.21[b]
CP Overhead [%]	13.5	5.25	6.7	6.67
TTI Size [μs]	167.3	200	250	1000
OFDM Symbols/TTI	45	3/6	14	14
GP Duration [μs]	$2 \cdot 0.2$	-	$3 \cdot 0.89$	$2 \cdot 33.33$
HARQ Processes	4	-	4	8

[a]The symbol time equals $71.87\mu s$ for the 1st and 8th symbols, and $71.35\mu s$ for other symbols

[b]The CP duration equals $5.21\mu s$ for the 1st and 8th symbols, and $4.69\mu s$ for other symbols

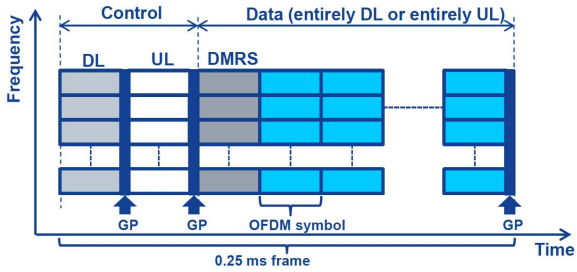
A. Selected Frame Structure Overview

The key RRM techniques for 5G presented in this contribution are evaluated using the 5G frame structure proposed in [6] due to its applicability in indoor small cell deployment scenarios. This subsection provides further details on the selected frame structure.

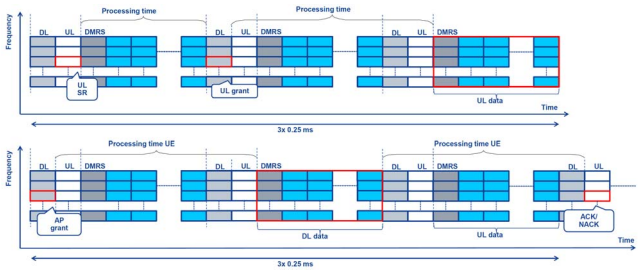
The selected frame structure features a control part followed by a data part, to enable efficient pipeline processing at the receiver. A guard period (GP) is inserted between the two parts, thus accommodating transmission switching time. The DL control information includes parameters such as the modulation and coding scheme (MCS), the allocated physical resource blocks (PRB) for both UL and DL, and the precoding matrix information (PMI) in case of MIMO transmission. An user equipment (UE) wishing to transmit sends a scheduling request in the UL control channel containing control information such as the channel quality indicator (CQI). The data part of the frame can be allocated to either UL or DL, but switching the transmission mode within a TTI is not supported in the interest of stabilizing the interference within a frame.

The first symbol of the data part is dedicated to the Demodulation Reference Sequences (DMRS) for enabling channel estimation at the receiver. Since the cells are synchronized, they will be transmitting their reference sequences in the same symbol, allowing accurate estimation of the interference covariance matrix (ICM), provided orthogonal reference sequences, e.g. in the code domain, are used. The cross-link channels' (e.g., AP-to-AP, or UE-to-UE) contribution to the ICM can also be estimated due to the UL and DL directions having the same frame format. Such ICM estimate facilitates the use of advanced receivers like the interference rejection combiner (IRC), which aims at suppressing parts of the interference signal regardless of their transmission direction, as further detailed in Section III.

Orthogonal Frequency Division Multiplexing (OFDM) modulation is assumed, given its cost efficient multipath mitigation capabilities. Differently from LTE, the same waveform is used in both UL and DL [8]. The OFDM subcarrier spacing is set to 60 kHz, as opposed to 15 kHz in LTE. This ensures robustness to phase noise at significantly high carrier frequencies. Only two symbols out of 14 in



(a) Details of a single sub-frame.



(b) Pipeline Processing supporting sub-ms latency.

Fig. 1: The proposed 5G Frame Structure with DMRS symbol supporting accurate interference covariance matrix estimation.

each subframe are assumed to be dedicated to the control part (one symbol each for the DL and the UL). Given the shorter expected delay spread in indoor small cell scenarios, the CP duration $(1\mu s)$ is considerably lower than that in LTE. With the low cell range and the low transmit power in small cells, the GP is here set to be extremely short $(0.89\mu s)$ and only intended to compensate the on-off power transition of the hardware circuitry. The combined overhead of CP and GP of 6.7% is equivalent to that of LTE (6.67%).

III. Interference Management Techniques

Network densification with small cells leads to specific challenges in interference management. With shorter inter-site distances (ISD) and fewer active users per cell, interference powers in dense small cells exhibit a larger variation and hence, need to be prudently managed. Interference management techniques specifically designed for supporting eMBB services in indoor small cells are presented in this section.

A. Support for Advanced Receivers

Advanced interference suppression/cancellation receivers, such as the IRC and Successive Interference Cancellation (SIC) receivers, can potentially improve interference resilience. The IRC receiver, which is built on the minimum mean squared error (MMSE) criteria [9], suppresses parts of the interference signals by projecting the desired signal onto the subspace with the weakest interference contribution. An accurate ICM estimation is required for the IRC receiver operation.

In LTE-Advanced, pilot symbols known as the downlink reference signals (RS) that are sparsely inserted in the OFDM time-frequency grid can be used to estimate the transmission timing and channel matrices of the interfering cells. The adopted 5G frame structure is specifically designed to support an accurate ICM estimation by allowing the transmission of a DMRS symbol as the first symbol in the data part of the frame. Conducting a similar operation in LTE-TDD is much more challenging, since different access technologies, ODFMA and SC-FDMA, are used in the DL and UL, respectively.

The adopted frame structure can also support more advanced interference cancellation type receivers, such as the non-linear SIC receiver. SIC receivers detect the received streams sequentially such that the interference contribution of the streams detected first can be cancelled from the remaining signal. The SIC principle can be applied either to the streams simultaneously transmitted from the desired user (intra-stream SIC) or to the interfering streams from neighboring cells (inter-cell SIC). The support for intra-stream SIC is straight-forward since the control information required to decode and potentially cancel the intra-stream interference signals is readily available within the DL control information [6]. Exploiting SIC receivers to cancel the Inter-Cell Interference (ICI) is much more complex as it requires signaling of the used transport block size among neighbor cells. We therefore restrict our focus to the usage of intra-stream SIC.

B. Rank Adaptation Enablers

Interference mitigation techniques in LTE rely on ICI coordination, such as coordinated scheduling, power control, etc. Multiple antennas at the transmitter and the receiver open up the possibility to coordinate in the rank domain as well, i.e. by adjusting the number of transmitted streams. Rank coordination to maximize a network utility function has been found to greatly enhance the network performance compared to myopic transmissions aimed at optimizing the performance independently at each user [10]. The interference mitigation properties of advanced receivers further enhance the gains of rank coordination due to their ability to suppress/cancel a number of interfering streams.

In our envisioned 5G small cell concept, we propose a practical interference aware rank coordination algorithm to control the ICI [10]. The concept of 'pricing as a control parameter' is applied to enforce coexisting cells to behave altruistically by accounting for the impact of the interference generated at neighbouring cells. Such a rank coordination method relies on the Channel State Information (CSI) availability between the transmitter and the interfered receiver; and the periodic exchange of cell-specific 'interference price' information among the coexisting cells. The DMRS symbol integrated into the frame structure, and the assumed TDD format readily accommodates obtaining the necessary CSI information from the reverse communication direction; whereas the latter 'interference price' can be conveniently incorporated as part of the DL control symbol.

C. Interference Management Simulation Results

The cumulative distribution function (CDF) curves of the mean throughput with advanced receivers and interference aware rank coordination in a 3GPP defined indoor office area like scenario with 20 cells of dimension 10 m $\times$10 m is shown in Figure 2. The Winner-II channel with a full buffer traffic model is assumed. The baseline performance corresponds to that with the maximal ratio combining

(MRC) receiver which treats the ICI as noise. IRC receiver is found to provide an average throughput (TP) gain of around 35% over conventional MRC receivers, whereas intra-stream SIC (IS-SIC) adds a further improvement of around 30% in terms of the peak $(95\% - ile)$ TP. An outage $(5\% - ile)$ TP gain of around 30% TP gain is observed with interference-aware rank coordination.

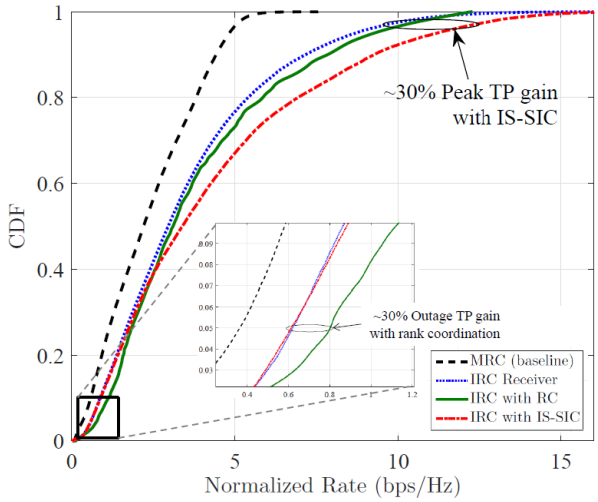


Fig. 2: CDF of the achieved rate with interference suppression/cancellation receiver, and rank coordination.

IV. Low Latency Techniques

5G targets an end-to-end latency of 1 ms for certain use cases while the Quality of Experience will also improve for eMBB users if the latency is reduced. LTE is unable to support such low latencies due to the 1 ms TTI. This Section discusses how dynamic TDD and Full Duplex Communication can reduce the latency. Related simulation results demonstrating the latency improvement of the above techniques are also presented.

A. Dynamic Time Division Duplexing

Dynamic TDD allows the transmission direction to be independently decided at each TTI, providing flexibility to react to the instantaneous traffic conditions. In small cells with typically low aggregate traffic volume, adapting swiftly to rapidly varying traffic conditions can help to reduce the latency and temporally minimise the perceived interference conditions, since the traffic is served faster.

Dynamic TDD is investigated in LTE in the context of the LTE-A Release 12 feature "enhanced Interference Mitigation and Traffic Adaptation" (eIMTA) [11]. Dynamic TDD in LTE introduces the problem of cross-link interference between neighbouring cells, and potentially severe variations in interference power between successive TTIs, which can seriously deteriorate the performance in the absence of specific interference mitigation measures [11]. Using the same frame format for both UL and DL directions enables accurate estimation of the cross-link channels. In addition, the short ISD in small cells scenarios and the balanced UL and DL transmit powers result in stabilizing the interference power variation across TTIs [12]. Moreover, the frame's in-built support for advanced receivers further mitigates the impact of any such interference variation.

B. Full Duplex Communication

Full Duplex Communications (FDC) have recently gained significant attention owing to the promise of enhancing the network capacity and reducing the latency by supporting simultaneous transmissions and receptions. However, the increase in the number of active (interfering) links in neighboring cells increases the interference footprint in the network and can significantly limit the potential latency and throughput gains. Moreover, the self interference signal, from the transmission-end, at the receiver side can be overwhelming stronger than the desired signal and has to be suppressed by an order of $80 - 100$ dB for FDC to be practically feasible.

The adopted frame structure's support for interference mitigation techniques and the use of the same frame format in both UL and DL provides further support for FDC. Experimental evaluations have shown that around 100 dB of isolation for the self interference signal is practically achievable [13]. Coupled with the strong desired signal due to the short transmitter-receiver distance, such a degree of self-interference isolation can enable practical implementation of FDC in dense small cell scenarios.

C. Low Latency Simulation Results

The latency reduction and throughput gain achieved with dynamic TDD over fixed TDD, and FDC over conventional half duplex communication are summarized in Table II. A Poisson arrival traffic model is assumed, with the load reflecting the packet arrival intesity. Details of the simulation settings and parameters are presented in [12], [14]. In terms of the latency reduction, both dynamic TDD and FDC offer a small increase in performance in the traffic heavy link direction, whereas a large performance gain can be observed in the lightly loaded link direction with asymmetric traffic. Dynamic TDD mode results in the most TP gains under an asymmetric traffic condition with a low load, whereas the highest gains with FDC are observed under symmetric traffic conditions with a relative heavy load.

TABLE II: TP Gain and Latency Reduction with Dynamic TDD and Full Duplex Communication.

(a) Gains of Dynamic TDD over fixed TDD

	Session TP			Latency Reduction		
	Percentile					
Load	5%	50%	95%	5%	50%	95%
30 %	63%	41%	50%	43%	49%	43%
70 %	44%	38%	48%	42%	41%	25%

(b) Gains of FD over conventional Half Duplex

	Symmetric		Asymmetric (DL:UL ; 6 : 1)			
Load	TP	Delay	DL TP	UL TP	DL Lat.	UL Lat.
25 %	1%	8%	1%	3%	4%	12%
50 %	14%	23%	4%	17%	6%	35%
75 %	34%	29%	17%	130%	28%	84%

V. A Note on Energy Saving

User equipment battery life is an important KPI for 5G, regardless of whether the UE is a smartphone or an MTC device. A key energy issue in LTE is the grouping of the control and data channels. Here, the scheduling information carried in the Physical Downlink Control Channel (PDCCH) is followed by the Physical Downlink Shared Channel (PDSCH), which may contain data for the user [8]. Since there is no time separation between the PDCCH and PDSCH the UE is forced to receive and buffer the PDSCH, while decoding the PDCCH to determine if it is actually scheduled in that subframe. If the UE is not scheduled the buffered PDSCH data cannot be decoded and thus energy is wasted.

The frame structure proposed in [6] is designed to provide a scheduling grant for UL or DL traffic, in the corresponding control channel, one frame ahead of the data as shown in Figure 1b. This structure allows the UE to determine in advance whether it will be scheduled in the following frame. If the UE is not scheduled it may enter a low-power mode called microsleep, potentially saving around 20% energy as compared to LTE [15].

The short time frame also results in longer UE battery life, because it reduces the energy-intensive total ON time. Using the short frame the UE is able to connect to the network, transfer the data, and return to a low-power sleep mode within $4-5$ frames. This is a major improvement over LTE-TDD, which, depending on the TDD configuration, requires $10-19$ subframes to complete a transfer [15]. Furthermore, the reference signals used for synchronization, which is often required after extended deep sleep, occurs at every frame, i.e., more frequently than the 5 ms periodicity of LTEs Primary and Secondary Synchronization Signals. This reduces the time, and thus energy, the UE spends scanning for the synchronization signal. In total, the short and optimized frame structure significantly improves the energy saving potential of Discontinuous Reception/Transmission (DRX/DTX), where a UE is allowed to only monitor the control channels periodically while applying low-power sleep modes for longer durations. Figure 3 illustrates the battery life of a UE applying DRX/DTX in TD-LTE and our proposed 5G frame structure. The results show that the 5G frame structure leads to $5-15$ times longer battery life for various activity patterns. The short frame also facilitates the use of DRX/DTX for high activity levels (the lower right area) where the LTE frame structure would require the UE to be always ON.

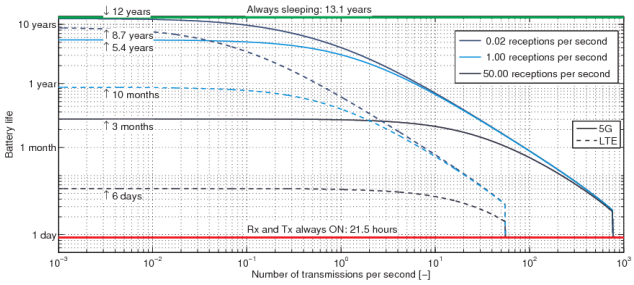


Fig. 3: UE battery life for LTE and 5G. Discontinuous Reception and Transmission is applied.

VI. Conclusion

The goal of this article is to present components of a 5G air interface that is adaptable to the diverse services and design requirement of the future 5G system. A comprehensive State of the Art in 5G frame design is first reviewed, followed by a presentation of RRM techniques designed for eMBB and mMTC services in a dense small cell deployment scenarios. The key RRM techniques for 5G are evaluated using a frame structure proposed specifically for dense small cell scenarios. The main design concepts for the adopted frame structure are a short TTI duration of 0.25 ms, a direction independent frame format and the presence of an embedded DMRS symbol. These features have been found to be instrumental in facilitating advanced interference management and latency reduction techniques and resulted in considerable spectral efficiency gain and latency reduction. More specifically, preliminary system level simulation results indicate that a mean throughput gain of around 63%, and up to 84% in latency reduction can be achieved utilizing the proposed RRM techniques supported by a flexible 5G frame structure.

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