Intermediate MAC Concept

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Abstract:
This deliverable is delivered together with M2. It will contain the main MAC structures for non-orthogonal waveforms and corresponding interfaces for the single-cell case. Particularly, main findings with respect to the robustness framework are described here.

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Executive Summary

This document presents intermediate MAC concepts within the 5GNOW project.

Chapter 1 gives an overview of state-of-the-art systems based on the LTE Release 8 and Release 10 standards, as far as it is necessary for the 5GNOW project. In addition, an overview of protocols with specific focus on the MAC architecture and the X2 interface for these systems is given. Moreover, networking issues such as interference management are treated and features for MTC are described.

Chapter 2 presents initial schemes, scenarios, and use cases for a robust transmission mode based on current LTE systems. For this, the tradeoff between signalling and payload is considered. Initial use case and scenario concepts for single-cell MAC, multi-cell RRM, as well as CoMP are provided.

Chapter 3 presents the 5GNOW vision for a robustness concept based on the new waveforms. Implications of the new unified frame structure concept on MAC design are given and advanced Random Access Channel concepts, in particular a novel compressive random access scheme, are discussed. Aspects such as imperfect channel state information (CSI) and imperfect time and frequency synchronization for CoMP are also covered in this chapter. Advanced interference alignment based solutions overcoming the limitations of current systems with respect to imperfect CSI are discussed and evaluated.

Chapter 4 concludes D4.1.

1 State of the art

In order to provide novel robustness concepts in MAC/networking scenarios, it is useful to have a common starting point on state-of-the-art systems, i.e., LTE Rel. 8 (as a baseline for robust MAC procedures and MTC) and LTE-Advanced Rel. 10 (covering carrier aggregation and networking/interference management). Thus, in this chapter we provide an overview of protocols with specific focus on MAC architectures and the X2 interface for these releases.
The chapter serves both as a baseline and as a reference, indicating which aspects we are treating and which not. The reader who is mainly interested in novel 5GNOW concepts can skip this section and start with Section 2. Please note, that all the acronyms are explained in the Abbreviations and References sections at the end of the document

1.1 LTE Rel. 8 MAC architecture

1.1.1 LTE protocol and channel architecture

The radio resource management for LTE is included at the RRC and MAC layers. While MAC is responsible for lower layer decisions regarding resource allocations and PHY resource management, RRC is responsible for higher layer management of the overall connection for individual UE, by setting the parameters for all the L2/L1 protocols including MAC policies. Figure 1.1.1 shows the overall protocol (from L3 to L1) architecture including all the logical, transport and physical channels and the mapping between them [3GPP300].

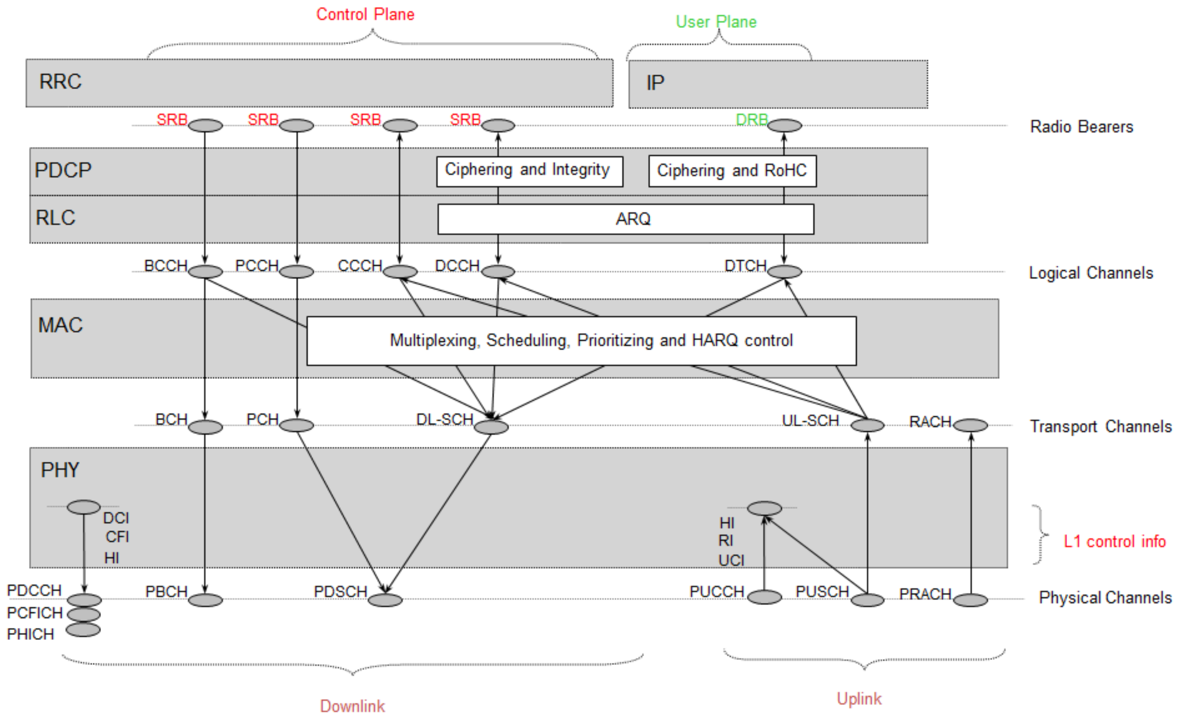

Figure 1.1.1 Protocol and channel architecture for LTE Rel. 8

Table 1.1 presents the corresponding channels description [3GPP300].

Table 1.1 Info type within LTE channel architecture

Info type	Channel name	Transmit direction	Channel description
Radio bearer	SRB	DL/UL	Carries RRC signaling and NAS encapsulated signaling
	DRB	DL/UL	Carries IP data for different services
Logical channel	BCCH	DL	A downlink channel for broadcasting system information
	PCCH	DL	A downlink channel that transfers paging information and system information change notifications. This channel is used for paging when the network does not know the location cell of the UE.
	CCCH	DL / UL	Channel for transmitting control information between UEs and network. This channel is used for UEs having no RRC connection with the network
	DCCH	DL / UL	A point-to-point bi-directional channel that transmits dedicated control information between a UE and the network. Used by UEs having an RRC connection
	DTCH	DL / UL	A Dedicated Traffic Channel (DTCH) is a point-to-point channel, dedicated to one UE, for the transfer of user information. A DTCH can exist in both uplink and downlink
Transport channels	BCH	DL	Carries MIB (SFN, BW size and PHICH config)
	PCH	DL	Carrier paging messages (uses DRX)
	DL-SCH	DL	Carries higher layer signalling and data. Shared between UEs. Uses HARQ
	UL-SCH	UL	Carries higher layer signalling and data. Shared between UEs. Uses HARQ
	RACH	UL	Detects use of RAP, maps RAP to RA-RNTI
L1 Control info	DCI	DL	Carries UL grants, DL allocations and TPC
	CFI	DL	Indicates size of CR
	DL HI	DL	Carries HARQ ACK/NACKs for UL-SCH transmissions
	UCI	UL	Carries CQI - DL radio channel measurements, PMI – codebook indications for MIMO transmission
	RI	UL	Indicates MIMO spatial channel characteristics
	UL HI	UL	Carries HARQ ACK/NACKs for DL-SCH transmissions
Physical channels	PDCCH	DL	Carries DCIs
	PCFICH	DL	Carries CFIs
	PHICH	DL	Carries DL HIs
	PBCH	DL	Carries BCH data
	PDSCH	DL	Carries DLSCH
	PUCCH	UL	Carries UCI / RI / UL HI
	PUSCH	UL	Carries ULSCH and UCI / RI / UL HI
	PRACH	UL	Reserved resources for Random Access Preamble transmission (RAP)
Physical signals	P-SS/S-SS	DL	Sync preambles (time / frequency / frame synchronization)
	CRS	DL	Pilots for channel estimation / demodulation, for HO / cell reselection measurements and DL channel sounding

Info type	Channel name	Transmit direction	Channel description
	DRS	UL	Pilots for UL channel estimation / demodulation
	SRS	UL	Pilots for UL channel sounding

Table 1.2 includes high level description of the protocols in LTE protocol stack [DPS+07].

Table 1.2 Protocol stack description in LTE protocol stack

Layer	Protocol name	Description
Layer 3	RRC	Manages the radio connection. Configures the lower layers with the use of RB concept. Responsible for Idle and Connected mode mobility management and setting / modifying / releasing of radio connections.
Layer 2	PDCP	Performs IP header compression to reduce the number of bits necessary to transmit over the radio interface. PDCP is also responsible for ciphering and integrity protection of the transmitted data. At the receiver side, the PDCP protocol performs the corresponding deciphering and decompression operations. There is one PDCP entity per radio bearer configured for a mobile terminal
	RLC	Responsible for segmentation / concatenation, retransmission handling, and in-sequence delivery to higher layers. There is one RLC entity per radio bearer configured for a terminal.
	MAC	Handles hybrid-ARQ retransmissions and uplink and downlink scheduling. The scheduling functionality is located in the eNodeB, which has one MAC entity per cell, for both uplink and downlink. The hybrid-ARQ protocol part is present in both the transmitting and receiving end of the MAC protocol
Layer 1	PHY	Handles coding/decoding, modulation/demodulation, multi-antenna mapping, and other typical physical layer functions

1.1.2 MAC block diagram and functions

Figure 1.1.2 shows the basic MAC architecture including channel mappings and MAC protocol separation onto functional blocks [3GPP321].

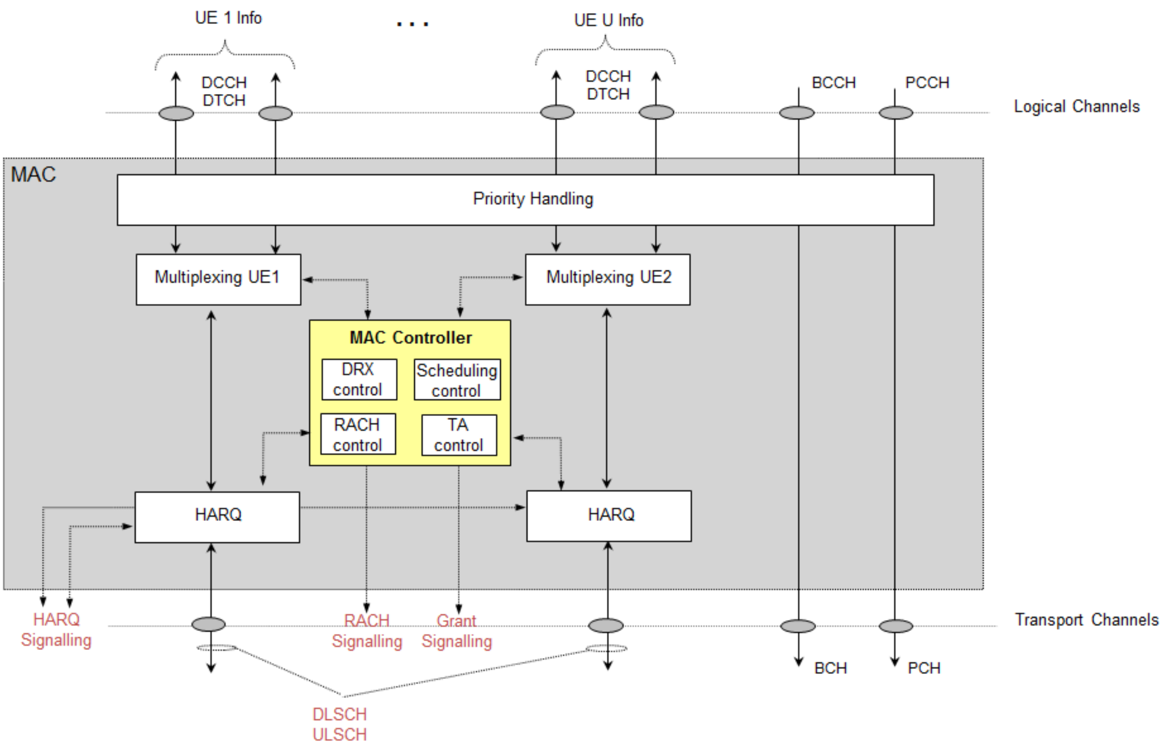

Figure 1.1.2 Basic MAC architecture

Figure 1.1.3 presents the high level separation of MAC functionalities and scheduler interactions with other protocols within the LTE protocol stack [DPS+07].

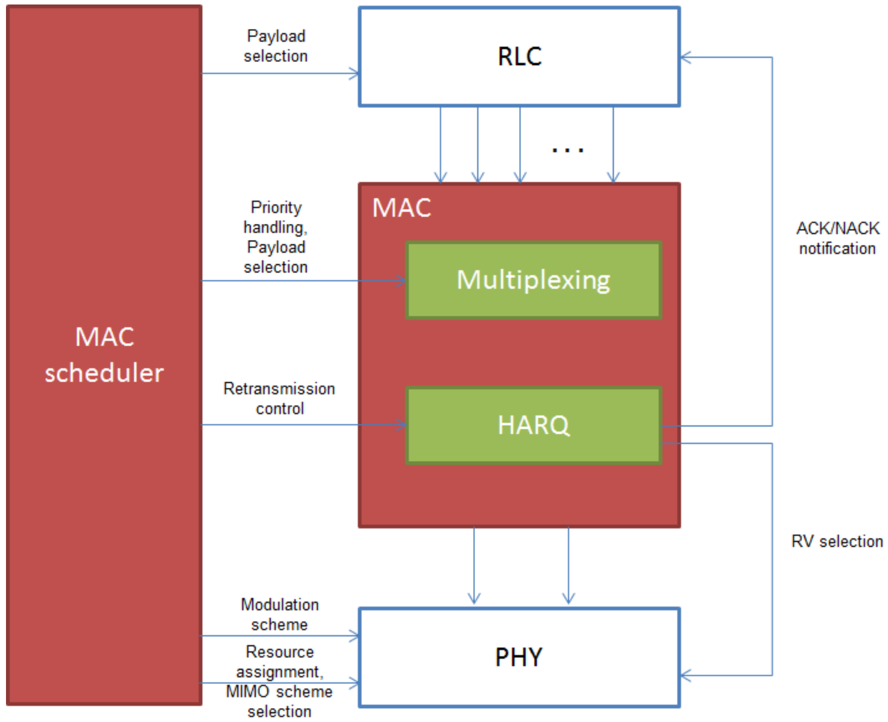

Figure 1.1.3 MAC high level functional separation

The MAC protocol performs the following functions [3GPP321]:

- providing a mapping between logical channels and transport channels – performed at UE DL, UL; eNB DL, UL;
- multiplexing of MAC SDUs from one or different logical channels onto transport blocks to be delivered to the physical layer on transport channels – performed at UE UL; eNB DL;
- demultiplexing of MAC SDUs from one or different logical channels from transport blocks delivered from the physical layer on transport channels – performed at UE DL; eNB UL;
- scheduling information reporting – performed at UE UL;
- error correction through HARQ – performed at UE DL, UL; eNB DL, UL;
- priority handling between UEs by means of dynamic scheduling – performed at eNB DL, UL;
- priority handling between logical channels of one UE – performed at eNB DL, UL;
- logical Channel prioritisation – performed at UE UL; and
- transport format selection – performed at eNB DL, UL.

1.1.3 MAC procedures

Table provides the summary of key MAC procedures [3GPP321] from the LTE standard. As can be seen, the functionality of MAC scheduling procedure is not mentioned, since it is up to vendor implementation how to assign resources.

Table 1.3 MAC Procedures

Procedure name	Purpose / description
Random Access procedure	Main purpose: get uplink grant. Used for: - get initial uplink grant / sync to network - get access after HO - restore TA / get new TA

Procedure name	Purpose / description
	- get to sync mode (no UL data, but DL data available) Modes: contention resolution (common preamble) and non-contention resolution (dedicated preamble)
Maintenance of Uplink Time Alignment (TA)	Main purpose: have sync to UL frame Used at: - initial TA obtaining - TA timer expiry
DL-SCH data transfer	Purpose: receive proper data in DL-SCH. Includes sub-processes: - DL assignment reception (reading DCI) - HARQ operation (transmission and retransmission indications, acknowledging received data) - Disassembly and demultiplexing
UL-SCH data transfer	Purpose: transmit proper data in UL-SCH. Includes sub-processes: - UL Grant reception (reading DCI) - HARQ operation (transmission and retransmission indications, acknowledging received data) - Multiplexing and assembly (logical channel prioritization, multiplexing of MAC control elements and SDUs)
Scheduling Request	Purpose: request ULSCH resources for new transmission
Buffer Status Reporting	Purpose: provide serving eNB with information about the amount of data available for transmission in the UL buffers of UE.
Power Headroom Reporting	Purpose: provide serving eNB with info about the difference between the nominal UE max tx power and estimated power for UL-SCH transmission.
PCH reception	Purpose: listen periodically to paging messages
BCH reception	Purpose: get basic information on cell (BW, SFN)
Discontinuous Reception (DRX)	Purpose: control of UE's PDCCH monitoring activity. If used – UE can monitor PDCCH discontinuously – saving battery power.
Semi-Persistent Scheduling (SPS)	Purpose: decrease amount of required signalling for DL assignments and UL grants for services, in which transmission of packets occurs periodically.

1.1.4 MAC scheduler

The main algorithm of MAC, i.e. the scheduler, takes decisions of UL grants and DL assignments based on PHY layer measurements and higher layer information (e.g. QoS priorities). Figure 1.1.4 shows the inputs to the DL and UL schedulers appropriately.

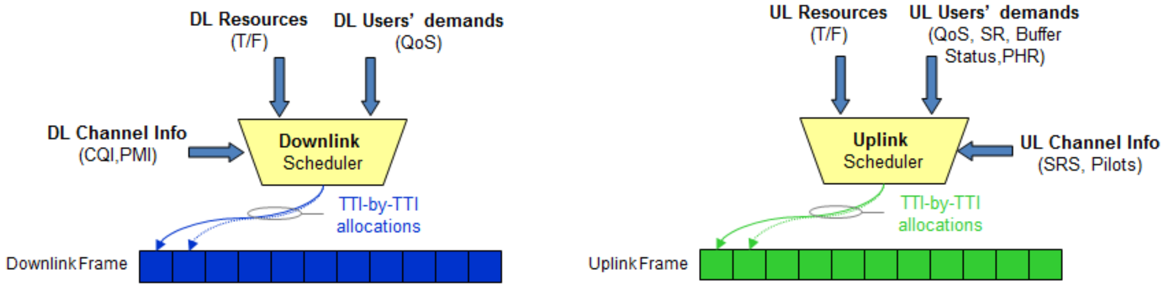

Figure 1.1.4 DL and UL scheduler inputs

In LTE, the DL assignments and UL grants have different timings, i.e. for the DL the allocation comes along with actual DL-SCH data transmission within the same subframe. However for the UL, this relation is 4 subframes, in terms shift between the UL grant and ULSCH transmission (see Figure 1.1.5).

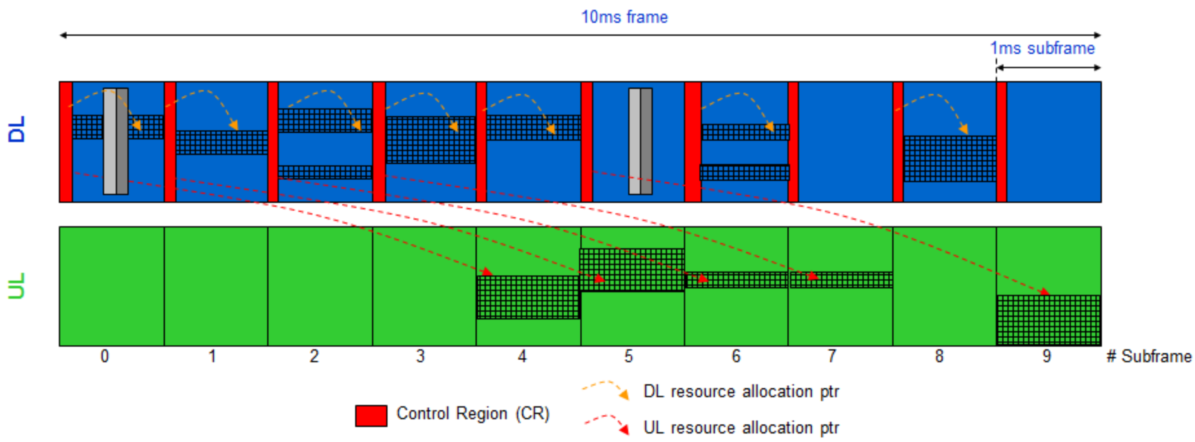

Figure 1.1.5 LTE scheduling assignments and grants

1.1.5 MAC / PHY interface

The MAC protocol is steering the PHY layer and obtains measurements from PHY. Thus the signalling at PHY layer includes resource allocation and corresponding measurements for DL and UL directions correspondingly. The assignments / grants include: MCS, MIMO configuration, PRB allocation, RV, TPC. The feedback includes: CQI, PMI, RI. Depending on the scenario, there might be larger or lower amount of data within DCI / CQI reports (e.g. depends on the higher layer signalling that is sent over the air – e.g. if BCCH is used, then all users need to receive the data and thus more robust scheme shall be used with common settings and no MIMO). Table 1.4 summarizes the options for resource allocations and feedback signalling included in the DCI messages and CQI reports correspondingly [3GPP213].

Table 1.4 PHY Signaling for MAC scheduler usage

Info type	Name	Description
DCI	DCI format 0	UL grants

	DCI format 1	DL assignment with a single codeword
	DCI format 1a	DL assignment with a single codeword (compact format)
	DCI format 1b	DL assignment for rank 1 transmission
	DCI format 1c	DL assignment with a single codeword (very compact format)
	DCI format 1d	DL assignment for MU-MIMO
	DCI format 2	DL assignment for CL MIMO
	DCI format 2a	DL assignment for OL MIMO
	DCI format 3	TPC commands for multiple users with 2 bit power adjustment
	DCI format 3a	TPC commands for multiple users with 1 bit power adjustments
CQI	Wideband CQI	Provide channel quality info of the entire system BW of the cell (may be periodic or aperiodic – using PUSCH or PUCCH)
	Subband CQI	Provide channel quality info of some subset of system BW of the cell (may be periodic or aperiodic – using PUSCH or PUCCH)
PMI	Wideband PMI	Provide indication for precoding matrix selection suited the UE in the entire system BW of the cell (may be periodic or aperiodic – using PUSCH or PUCCH, sent together with CQI)
	Subband PMI	Provide indication for precoding matrix selection suited the UE in the subset of system BW (may be periodic or aperiodic – using PUSCH or PUCCH, sent together with CQI)
RI	Wideband RI	Provide indication of the number of supported spatial layers

The PHY layer is performing the procedures according to MAC decisions. The procedures are therefore cross-used between MAC and PHY, and have an impact on the overall signaling overhead. Table 1.5 includes all the key L1 (PHY) procedures [3GPP213].

Table 1.5 PHY layer procedures

Procedure name	Purpose / description
Synchronization procedures	Used for DL synchronization and UL timing adjustment (e.g. RLM, Inter-cell sync)
Power control	DL and UL power control for assuring proper SNIR for given MCS and interference coordination
Random access procedure	Transmission of RAPreamble and receiving RAR grant
PDSCH related procedures	Procedures for obtaining data and reporting about channel quality in DL Include: - UE procedure for receiving PDSCH - UE procedure for report CSI - UE procedure for reporting HARQ-ACK
PUSCH related procedures	Procedures for transmitting UL data Include: Include - UE procedure for transmitting PUSCH - UE sounding procedure - UE HARQ-ACK procedure - UE PUSCH hopping procedure - UE Tx Antenna selection
PDCCH procedures	Procedures for reception and configuration of PDCCH Include:

Procedure name	Purpose / description
	- UE procedure for determining PDCCH assignment - PDCCH validation for SPS
Scheduling Request Procedure	Sending signals for UL channel quality measurements

1.2 LTE Advanced MAC architecture for Carrier Aggregation

1.2.1 MAC architecture for use of CA

Figure 1.2.1 and Figure 1.2.2 show the DL and UL MAC architecture, respectively, for the use of the carrier aggregation concept [3GPP300]. There is only the MAC (and RRC from higher level perspective) that:

- sees the difference between non-CA and CA usage, and
- configures CA usage.

The PHY layer is a copy of the R8 LTE PHY with some extensions in DCI messages to support cross-carrier scheduling.

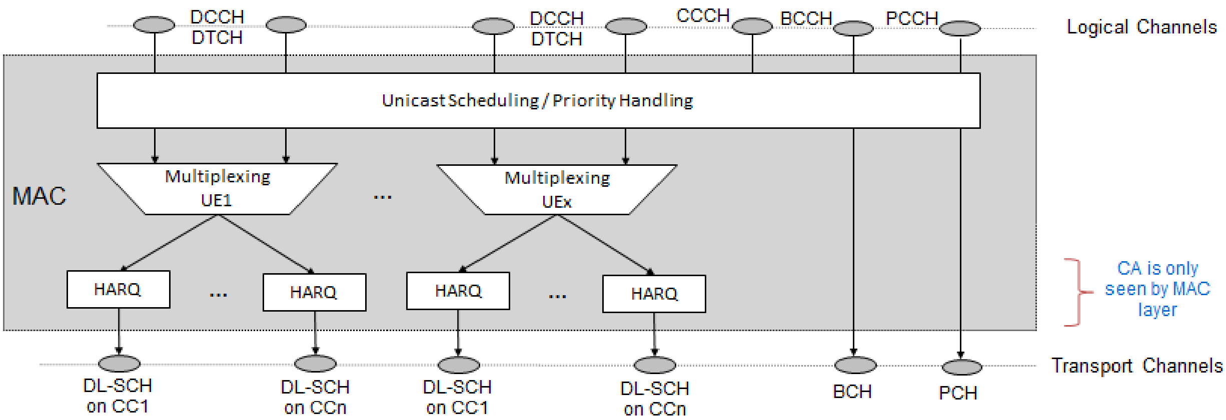

Figure 1.2.1 DL MAC architecture for CA

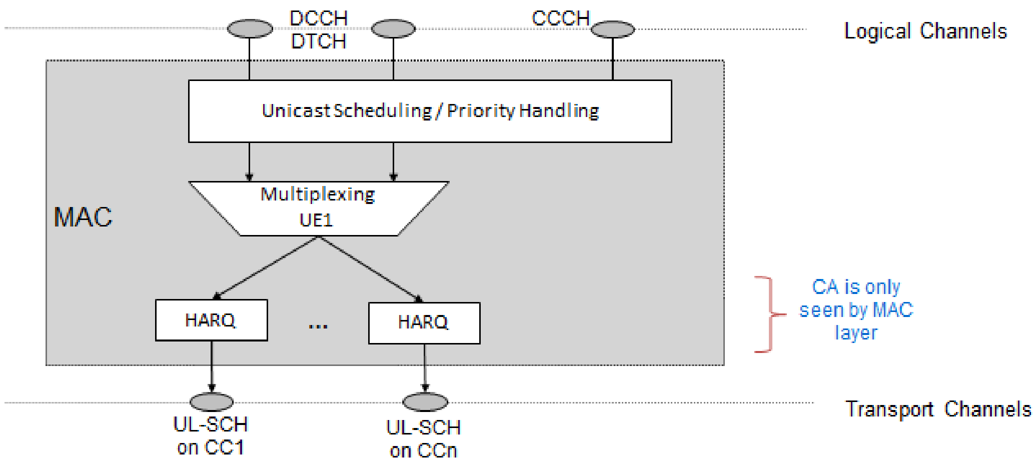

Figure 1.2.2 UL MAC architecture for CA

The extension to L1 procedures / MAC for LTE-Advanced include [3GPP300][3GPP321][3GPP213]:

- Carrier Aggregation
    - activation / deactivation procedure at MAC (MAC signalling and information included in MAC headers)
    - cross carrier scheduling indications in DCI formats
- MIMO
    - New transmission format for 8x8 MIMO for DL
    - New DCI format 4 for 4x4 UL MIMO
    - New configurable pilots for DL MIMO, i.e. DM-RS, CSI-RS

If CA is configured for a particular UE, the operation is based on the following assumptions [3GPP300][3GPP201]:

- There is always one Component Carrier, that the UE is camped at and that is used for signalling (RRC and NAS) – this is called Primary Component Carrier (PCC),
- If there is more than one CC configured, it is used as an extra resource for data transmission – this is called Secondary Component Carrier (SCC),
- There is a linking between PCC in DL and UL,
- Number of CCs in the DL shall be larger or equal to number of UL CCs,
- Each CC can have different BW size,
- Each UE can have different CC configuration and different configured PCC,
- Switching between CCs - for PCC change - is based on HO procedure,
- UE measures all the CCs in the DL, and sends PUCCH only in UL PCC, and
- The grants and assignments may be done with the use of cross-carrier scheduling (i.e. for example DCI in DL CC1 can allocate resources in DL CC2).

Figure 1.2.3 shows example configuration for CA for different UEs.

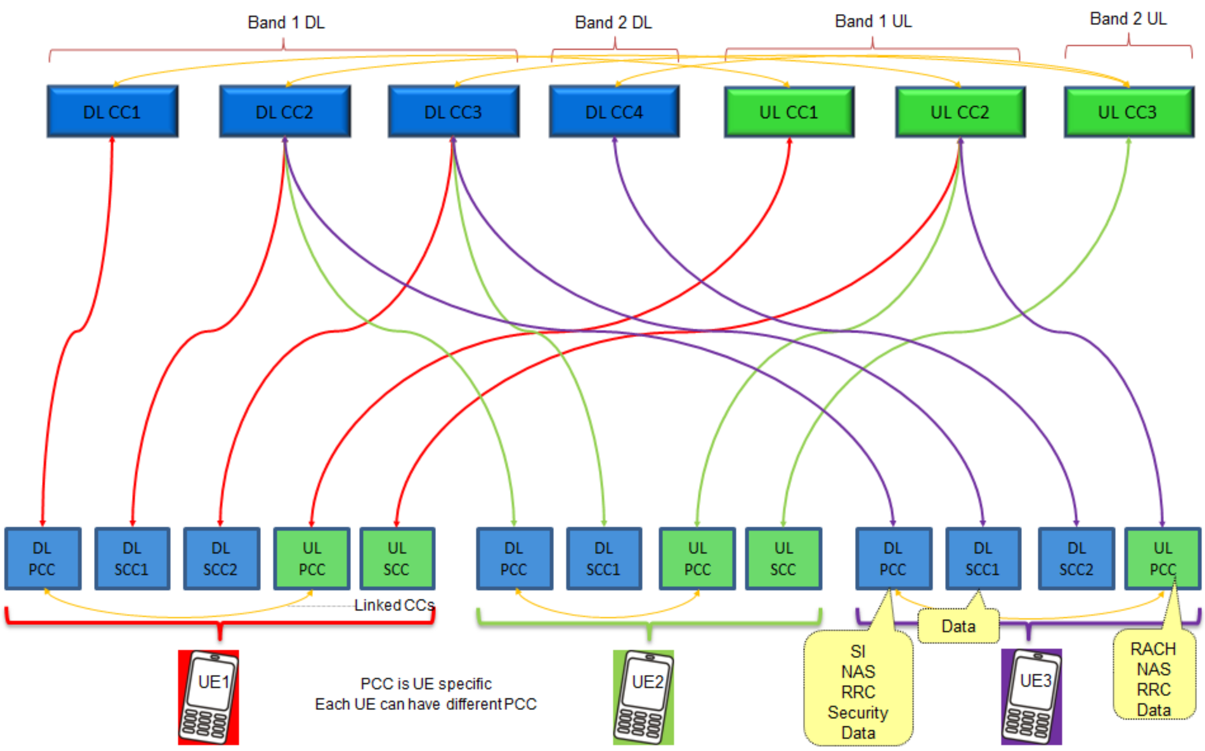

Figure 1.2.3 Primary and secondary Component Carriers example configuration

1.3 Networking issues (e.g. interference management)

High level RRM management in case of LTE systems might be considered as usage of the ICIC (inter-cell interference coordination) feature. The management is performed either with the use of the scheduler, that avoids allocation of interfered portions of the band, or with the use of the X2 interface and specific ICIC procedure. Table 1.6 summarizes various methods for interference coordination.

Table 1.6 ICIC schemes

Scheme type	Advantages	Disadvantages	Application
Static	• No signalling • X2 not required	• A-priori frequency planning required • Does not adapt to instantaneous channel / load conditions • Generates suboptimal resource distributions	Theoretical methods
Semi-dynamic	• A-priori frequency planning not required • Adapts to slow changes of channel / load conditions (200 ms – several seconds, minimum 20ms according to X2 signalling requirements)	• May or may not require extra signalling • X2 may or may not be required	Practical for inter-eNB coordination
Dynamic	• A-priori frequency planning not required • Adapts to fast changes of channel / load conditions (every frame) • Resource distribution close to optimal	• Extra signalling usually required • X2 usually required	May be a choice for intra-eNB coordination. Can be used for inter-eNB with use of X2

The procedure description for the X2 interference management and Load Information message including DL and UL interference notifications is shown below in Figure 1.3.1. The message exchange regarding Load Information between individual eNBs can be performed with a minimum of 20ms in-between consecutives messages [3GPP423].

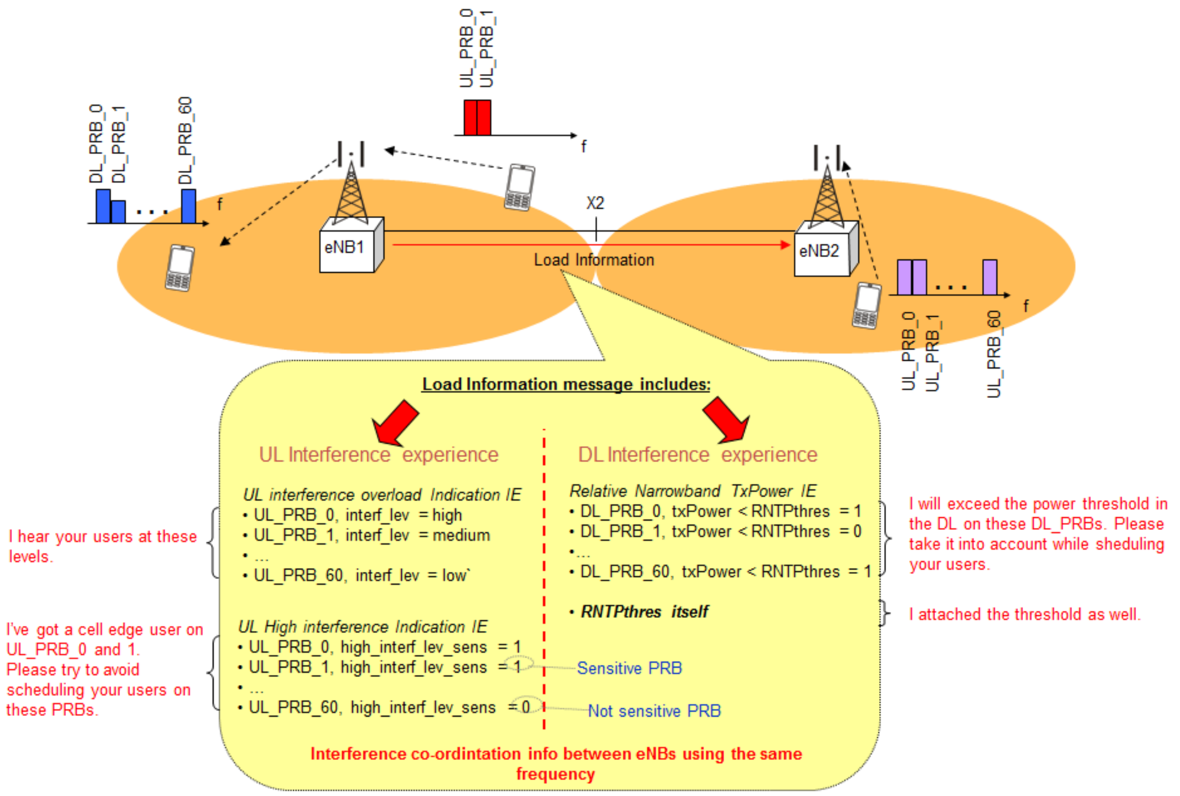

Figure 1.3.1 ICIC messaging in LTE

1.4 MTC features

MTC is a specific type of communication with no human interaction needed to setup a call. Figure 1.4.1 shows the basic concept.

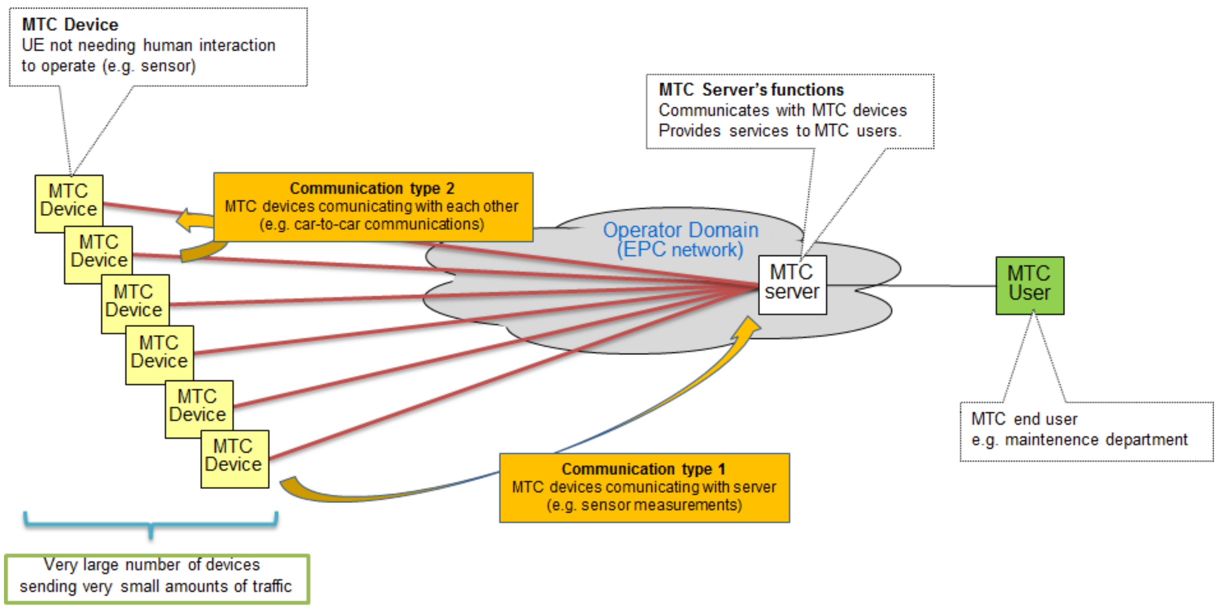

Figure 1.4.1 MTC concept (Rel. 11)

MTC depends on the type of application and 3GPP has defined the following several MTC features (that are included in the subscription profile of a particular UE) [3GP11a]:

a) Low Mobility
b) Time Controlled
c) Time Tolerant
d) Packet Switched (PS) Only
e) Small Data Transmissions
f) Mobile Originated Only
g) Infrequent Mobile Terminated
h) MTC Monitoring
i) Priority Alarm
j) Secure Connection
k) Location Specific Trigger
l) Network Provided Destination for Uplink Data
m) Infrequent Transmission
n) Group Based MTC Features
   - Group Based Policing
   - Group Based Addressing

Having the above as a starting point we can provide concepts for signalling reduction for MTC operation. Figure 1.4.2 shows examples of the possible signalling optimization issues / targets related to some of the above features.

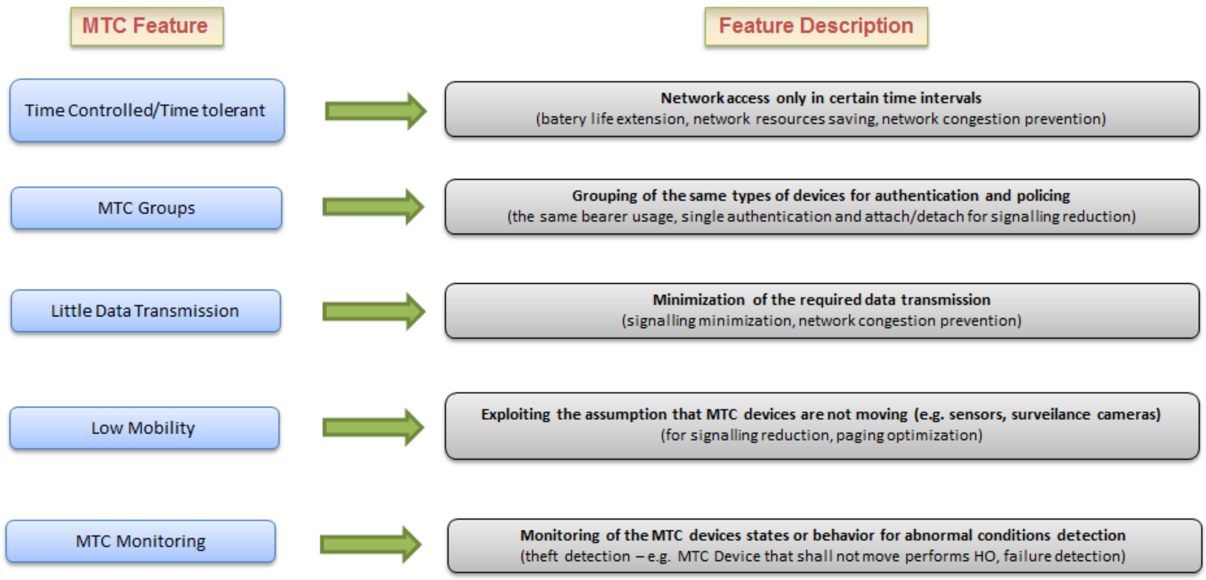

Figure 1.4.2 Example MTC features description

2 Proposed concepts for initial schemes / scenarios / use cases

The following chapter includes some initial concepts of a robust scheme design as well as a framework for multi-cell and single cell MAC scenarios.

2.1 Tradeoff signalling / payload

The overhead in LTE radio communications include [3GPP300]:

- Protocol overhead for IP packets (including PDCP, RLC, MAC headers and PHY redundancy coding and CRC),
- NAS signalling related to UE communication with core network (NAS signalling is packed into RRC messages),
- RRC signalling related to system info, paging and dedicated connection management,
- PDCP, RLC and MAC signalling related to each protocol side info – e.g. retransmission info, RoHC feedback, buffer / power statuses of UE,
- PHY signalling including resource allocations and feedback reporting, and
- PHY signals for synchronization and channel measurements as well as RACH resources.

For 5GNOW one of the most important goals is to optimize / decrease the impact of lower layer overhead. From one side, it would be beneficial to decrease the amount of PHY signalling and PHY signals to have more resources for actual data transmission. On the other side having less e.g. pilots or less complete feedback, the channel quality estimation may be of lower quality and thus the overall transmission can be less robust with respect to changing conditions.

Another issue is the resource scheduling information. E.g. for LTE we use: MCS, MIMO mode and precoding matrix, PRB allocation, and the RV (Redundancy Version) to tell the UE how to process DL-SCH or UL-SCH. There is a trade-off between the granularity of the resources and the accompanied signalling – e.g. a PRB of 12 subcarriers in the frequency domain is allocated as a lowest possible resource assigned to UE. We could imagine a situation, where we would use a per subcarrier allocation to have the possibility to pick the best spectrum portions for a UE. However the amount of allocation information to be sent to the UE would be very large. From another perspective, if the allocation would be on a subcarrier basis, to have information about the quality of each individual subcarrier the size of the CQI stream would need to be very large also, having negative influence on the UL frame capacity.

For a new waveform definition, in order to create a reliable transmission, there is therefore a need to define basic structures and modes for operation to build a required accompanying signalling.

Within a framework of signalling for reliable transmission it would be benefitial to define transmission types and to differentiate between various service / transmission types, e.g.:

- Normal UE data transmission: robustness mode selection for mobile and stationary users;
- CoMP scenario: with high requirement on reliable feedback and measurements; and
- MTC mode: robust / low data transmission.

For the above modes different kinds of RACH, pilots, signalling can be defined, each optimized for the particular transmission type, thus decreasing the overall PHY layer signalling. This approach would be different to current LTE scenario, where all types of transmission are to some extent treated in the same way (e.g. high throughput service is treated the same way as MTC transmission scenario in terms of e.g. feedback, pilot structure, allocation data).

The main parameters for the signalling / feedback could be for example:

- Granularity of resources in time and frequency,
- Modes of operation / transmission scenarios (e.g. for MIMO, for MTC, etc),
- Structure of pilots and resulting BER vs SNR requirements for various channel conditions,
- Required quantization of the allocation / feedback,
- Periodicity of transmissions and feedback to assure required quality,
- Types of FEC and required processing time for ACK/NACKs, and
- Waveform parameters (e.g. subcarrier spacing, BW size, processing matrices) dedicated to 5GNOW selected waveform.

The types of PHY layer signalling / PHY signals can include:

- Resource allocation (time / frequency / space resources, MCS, MIMO parameters, etc.),
- Feedback channel for UL (channel state information, MIMO feedback, etc.),
- Synchronization preambles,
- RACH resources,
- UL pilots for eNB channel estimation and DL sounding,
- DL pilots for UE channel estimation and DL sounding,
- Scheduling request notification, and
- Basic system info (e.g. BW or other parameter that will be important at initial UE camping).

2.2 Initial robust LTE mode concept

LTE defines several types and parameters for feedback, allocation, modes of operation and higher layer protocol configuration. A robust LTE mode is a transmission mode where we assume to relax requirements for synchronization, throughput, complexity and signaling for a transmission. For a robust LTE mode we assume to use the less overhead consuming configuration (the type that is used for providing e.g. paging, system info).

The basic assumptions for this mode are:

- non channel aware scheduling,
- minimize required feedback info,
- minimize required signaling for allocations,
- small amount of data transmitted,
- fast dormant-to-active switch, and
- periodic data transmission with defined periodicity.

Table 2.1 gathers the proposed parameters for robust LTE mode [3GPP321] [3GPP213] [3GPP201] [3GPP300] [HT01] [STB01].

Table 2.1 LTE robust mode

Parameter	Usage of parameter	Value / mode / description	Purpose of selection of certain value
CQI	Feedback	Frequency non-selective Transmitted over PUCCH Periodic reporting Wideband CQI	Decrease of amount of feedback data. No need for frequency selectivity info
MCS	Allocation	QPSK 1/3	Most robust MCS available
PMI/RI	Feedback	No PMI / RI (no MIMO)	No MIMO used for reduced complexity
Transmission mode	Allocation	Mode 1, SISO	No MIMO used for reduced complexity
DCI format	Allocation	1A, compact format	Simplest format for allocation (lower number of required bits to encode allocation data)
RACH	Getting UL grant if no resources	Non-contention based RACH Use of dedicated preamble	Fast dormant-to-active switch, assign dedicated preamble for RACH. No collisions
RRC Measurement reports	Handover	Event triggered (event A3 –neighbor becomes offset better than source)	Reduced L3 signaling. Report only when HO is very probable
DRX configuration / SPS	SPS usage, battery saving	Largest possible value, for sending periodic data (2.5sec)	Reduce signaling (PDCCH) and save battery power
Closed loop Power Control	Link adaptation	Not used	Reduce PDCCH signaling (no TPC)
TA timer	Timing alignment	Largest possible value (10.2 sec)	Reduce number of PRACH transmissions
RLC mode	Retransmission type	Unacknowledged mode (UM)	Reduce number of retransmissions at L2
Service mix	Resource prioritization / QoS	One service w/o QoS Only PS	Reduce complexity of assignments. Reduce complexity of scheduling
BSR	Buffer status, UL scheduling	New data indication, periodic BSR with largest possible value (2.5 sec) Short BSR	Reduce MAC signaling. Only periodic type of data sent. Low number of data sent each time
PHR	Power status, UL scheduling	Upon large pathloss change	Reduce MAC signaling. Transmit only when really necessary (i.e. radio link failure threat)

Parameter	Usage of parameter	Value / mode / description	Purpose of selection of certain value
CA	More resources for data	1 component carrier	Reduce signaling at PHY. Reduce scheduling complexity
Resource allocation type	Allocation	Resource allocation type 0 (RBG allocation)	Use simplest type of allocation. Reduce receiver complexity for allocation derivation
UL Hopping	Averaging frequency selective fading and interference	Switched ON	Reduce scheduling complexity. Reduce amount of L1 signaling (PDCCH) – one DCI for multiple TTIs
SRS usage	UL channel sounding	Switched OFF	Reduce UL signaling. Reduce scheduling complexity (no channel aware). Increase available number of data resources at UL Radio frame
Scheduling type	Resource distribution	Random / predefined hopping pattern, non-channel adaptive	Reduce scheduling complexity.
Mobility	Mobility measurements and HO types	Intra-frequency only	Reduce battery consumption. Reduce measurement complexity. Reduce L3 signaling.
HARQ ReTx Configuration	Number of retransmissions at PHY layer	Low number	Reduce number of retransmissions. Reduce number of L1 signaling.

The LTE robust mode can be used e.g. for MTC or simplified communication, with relaxation to overall complexity of the transmission / reception (e.g. channel estimation, feedback reporting, robust to various radio conditions, robust to frequent channel quality changes, fast UL transmission renewal).

Having the basic LTE robust mode for simple communication types (e.g. MTC), over the time of the project this approach can be extended towards more sophisticated/demanding or more data hungry scenarios. One of the examples could be e.g. extending the transmission scheme with the use of higher order modulation, dynamic allocations with channel aware schedulers and carrier aggregation.

Over the time of 5GNOW project, it may be beneficial to compare the performance of the above scenarios using practical tools. The scope of the comparison may include performance results under e.g. the presence of various synchronization mismatches (e.g. time, frequency, sampling, phase offsets), and the presence of interference and frequent channel changes to provide real robustness limits for the schemes (i.e. to obtain maximum synchronization offsets under which the system still works).

2.3 Initial use case scenario concepts for Single Cell MAC / Multi Cell RRM / CoMP

2.3.1 Single cell MAC

Single cell resource management include the resource distribution among active UEs – i.e. scheduling and link adaptation. In the 5GNOW project we take into account at least two different types of communication which can be treated differently in terms of QoS or scheduling policies, namely typical UE DL data hungry service, and MTC scenarios. The first one can be treated as it is already done in LTE/LTE-A, where according to various QoS profiles for normal data transmission the scheduler sets priorities and serves the users with respect to various schemes, e.g. Round Robin, Proportional Fair (PF) and Maximum CQI. The most used one is PF and variations of it (e.g. LWDF-PF, Largest Weighted Delay First with PF). The same concepts can be applied in 5GNOW, however the new waveforms' properties shall be incorporated in the scheduler design. The second type of communications, i.e. MTC, should be treated differently when optimizing the NW resources for MTC specific characteristics (e.g. very small amount of data sent only periodical). For MTC it would be beneficial to incorporate this properties within the scheduler design (e.g. set some predefined slots for MTC transmission, and change them dynamically according to number of MTCs). There is a necessity, however, for proper communication between the two modes / two types of internal scheduling algorithms to assign resources efficiently. The overall MAC scheduler can be defined as a coordinator for that communication type. The scenario (logical concept) is shown in Figure 2.3.1.

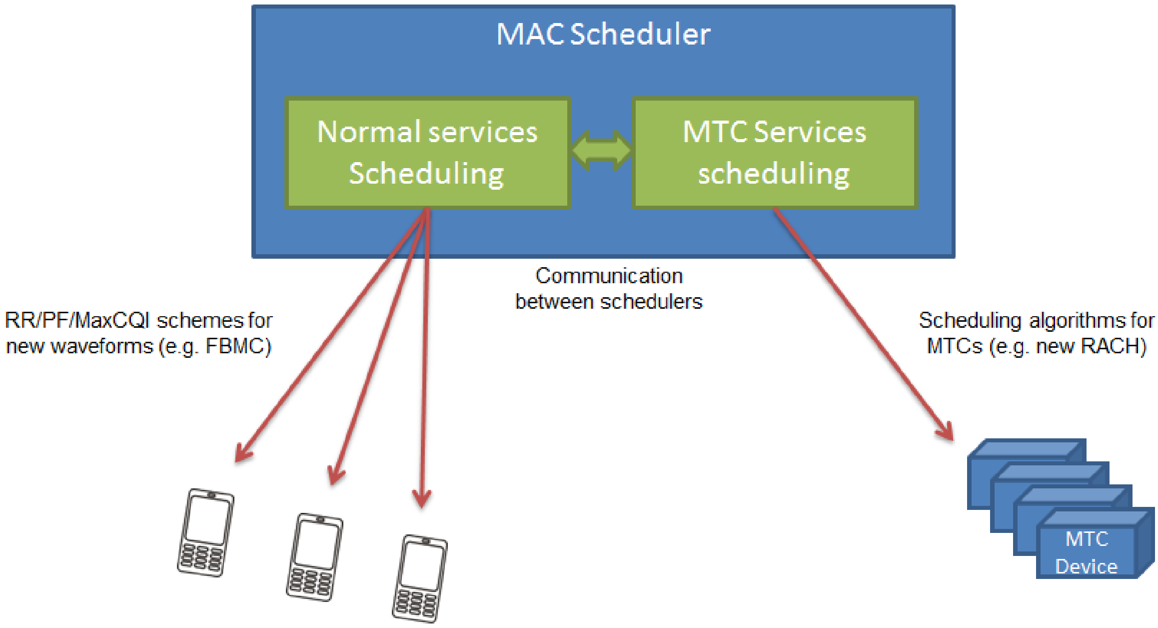

Figure 2.3.1 Initial single cell MAC design concept

2.3.2 Multi Cell RRM and initial CoMP use case scenario concepts

Multi cell resource management includes interference coordination and CoMP. For that purpose the single cell MAC scheduler shall be extended to take into account resource distributions from other cells. Therefore it is necessary to define communication between various nodes (or various cells within the same node). For the overall networking scenario we might design a hierarchical MAC structure: i.e a multi-cell MAC including individual cell MACs together with X2 interface communication in-between, where each individual cell MAC includes individual service type based MAC schedulers with an internal interface in-between.

For that approach, we might optimize different parts of the MAC hierarchy separately and define various algorithms specialized for one type of layer only, thus having the possibility for efficient resource management at various levels of the network. The scenario is shown in Figure 2.3.2.

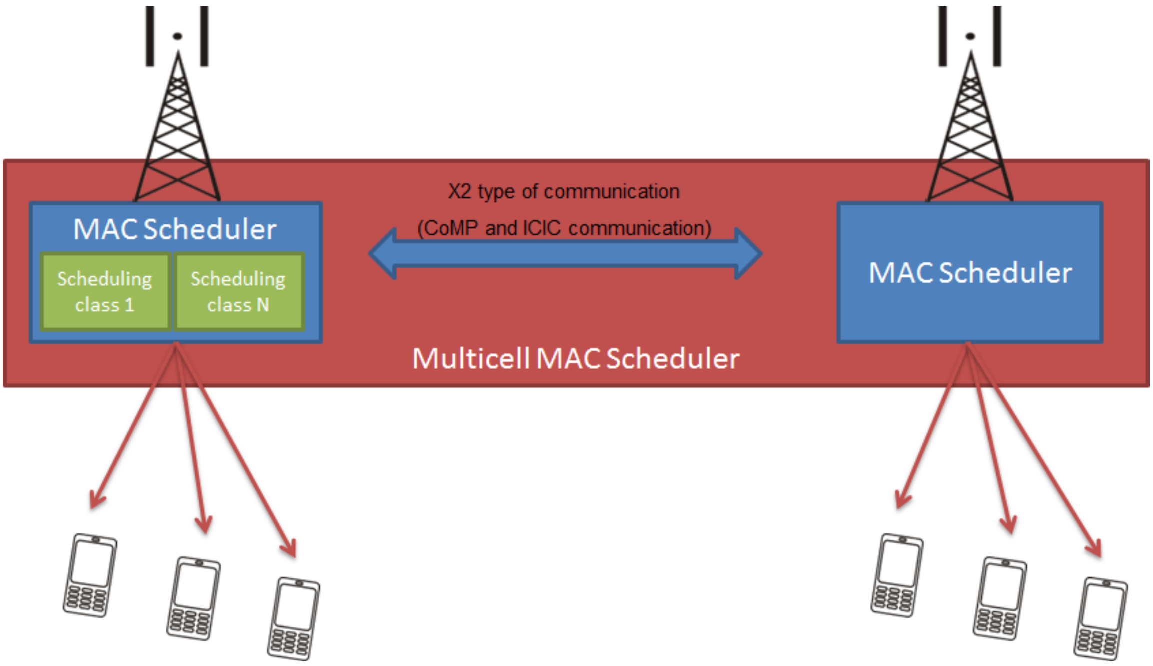

Figure 2.3.2 Multicell RRM MAC scenario

Figure 2.3.3 and Figure 2.3.4 show the DL and UL use cases that require X2 interface extension in terms of signalling. They relate to 3GPP defined LTE-Advanced CoMP scenarios.

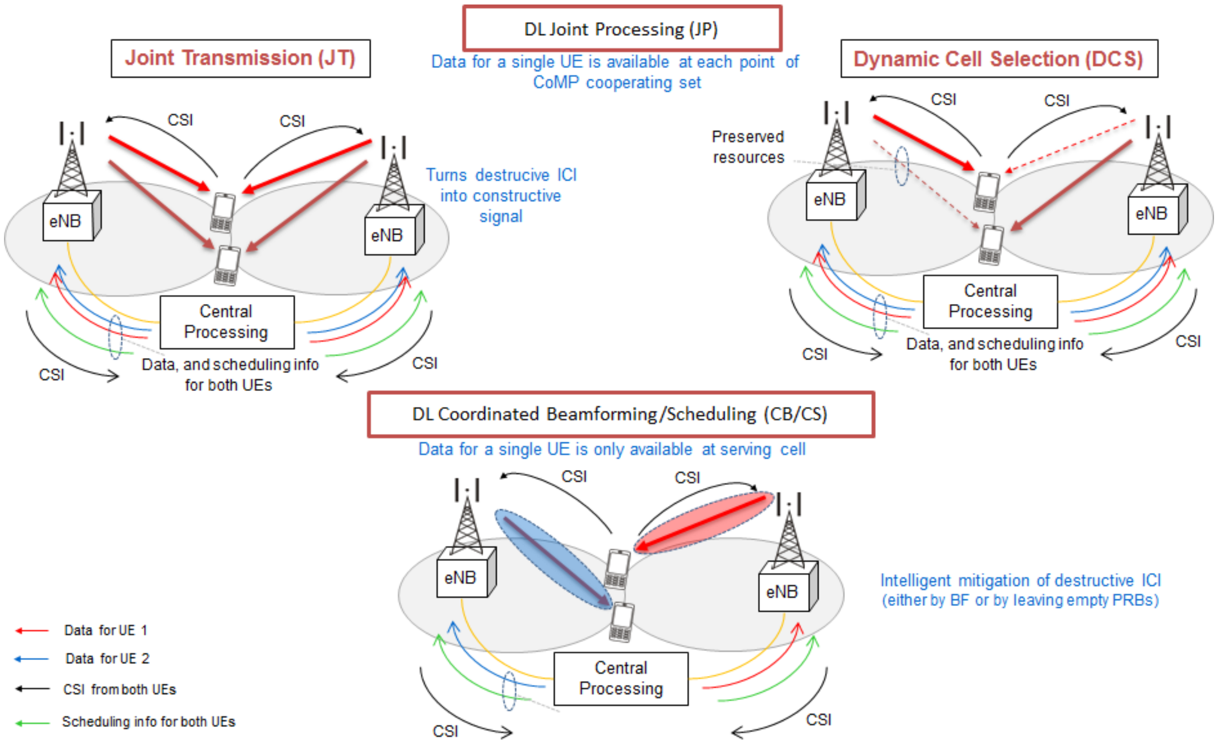

Figure 2.3.3 DL CoMP scenario

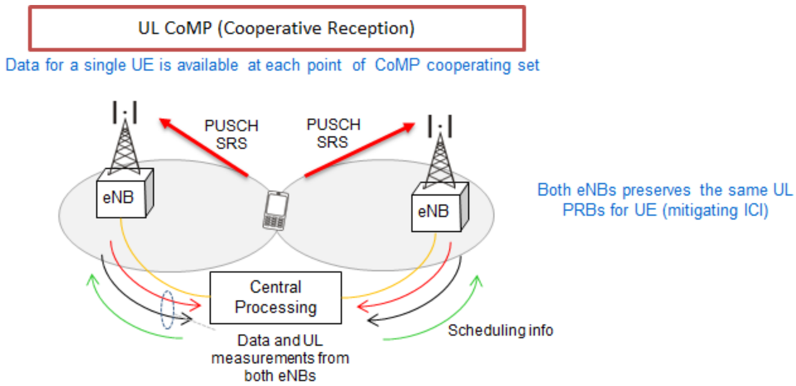

Figure 2.3.4 UL CoMP scenario

CoMP issues and limiting factors include:

- Backhaul latency and capacity (need for fast exchange of scheduling info, CSI, BF weights, data),
- Uplink CSI feedback overhead (radio channels' measurements to all cooperative points in the serving set),
- Reference signals overhead in DL (more resources needed for DL measurements, e.g. use of CSI RS for CoMP),
- Synchronous data exchange and clock synchronization between eNBs (for proper timing of coordinated transmission), and
- Uplink CoMP is implementation matter only (does not require any changes to radio interface).

The standardization roadmap for CoMP is as follows:

a) Rel. 10 – CSI and DM RS, CoMP Scenarios definition
b) Rel. 11 – Coordinated beamforming and scheduling (DL CoMP), UL CoMP
c) Rel. 12 – Joint processing (DL CoMP).

One of the proposed solutions for CoMP is the use of FBMC. Filters Banks Multicarrier (FBMC) is a multicarrier modulation technique that was first investigated in the 1960s, prior to OFDM. Today FBMC, which complexity is higher than OFDM, is experiencing renewed interest due to significant increase in computational capacity of electronic equipment. FBMC is characterized by a prototype filter that can be optimized regarding to the target application and to the dispersive nature of the channel, either in time or in frequency or both. Subcarriers filters can then be for example designed with arbitrarily low secondary lobes, making FBMC a good candidate for multiple access communications or opportunistic spectrum access. FBMC is often referred to as a non-orthogonal modulation technique as FBMC symbols overlap in the time domain and as adjacent subcarriers overlap in the frequency domain. This structural absence of orthogonality at the transmitter somewhat relaxes the constraints of orthogonality at the receiver and implies no need for Guard Interval, increasing the bandwidth efficiency.

One objective of the 5GNOW project is to investigate the opportunity to use FBMC for Multi-User (MU) DL cooperation between cells (CoMP). In CoMP operation, multiple points coordinate with each other in such a way that the transmission signals from/to other points do not incur serious interferences or even can be exploited as a meaningful signal. MU-CoMP enables to provide good quality of service (QoS) to cell edge users while maintaining a high spectral efficiency in the system. There are many challenges for such a scenario. First, cooperation between cells implies non synchronized signals at the receiver, due to the different distances between the receiver and the cooperating Base Stations (BSs). Furthermore, MU transmission requires feedback information from the receivers to the transmitters; the bandwidth occupied by this control information must be kept as low as possible.

As depicted in Figure 2.3.5, one scenario of interest comprises two user devices (UE1 and UE2) in two adjacent cells (BS1 and BS2). The BSs transmit towards the UEs in the same band. The objective is to demonstrate the feasibility of DL CoMP for 5G systems with non-orthogonal FBMC waveforms, taking into account realistic parameters such as:

- Sources of offset
  - Received signals from multiple cells may not be aligned in time at the receiver due to propagation delay differences and to possible time synchronization mismatch between cooperating BSs. This offset causes pilots rotations at the receiver that make the estimation of the channel difficult. High time delays will be studied.
  - Clocks at the BSs and at the UE side may not be perfectly synchronized in frequency, causing Carrier Frequency Offset (CFO) at the receiver. The impact of the CFO will be studied.
- Return link
  - In order to deal with different time of arrivals from different BSs, the receiver may estimate the delay and feedback the information to the BSs. The cost of this operation, in term of UL bandwidth, will be studied.
  - MU-CoMP implies CSI knowledge at the transmitter side. The necessary information to be feedback to the BSs will be investigated.

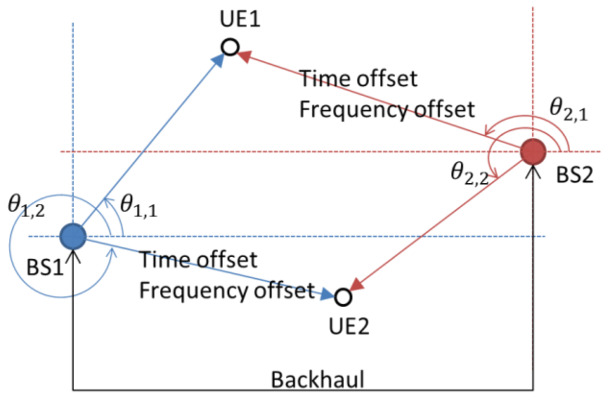

Figure 2.3.5: Example of use case for the CoMP scenario in the downlink

2.3.3 MAC – PHY interfacing

The activities in WP4 and WP3 so far are merging to an approach where the different types of traffic (see Section 3.1.1.1) are treated according to their specifics (e.g. traffic behaviour). A unified frame structure uses different kinds of waveforms suited for a traffic type, whereas MAC design is divided into parts with different scheduling approaches depending on the traffic type to minimize signalling where e.g. a synchronous approach with scheduling commands is not needed. The work in 5GNOW WP4 will focus on a more detailed description of single cell scenario (i.e. Section 2.3.1) with lighter treatment of multi-cell scenarios (Section 2.3.2). A definition of specific interfaces between MAC and PHY corresponding to a unified frame structure will be provided in the future.

A possible approach for the definition of MAC can be to use standard, well known resource scheduling mechanisms (e.g. PF, RR, max CQI, MLWDF) and apply them for the new waveform and Unified Frame concepts, such that they suit well for different application/traffic types. In that context, an example multiple access schemes might be defined as follows (taking as an example traffic types defined in Section 3.1.1.1):

a) Dynamic, channel adaptive resource scheduling for traffic type 1 using standard resource scheduling mechanisms.
b) Semi-static/persistent scheduling (SPS) for traffic type 2 – e.g. IDMA for MTC in UL with medium traffic volume. From MAC point of view it is necessary to decide on amount of resources allocated for this type of traffic, since scheduler will not adapt to specific part of frequency (may also be used for high speed UEs). IDMA fits well, since it does not provide possibility for channel adaptive scheduling and don't need spreading code to be allocated to an individual UE.
c) One shot transmission (low amount of data + pilots) with contention based approach using D-PRACH (traffic type 3 and 4). For this scenario MAC shall define/steer the amount of resources dedicated for DPRACH usage.

The a-priori knowledge of the type of MTC device (e.g. as defined in Chapter 1.4 and [3GP11a]) may also be useful to support direct decisions in the multiple access approach in order to minimize signalling and learning part (e.g. a type of MTCD provided to the network during NW attach). As an example, the knowledge that a MTCD is low mobile (or even static) can help to:

- Decrease feedback rate and granularity;
- Decide on scheduling approach – e.g. SPS, and
- Define the granularity of pilots (e.g. decrease the amount of pilots) – to be incorporated in the Unified Frame structure design (e.g. define the different pilot patterns for different traffic classes).

3 Initial robustness concept based on the new selected waveforms

In this chapter we first describe the implications of our unified frame structure concept, which aims at handling a large set of requirements in a single 5G system, on MAC design. Moreover we describe novel robustness concepts as means to overcome current systems' limitations. In addition the influence of CSI on CoMP is investigated.

3.1 Implications of unified frame structure and new RACH on MAC design

3.1.1 Unified frame structure

3.1.1.1 Unified Frame Structure Overview

As outlined and introduced in [WKW+13] and [5GNOWD3.1], Figure 3.1.1 depicts schematically the Unified Frame Structure concept, which aims at supporting different sets of requirement and service classes efficiently within a single carrier.

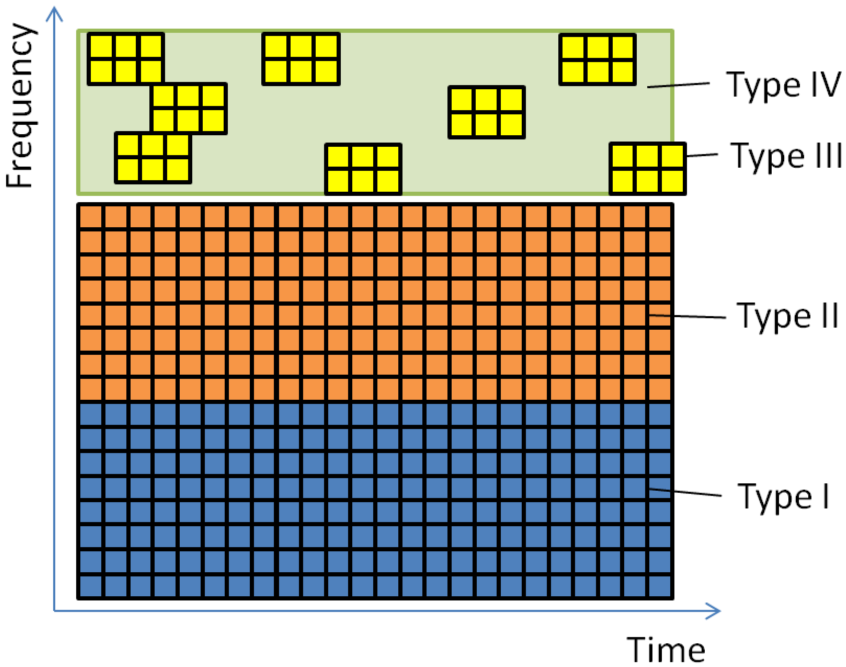

Figure 3.1.1: Unified frame structure

The basis of the universal frame structure is a multi-carrier transmission technique (such as the discussed waveforms in [5GNOWD3.1]). Each square in Figure 3.1.1 represents a single resource element, a single subcarrier of a single multi-carrier symbol. For supporting the heterogeneous 5G system requirements, the frame is divided into different areas, as shown in Table 3.1 and discussed in [5GNOWD3.1].

Table 3.1: Traffic Types in the Unified Frame Structure

Traffic Type	Synchronization	Access Type	Properties
I	closed-loop	scheduled	classical high volume data services
II	open-loop	scheduled	HetNet and/or cell edge multi-layered high data traffic
III	open-loop	sporadic, contention-based	few bits, supporting low latency, *e.g. smartphone apps*
IV	open-loop/none*	contention-based	energy-efficient, high latency, few bits

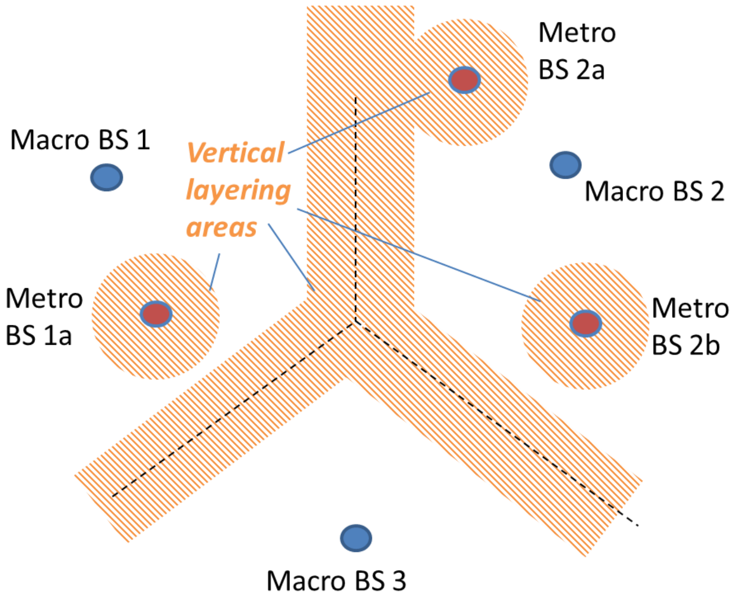

Figure 3.1.2: Areas applying vertical layering across multiple cells.

Naturally, the unified frame structure only becomes efficient, if combined with respectively tailored signal processing and waveforms. The waveform designs proposed in [5GNOWD3.1] are prepared to support this: One of the key characteristics here is the reduced side-lobe behavior common to these proposals compared to conventional OFDM, as it directly leads to reduced inter-carrier interference in case of relaxed time-frequency alignments.

Ongoing research studies in the framework of the unified frame structure will assess the capability of the underlying waveform to support the overall concept. First results, using the Universal Filtered Multi-Carrier (UFMC) waveform, are presented in [5GNOWD3.1]. They demonstrate the superiority of UFMC to OFDM in supporting the Unified Frame Structure in the relaxation of time- and frequency-alignments. UFMC shows much more robustness against inter-carrier interference, caused by timing and frequency offsets.

The introduction of vertical signal layers in a MC-CDMA or IDMA [PLW+02] fashion introduces additional degrees of freedom for resource allocation and handling multi-user- and multi-cell-interference. Efficient multiuser receive strategies can be implemented e.g. with the Elementary Signal Estimator (ESE) [PLW+02]. Those vertical signal layers can be combined well with a multi-carrier modulation, as discussed in [5GNOWD3.1].

3.1.1.2 Uplink and Downlink Aspects

The introduction of MTC and IoT naturally shifts the focus to the uplink, e.g. triggered by traffic caused by the large amount of data.
The Unified Frame Structure concept takes care for this in the uplink by the addition of contention-based data transmission (type III and IV traffic).
However, in the downlink, relaxation of synchronicity applies as well in conjunction with CoMP and multi-cell in general, e.g. driven by heterogeneous networks for type II traffic. (Note that Type III and IV traffic might not be relevant for the downlink.)

3.1.1.3 General implications on MAC design

The Unified Frame Structure concept provides the possibility to have scheduled access and contention-based access in parallel. For MAC design, compared to LTE, additional decision functionality is required in order to decide whether a user shall use the system in a contention-based or a scheduled way. For some devices, like low-end MTC devices with only sporadic traffic, the choice might be static and handled by the introduction of a new device class – for this example only using contention-based access. For other devices like smartphones, the best choice might very well depend on the particular application.
In general, in order to make best use of the Universal Frame Structure, quality of service (QoS) related information is important to 5G wireless systems, helping to decide, which of the supported traffic types (e.g. I-IV in the above depicted classification) is relevant for a particular data transmission.

The main approach of 5GNOW relating to the above considerations is to treat various types of traffic differently, according to specifics of their behavior (e.g. DL hungry, UL only, synchronous, etc.). Thus, taking all the considerations above (i.e. approaches of new frame structure and a new RACH design) on the physical layer, additional aspects are appearing from the multiple access perspective, e.g.:

- Another building block with respect to the unified frame structure concept is feedback that needs to reflect the requirements on the transmission modes. The feedback type may be incorporated in an overall system design to adjust the feedback policy with the corresponding scenario (e.g. CoMP, MTC, single-cell bit pipe). The parameters of feedback (e.g. bit rate, quantization and periodicity) shall be adjusted to the type of transmission with respect to required performance / robustness of this traffic type.
- A multiple access scheme including an adaptive frame structure depending on UEs mobility and distance from the eNB. The number of resources could be dynamically adapted within the frame structure depending on the traffic type and QoS. While fixing the overall frame size, the possible parameters for adaptations could be: amount of resources per each traffic type, CP size, subcarrier separation and waveform type.

3.1.1.4 Multi-layer implications on MAC design

As mentioned above, Interleave-Division Multiple Access (IDMA) could be a characteristic feature of the universal frame structure, by introducing multiple vertical signal layers to support both scheduled access and contention-based access. Especially in the uplink, the Base Station (BS) is capable of exploiting several iterations jointly between the ESE and Forward Error Correction (FEC) decoder to efficiently separate the signals of the IDMA users. On the other side, a dedicated MAC design for IDMA is also necessary, e.g. reconsidering the link adaptation (the choice of modulation and coding scheme per user) etc. Generally, the IDMA concept prefers low rate data communications. Hence, the time and frequency resource allocation for a given user could be physically wider as usual, and multiple users are allowed to share the same resource. This could more or less relax the MAC design, as superposition of signals are possible, leading to a “soft limit” of the system. The most important of all, for both scheduled access and contention-based access, the IDMA detector (in conjunction with the appropriate multi-carrier waveform) can robustly combat against the asynchronicity of multiple users. Being an important part of future investigations, a low rate FEC code will be in focus, which can be regarded as a common issue for both PHY and MAC design. The preferred FEC should not only deliver high performance, but also flexibly enable short code block length and possibly support diverse code rates, which is appropriate to sporadic machine type traffic. Further, we have to investigate, how many simultaneous IDMA users can be sub-optimally served, by considering and trading-off the issues, such like MAC overhead, PHY performance degradation, detection complexity.

3.1.1.5 Multiple access scheme selection challenge

An on-going research challenge across the work packages 3 and 4 in 5GNOW will be the choice of an appropriate multiple access scheme in conjunction with the waveform for particular scenarios and operation points. The usage of multiple signal layers, as in IDMA, provides different design options. One important comparison case for the uplink, using the Unified Frame Structure is discussed here with respect to effects occurring at the edges of different user allocations and traffic types, due to potential timing and frequency misalignments.

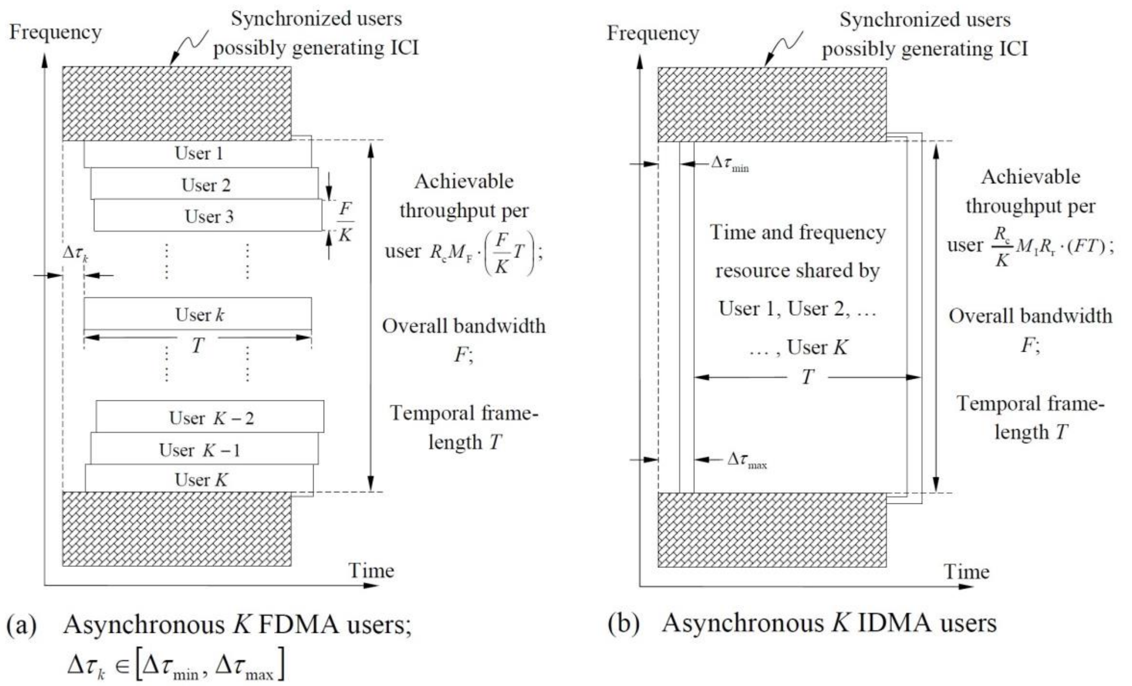

Figure 3.1.3: A scenario and model for comparison between FDMA and IDMA

In Figure 3.1.3, a scenario and model for comparison between FDMA and IDMA is provided. In FDMA, a relatively narrow frequency bandwidth F/K is assigned to an arbitrary user k, with $1 \leq k \leq K$, where K denotes the number of total users. We consider an FEC code rate R_c and a fixed temporal frame-length T, by deploying the modulation scheme, which maps M_F bits to a data symbol. The achievable throughput per user is $R_c M_f \cdot (FT/K)$. In IDMA, all users are allowed to share the complete bandwidth F, by reducing the effective FEC code rate to R_c/K, mapping M_I bits to a modulated symbol and optionally deploying a repetition coding with rate R_r. This yields an achievable throughput $\left(\frac{R_c}{K}\right) M_I R_r \cdot FT$.

Notice that we have the degrees of freedom to adjust the parameters R_c, M_F, M_I, K and R_r, to enable an identical achievable throughput for a fair comparison between FDMA and IDMA. We expect that the MAC design in Figure 3.1.3 can significantly benefit the IDMA scheme due to high potential frequency diversity and low ICI introduced by adjacent users. Especially, the reduced FEC rate can guarantee a robust IDMA performance.

Future work will investigate the performance of the multiple access choices, based on this scenario and model setting.

3.1.2 Advanced RACH concepts

5G networks will have to accommodate traffic classes with very diverse (virtually contradicting) requirements in the uplink. For example, sporadic traffic generating devices (e.g. devices in the Internet of Things, but we also think about smartphone apps etc.) are most of the time inactive but regularly access the Internet for minor/incremental updates with no human interaction.

Interestingly, smartphone apps show a similar behavior (e.g. weather forecasts, stock prices, navigation position, location-dependent context information etc.) resulting in significant control signaling growth and network congestion threat. Such traffic should not be forced to be integrated into the bulky synchronization procedure of current cellular of 4G. By doing so MTC traffic would be removed from standard uplink data pipes with drastically reduced signalling overhead improving operational capabilities and network performance as well as user experience and life time of autonomous MTC nodes.

Sporadic traffic will dramatically increase in the 5G market and, obviously, cannot be handled with the bulky 4G random access procedures. Two major challenges must be addressed:

1) The unprecedented number of devices asynchronously access the network over a limited resource, and

2) the same resource carries control signalling *and* payload.

Dimensioning the channel according to classical theory results in a severe waste of resources which, even worse, does not scale towards the requirements of the IoT. On the other hand, since typically user activity, channel profiles and message sizes are compressible within a very large receive space, sparse signal processing methodology is a natural framework to tackle the sporadic traffic. In addition, as clearly outlined in [Fet12] the *Tactile Internet* requires ultra-fast acquisition in the order of 100μs on the physical layer to enable 1ms round trip delay. This is far shorter than current 4G cellular systems allow for, missing the target by nearly two orders of magnitude. Notably, this implies that even small, say 1kBit data bursts, result in huge bandwidth requirements. Again, we will argue that classical theory requires that for each real-time connected device a significant control signalling overhead is necessary to allow for swift channel estimation, equalization and demodulation. Since, in addition, this traffic class must be also extremely reliable, control signalling must be separated from data which is again very inefficient. Consequently, many traffic classes such as sporadic traffic, real-time etc. require very fast acquisition and therefore an efficient common control signalling channel.

In the following sections, we will outline a new architecture using a suitable sparse signal processing concept to efficiently deal with the sporadic traffic and control signalling problem. In fact the ratio of control and data can be actually reversed by such concept to approach a value below 5% within 1ms sub-frame. Donoho and Candes have explored the key finding that in an over-determined system the signal components can be indeed identified if
1) the measurements are suitably constructed, and
2) the signal space is sparse, i.e. only a limited number of elements in some given basis are non-zero.
It has soon been recognized that this can be exploited for random access performing user identification and data detection in one step. Sparsity can be incorporated into ML estimation by a sparsity promoting term [ZG11]. This problem has been recently extended to the multipath fading channel modelling the problem by virtual nodes by Dekorsy. However, recent concepts deal either with data or channel estimation and an overall architecture is missing. Motivated by recent papers we provide a system concept and corresponding analysis and simulations.

3.1.3 The design problem

The design problem for random access can be identified as follows: terminals require access to a system over the physical layer random access channel (PRACH). We assume for comparability a sampling rate of 32k samples per 1ms subframe similar to LTE. The only source of information that they have is the broadcast channel of the system to which they seek access. Hence, one can assume that some rough synchronization is available. Hence, for a cell size of roughly 1.5km we can assume that according to the sampling rate the channel delay vectors are of length 300 at maximum.

Each user has a data and control signal part which might overlap with each other. However, detectability becomes erroneous the more control is interfering with the data (after the channel). On the other, the control must somehow interfere with data in order to allow for estimation of the channel. This seems to a contradicting, irresolvable task at first sight. However, with sparse signal processing we can cope with that task as follows:

Let us introduce a control part (C-PRACH) and data part (D-PRACH) of the RACH. We assume that the data signalling leaves out some space for the identification of users. Otherwise, the user identification performance is severely degraded and not compliant with current standards. Actually, where this observation window lies is immaterial! We assume that it complies with the standard LTE PRACH in the middle of the bandwidth for simplicity. (This has some advantages in terms designing sequences with certain properties.) Hence, we conclude that as long as the control channel occupies the standard PRACH there is no difference to identification performance of LTE. However, as said, we also want to estimate the channel for the user in the D-PRACH. To do so we will spread the signalling over the whole signal space (underlay signalling) and potentially collect it within the observation window again. For this underlay signaling the design task we are facing is to keep as much structure to ensure proper identification but incorporate as much randomness in the signal to enable proper estimation. The proposed scenario is illustrated in Figure 3.1.4. In the following sections the details are outlined.

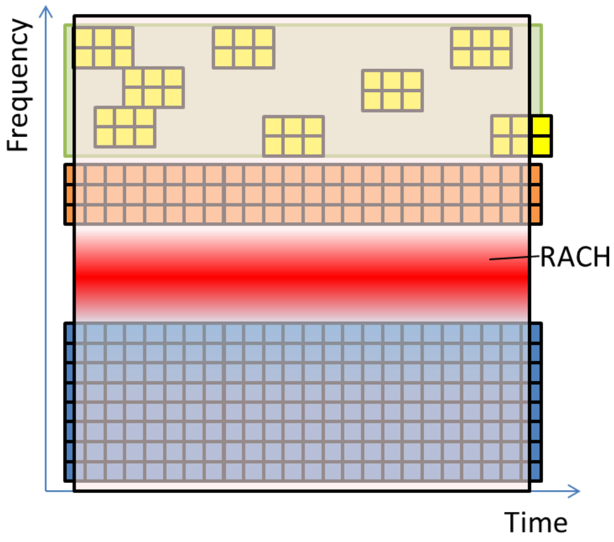

Figure 3.1.4: Illustration of D-PRACH within unified frame structure

3.1.4 Compressive Random Access

3.1.4.1 Underlay Control Signalling

We start by considering first the following generic single–user system model. Let $p \in \mathbb{C}^n$ be a pilot (preamble) sequence which is unknown but from a given set $\mathcal{P} \subset \mathbb{C}^n$ and $x \in \mathbb{C}^n$ be an unknown (coded) data vector. Both are transmitted simultaneously and use potentially the same resource. We set $\mathbb{E}\frac{1}{n}\|p\|_{l_2}^2 = \alpha$, and $\mathbb{E}\frac{1}{n}\|x\|_{l_2}^2 = 1-\alpha$. Hence, the control signalling fraction of the power is α and, due to the random nature of x we have $\mathbb{E}\frac{1}{n}\|p+x\|_{l_2}^2 = 1$, i.e. the total transmit power is unity. Note that in typical systems n is large, say n=24576 as in LTE/LTE-A.
The action of the channel is abbreviated by the bilinear mapping *B(x+p,h)* and h$\in \mathbb{C}^\tau$ denotes the vector of the τ channel coefficients. With the consideration regarding cell size in the section before we set $\tau = 300$. For ease of exposition we assume $\|h\|_{l_2}^2 = 1$. Due to the linearity we have *B(x,y)=C(x)y=D(y)x*. The AWGN is denoted as e$\in \mathbb{C}^\tau$ with $\mathbb{E}ee^* = SNR^{-1} \cdot I_n$. The received signal is then:

$$\begin{aligned} y &= \Phi B(h, p+x) + e \\ &= \Phi B(h,p) + \Phi B(h,x) + e \end{aligned}$$

where Φ denotes the overall sampling matrix (to be specified later on).
We restrict our contribution here to time–invariant channels and we use a cyclic model, which is achieved with OFDM–like signaling and the use of an appropriate cyclic prefix. The vector *h* is here the sampled channel impulse response with a maximum delay τ. Even in the unsynchronized setting the length of the cyclic prefix is chosen to match τ. In an OFDM system the FFT–size n is then chosen as $n \gg \tau$ and therefore, *[h,0]* $\in \mathbb{C}^n$ denotes the corresponding zero-padded channel impulse response. Hence, for circular convolutions *B(h,x)=[h,0]*x* we obviously have that *C(z)=D(z)=circ(z)* are both circular matrices with *z* on its first row. We can write this as

$$x * y = circ(x)y = \underbrace{\sqrt{n} \cdot W * diag(W,x)Wy}_{circ(x)} = \sqrt{n} \cdot W * (\hat{x} \odot \hat{y})$$

where W is (unitary) Fourier matrix with elements $(W)_{kl} = n^{-\frac{1}{2}} e^{-i2\pi kl/n}$ for $kl = 0 \cdots n-1$, i.e. $W^{-1} = W^*$ ($W^*$is the hermitation of W). We use here also $\hat{x} = WX$ to denote Fourier transforms and $\odot$ means point–wise product. With these definitions we get:

$$y = \sqrt{n} \cdot W^* \left[\hat{h} \odot (\hat{p} + \hat{x}) \right] + e$$

3.1.4.2 Receiver Operation

The primary goal is to estimate the data vector *x* from the observations *y* whereby also the vector *h* of channel coefficients is unknown. A possible strategy is to estimate separately first the channel coefficients $\tilde{h} = Q_h(y | x \in X)$, under certain assumptions on the data x. A simple approach here is for example to treat $\Phi B(h, x) + e$ as noise. In a second phase then the data $\tilde{x} = Q_x(y|h)\tilde{h})$ conditioned onto $\tilde{h}$ has to be estimated. Obviously, this procedure can then be iterated with or without data decoding. Let us now focus on the identification. The goal is the limitation to a relatively small observation frequency window, i.e. frequency indices in the set $\mathfrak{B}$ of cardinality $m = |\mathfrak{B}|$. Let us denote with $P_B : \mathbb{C}^n \to \mathbb{C}^m$ the corresponding projection matrix. For identifying which preamble is used in the system we observe:

$$y_I = \sqrt{n} \cdot P_B W^* \left[\hat{h} \odot (\hat{p} + \hat{x}) \right] + e.$$

The values are correlated with

$$d = W^* (W^* p_u \odot y_I).$$

Illumination and Partial Fourier Sampling: It is known that fixed Fourier windowing has several drawbacks (which will be explained later on). To introduce certain randomization we consider pointwise multipliers $\xi \in \mathbb{C}^n$ in time domain and we denote the corresponding $n \times n$ diagonal matrix as $M_\xi := diag(\xi)$. Summarizing, the $m \times n$ sampling matrix$\Phi = P_B W M_\xi$ will be considered. With the bilinear model we get for the observation vector y_B:

$$\begin{aligned} y_I &= \sqrt{n} \cdot P_B W M_\xi W^* \left[\hat{h} \odot (\hat{p} + \hat{x}) \right] + e \\ &= \sqrt{n} \cdot P_B \left[\hat{\xi} * \left[\hat{h} \odot (\hat{p} + \hat{x}) \right] \right] + e \\ &= \sqrt{n} \cdot P_B \cdot circ(\hat{\xi}) \left[\hat{h} \odot (\hat{p} + \hat{x}) \right] + \mathrm{e} \end{aligned}$$

The $m \times n$ matrix $P_B \cdot circ(\hat{\xi})$, is usually called partial circulant matrix. Note that $\hat{h}$ is sparse in the Fourier domain.

Channel Estimation: We assume to have a–priori support knowledge on h, i.e. $supp(h) \subseteq \mathrm{T}$ with T denotes for example the set $[0, \ldots, T_{cp}]$ due to the cyclic prefix. Preferable for sparse channel vectors h, is the l_1–penalized least square:

$$\tilde{h} = argmin_h \| \Phi D(p) h - y \|_{l_2}^2 + \lambda \|h\|_{l_1}$$

which occurs as Lagrangian for the basis pursuit denoising (BPDN). Such type of estimates can also by implemented by quite efficient greedy methods like CoSAMP [NT08] with precise guarantees in reconstruction performance.

Estimation of Sparse Data Symbols: Once the channel is estimated the corresponding pilot signal is subtracted for the received signal. We denote the error of this operation as $e = \hat{h} - \hat{h}_*$. Hence, the received signal is given by

$$y_I = \sqrt{n} \cdot (\hat{h}_* + d) \odot (\hat{x}) + \sqrt{n} \cdot [d \odot \hat{p}] + e$$

which is a set of parallel channels each with power $|\hat{x}_k|^2 = 1 - \alpha$ and $|e_k|^2 = SNR^{-1}$.

3.1.5 Performance estimation

It can be shown that altogether the capacity is given by

$$R(\alpha) \geq \log\big(1 + \mathrm{SNR} \cdot (1 - \alpha)\big) - \log\left(1 + m \cdot \left(\frac{4\sqrt{1 + \delta_{2k}}}{1 - (1 + \sqrt{2})\delta_{2k}}\right)^2 \cdot \left(\mathrm{SNR} \cdot \frac{1 - \alpha}{\alpha} + \frac{1}{\alpha}\right)\right)$$

Figures 3.1.5 and Figure 3.1.6 show numerical performance results, depending on the design parameter α which above given capacity lower bound is based on.

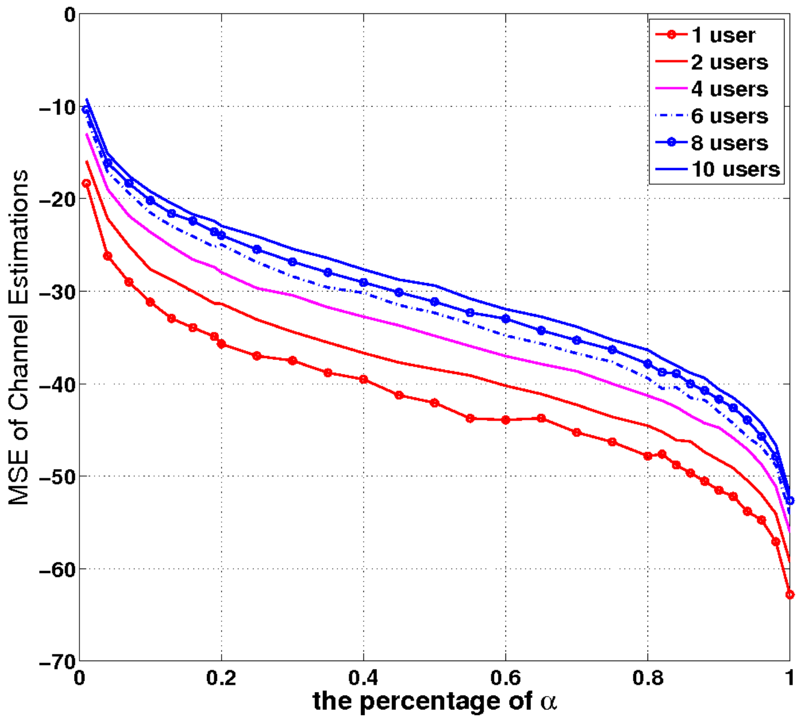

Figure 3.1.5: Performance with respect to MSE of channel estimations

Figure 3.1.5 depicts the MSE of channel estimations over the chosen parameter α. We can observe that the MSE decreases with α. Figure 3.1.6 shows the symbol error rate over α. From this we can conclude that an optimization over α is necessary to find the most suitable value. With that the symbol error rate with 10 users can be made smaller than 10^{-1}.

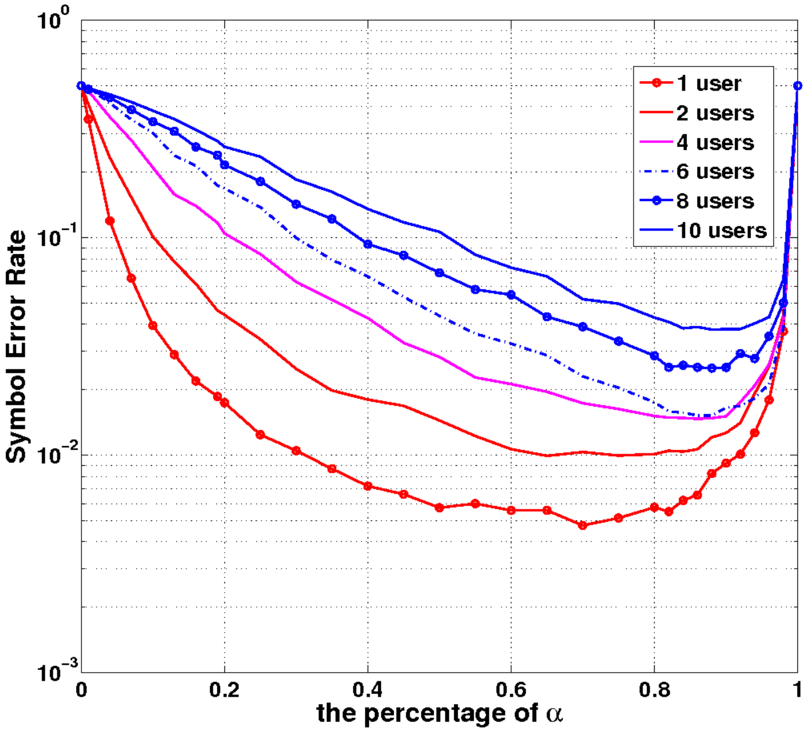

Figure 3.1.6: Performance with respect to symbol error rate

3.1.6 MAC D-PRACH: Example procedure of D-PRACH usage in MTC

Another aspect is the overall operation including feedback for the new RACH (D-PRACH) transmission (using RA preamble with data bits) in MTC applications. A possible D-PRACH procedure and operation including ACK/NACK feedback (see Figure 3.1.7) could be:

- The D-PRACH preamble is sent with data.
- If NACK is received, it means, the receiver failed to decode the data, but received the preamble sequence. In that case a notification is sent together with resource allocation and then retransmission of the data is sent over PUSCH.
- If ACK is received, it means, BS received data and preamble. In that case nothing else need to be send and MTC device is going to idle;
- If nothing (no ACK/NACK) is received, it means, the D-PRACH preamble need to be sent with higher power (possibly including backoff time).

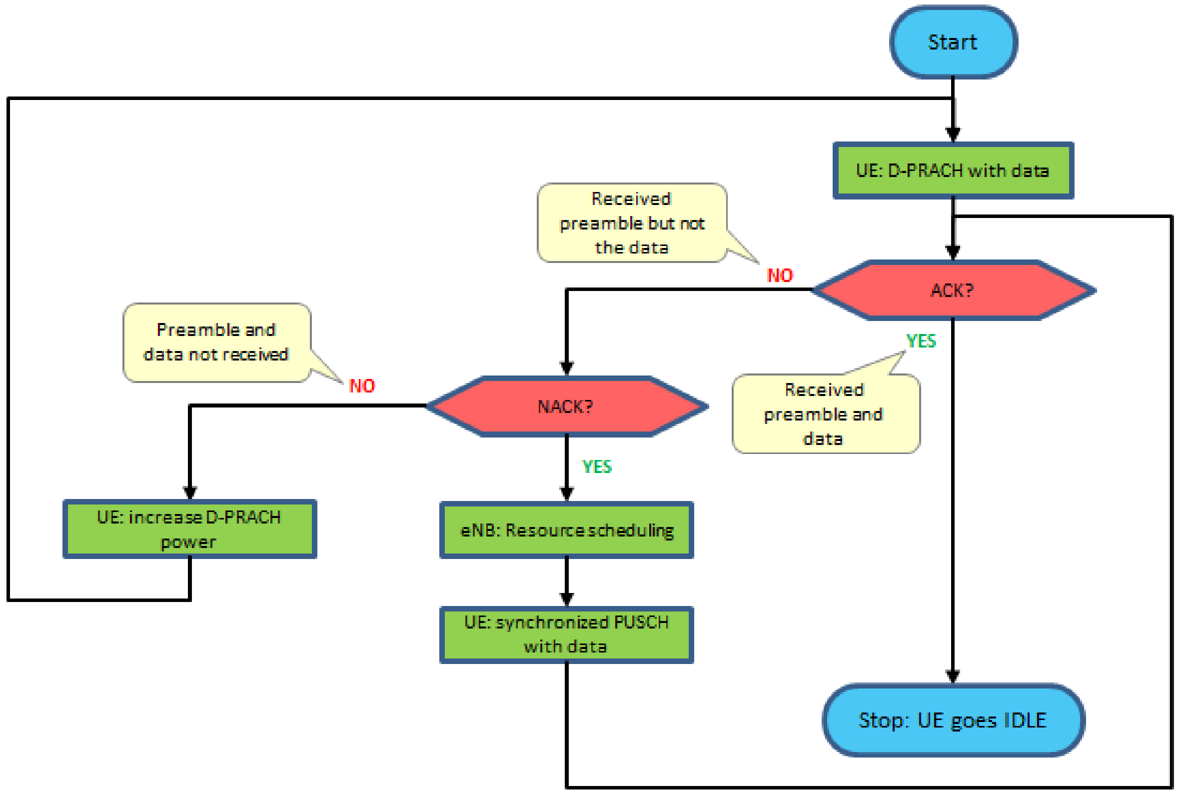

Figure 3.1.7: D-PRACH operation procedure

Figure 3.1.8 shows the signaling flows comparison for the typical LTE-like UL transmission with the proposed operation of D-PRACH.

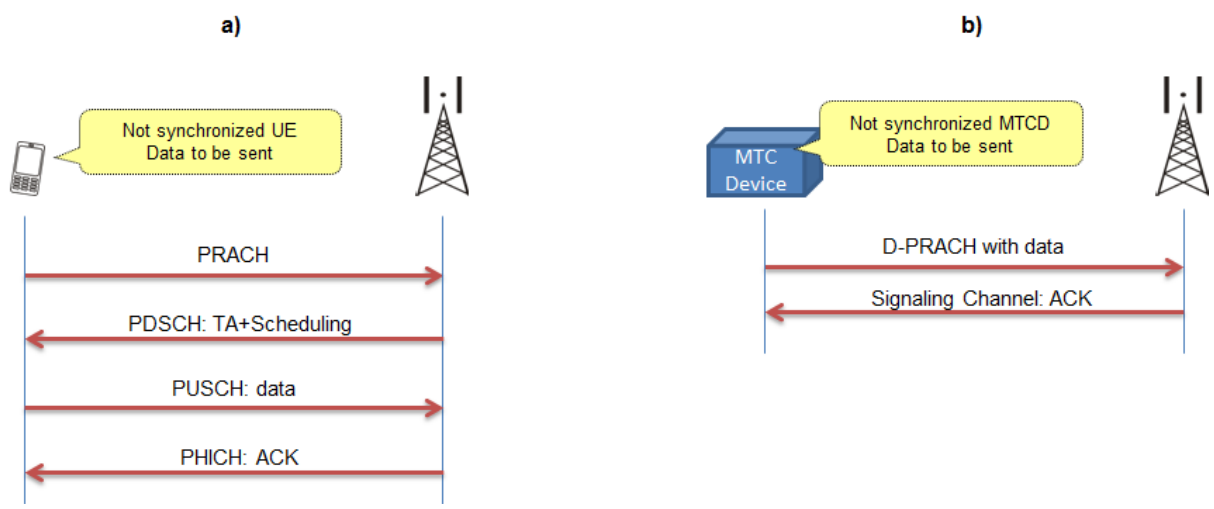

Figure 3.1.8: Signaling flows comparison for non-synchronized UE transmission: a) LTE-like UL; b) MTC scenario for D-PRACH

3.2 CoMP robustness concepts

3.2.1 Introduction

In cellular systems, cell edge users suffer from high distances from their serving BS and from high interference from neighboring cells, drastically impacting the total cell throughput. Cooperation between neighboring cells (CoMP), where users at the border of the cell are served by at least two BSs, is an efficient way to deal with this issue and allows exploiting the available spatial degrees of freedom (DoF) more efficiently leading to an increased system capacity in future cellular wireless communication networks, see [IDM+11] for an overview. However, such an approach entails huge additional overhead in terms of backhaul message sharing, base station synchronization, feedback of channel state information (CSI), forwarding of control information etc. On top, the approach is known to lack robustness against the actual extent to what the delivered information reflects the current network state in fact, it turns out that the achieved gains by CoMP transmission are still far away from the theoretical limits while even constraining the potential services in the network due to extensive uplink capacity use for control signaling [IDM+11]. CoMP robustness framework for new waveforms is a means to overcome current limitations.

The developed non-orthogonal PHY layer waveforms and their specific structure will be incorporated into the design of the control signaling on MAC layer leading to different designs for different waveforms. Such approach (see e.g. [WS12] incorporating spatial transmit codebooks) differs significantly from state-of-the-art methodology where typically the transmitted signals have no impact on the design of the control channel. The objective is measured in terms of reduced control signaling and appropriate metrics for the system's sensitivity to mobility, capacity limitations etc. Using non-orthogonal waveforms, the 5GNOW design for asynchronous signaling and increased robustness promises significant improvements. An example is the signaling overhead in the uplink. For the uplink, the analogical percentage of physical layer control signaling overhead equals to 17% for representative system settings (BW=20 MHz, normal CP, 1 PRACH per frame). This means that 83% of the theoretical physical layer capacity can be used to carry PUSCH data. An area for improvement with non-synchronized signaling is in removing the PUCCH, which would shift control signaling overhead from 17% to around 15%. A more optimistic figure of 25% improvement is anticipated from improvements in the channel estimation procedure.

3.2.2 Imperfect time and frequency synchronization for CoMP

CoMP enables to provide good quality of service (QoS) to cell edge users while maintaining a high spectral efficiency in the system. Multi-User transmissions exploit the spatial dimension to separate the users (transmission is done for all users in the same band in the same time slots) while cooperation aims at increasing the SINR of UEs far from their serving BS. Figure 3.2.1 (left hand side) shows an example of scenario for MU CoMP transmission. Figure 3.2.1 (right hand side) represents a transmission with the same spectral efficiency, without MU CoMP. All the transmissions are realized on the same time-frequency resource. The black dashed arrows represent the BS array broadsides.

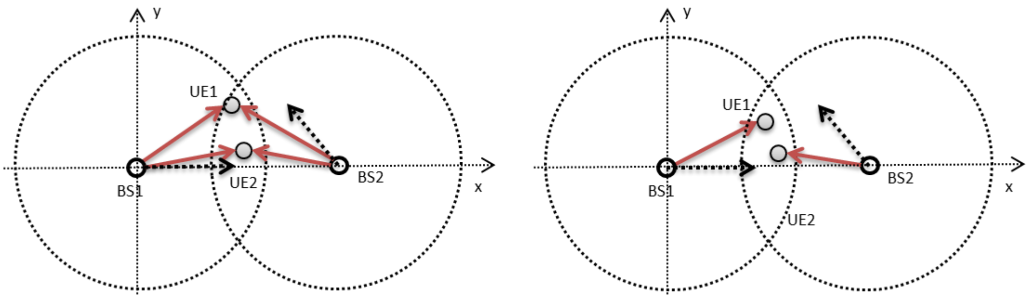

Figure 3.2.1. (left) Multi-User Coordinated MultiPoint transmission (right) Single-User Point to Point transmission

There are many challenges for such a cooperative transmission scheme. First, when BSs are transmitting to a UE, the different distances between the UE and the cooperating BSs create time de-synchronization at the UE that cannot be compensated by a GI. Independent quartz at the BSs and receiver clocks also generate frequency de-synchronization (Carrier Frequency Offset). Furthermore, MU transmission requires reliable spatial filtering at the BSs, so that the interference at the receivers remains low. Filters are computed based on the feedback from the UEs to the BSs of preferred weight vectors and associated SINRs, keeping in mind that the bandwidth occupied by this information must be kept as low as possible. Several operations are to be realized in order to allow MU CoMP as depicted on Figure 3.2.1. Each UE must first be synchronized in frequency and in time with both BSs. When UEs are synchronized, they are able to estimate their channel and feedback the necessary information for BSs to decide the MU transmissions parameters.

Figure 3.2.2 presents the system model for cooperation between cells. The BSs are 500 m apart. The UE is supposed to move on the axis y=0 (Figure 3.2.1) and the antennas at the BSs are considered omnidirectional, without loss of generality. The distance from BS1 is d. The UE is equipped with two receive antennas and performs Maximum Ratio Combining. Each BS is equipped with one transmit antenna. The whole system then forms a virtual 2x2 MIMO transmitter-receiver. The two BSs transmit in the same Resource Blocks (RB). Signal from BS2 is received at the UE with a delay τ regarding to the signal from BS1. This delay reflects the difference of over the air transmission times from both BSs. BS1 and BS2 are considered synchronized in frequency but not in phase. The CFO between the BSs and the UE is $\delta_{\Delta f}$ (expressed in percentage of the carrier spacing) and the initial phases are noted φ_1 and φ_2.

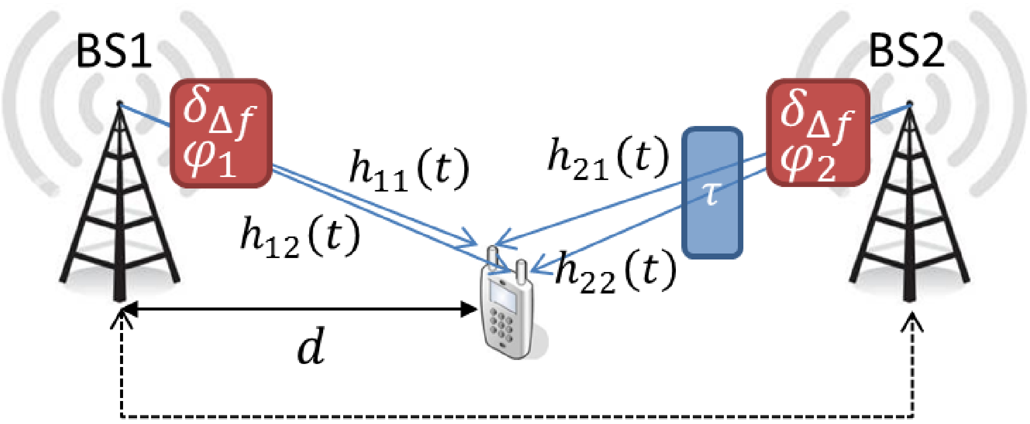

Figure 3.2.2. 2x2 cooperation scenario

The objective in the following section is to discuss from the robustness point of view the feasibility of DL CoMP for 5G systems with non-orthogonal FBMC waveform, taking into account realistic parameters such as:

- Sources of offset
    - Received signals from multiple cells may not be aligned in time at the receiver due to propagation delay differences and to possible time synchronization mismatch between cooperating BSs. This offset causes pilots rotations at the receiver that make the estimation of the channel difficult. High time delays have to be considered as worst case.
    - Clocks at the BSs and at the UE side may not be perfectly synchronized in frequency, causing Carrier Frequency Offset (CFO) at the receiver. The impact of the CFO has to be taken into account in the robustness framework.
- Return link

- In order to deal with different time of arrivals from different BSs, the receiver may estimate the delay and feedback the information to the BSs. The cost of this operation, in term of UL bandwidth, has to be discussed.
- MU-CoMP implies knowledge at the transmitter side of preferred UEs' weight vectors and associated SINRs. The bandwidth necessary for feeding back such information to the BSs must be investigated.

More specifically, time and frequency synchronization issues for one given UE are studied in Section 3.2.3 in order to highlight the benefits of FBMC with respect to OFDM waveform.

A Carrier Frequency Offset $\delta_{\Delta f} \neq 0$ causes Inter Carrier Interference (ICI) and signal power loss. In [MA03] the impact of the CFO on the BER of OFDM systems was computed. The black curve with squares on Figure 3.2.3 shows the results in an AWGN channel, with an uncoded QPSK modulation and a frame length of 0.1 ms (CP of 20 µs), at Eb/N0 = 10 dB. CFOs higher than 0.05 % of the subcarrier spacing cannot be tolerated without compensation. On Figure 3.2.3 the impact of the CFO on the performance of an FBMC transmitter-receiver is also illustrated. Here the frame is composed of 4 symbols for the preamble and {8,16} symbols of data, for a total duration of {1.1,1.6} ms, thus longer than in the simulation in [MA03] (a longer frame is an unfavorable case when CFO is present). The BER is measured in an AWGN channel, for a point to point QPSK 3/4 transmission, at SNR = {3.28, 4.17} dB. First, as expected, when looking at FBMC simulation results, the CFO most impacts longer frames: the BER increases more quickly with the CFO for the 1.6 ms frame compared to the 1.1 ms frame case. Then it must be noticed that FBMC is more robust to CFO than OFDM, even for long frames.

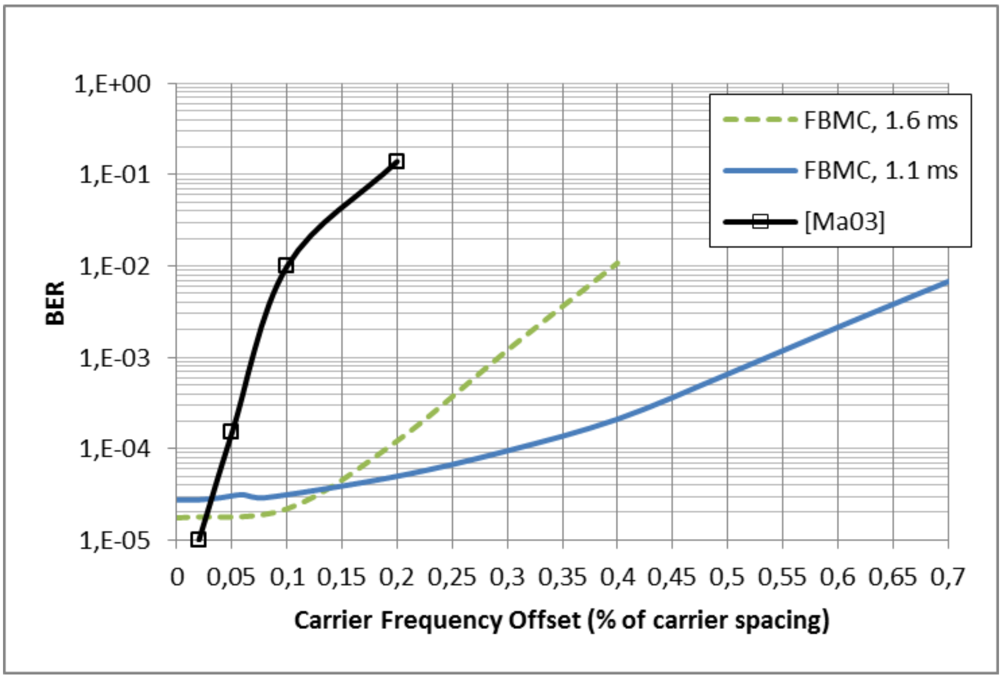

Figure 3.2.3. Impact of the CFO on the BER, with no correction

FBMC is more resistant to frequency de-synchronization than OFDM, due to the very good frequency localization of FBMC carriers.
Frequency synchronization (estimation and compensation of the CFO) with FBMC can be entirely realized at the UE in the frequency domain. The estimation relies on a two-step algorithm:

1. The most part of the CFO (the 'integer' part) is first accurately estimated thanks to a simple energy detection algorithm on the preamble carriers. The residual part of the CFO after this first coarse estimation is lower than 100/(2K)% (12.5 % with K=4, where K is the overlapping factor) of carrier spacing. This low value of the residual CFO after step 1 allows using a reduced-complexity algorithm for step 2. The same method applied to OFDM for estimation of the integer part of the CFO would lead to a much higher residual CFO of 50 % at maximum, forcing to use more complex algorithms for step 2.
2. The algorithm proposed to estimate the residual part of the CFO (the 'fractional' part) was described in [5GNOWD3.1]. It relies on a scalar product of $N_0 \times (2K - 1)$ pilot carriers of two preamble symbols, averaged on the two receive antennas. This algorithm exhibits reduced complexity while achieving good performance.

Figure 3.2.4 and Figure 3.2.5 show the residual CFO after step 2 ($\hat{\delta}_{\Delta f} = |\tilde{\delta}_{\Delta f} - \delta_{\Delta f}|$) on 200 draws. The actual CFO after step 1 $\delta_{\Delta f}$ is equal to 12.5 %, which is the highest possible value of the fractional part of the CFO (here the overlapping factor K is 4) and $d = 250$ m and 160 m. First it can be noted that the performance of the algorithm are nearly the same for BSs perfectly synchronized at the receiver or with a high time de-synchronization between the BSs at the receiver. Secondly, we can note that N_0 =20 is enough to ensure a negligible remaining CFO offset.

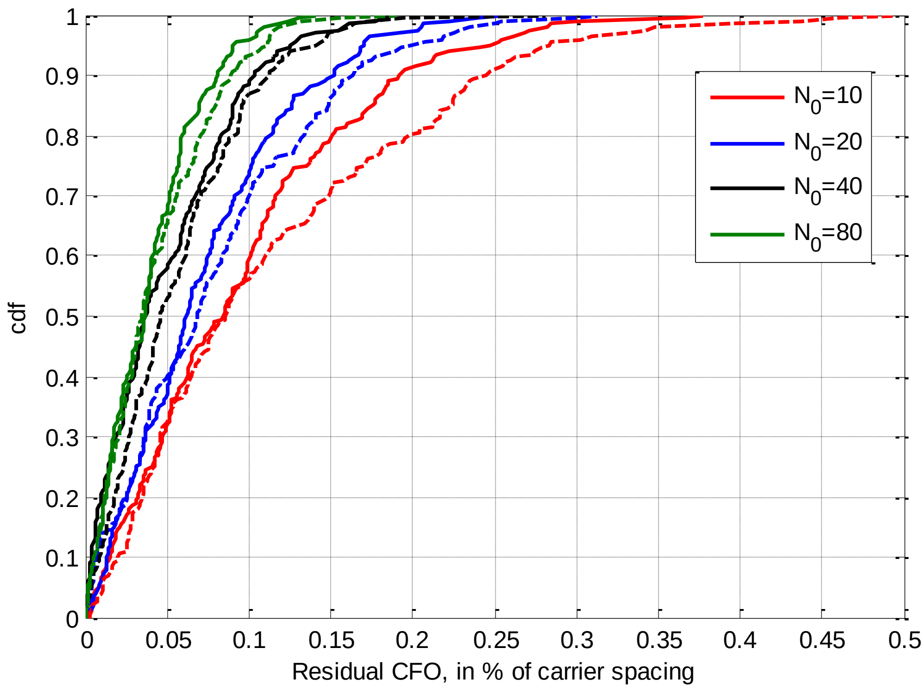

Figure 3.2.4. Residual CFO after step 2, in % of carrier spacing. $\delta_{\Delta f} = 12.5$ % (after step 1), $d = 250$ m. Solid lines: $\tau = 220$ samples, dashed lines: $\tau = 0$ sample.

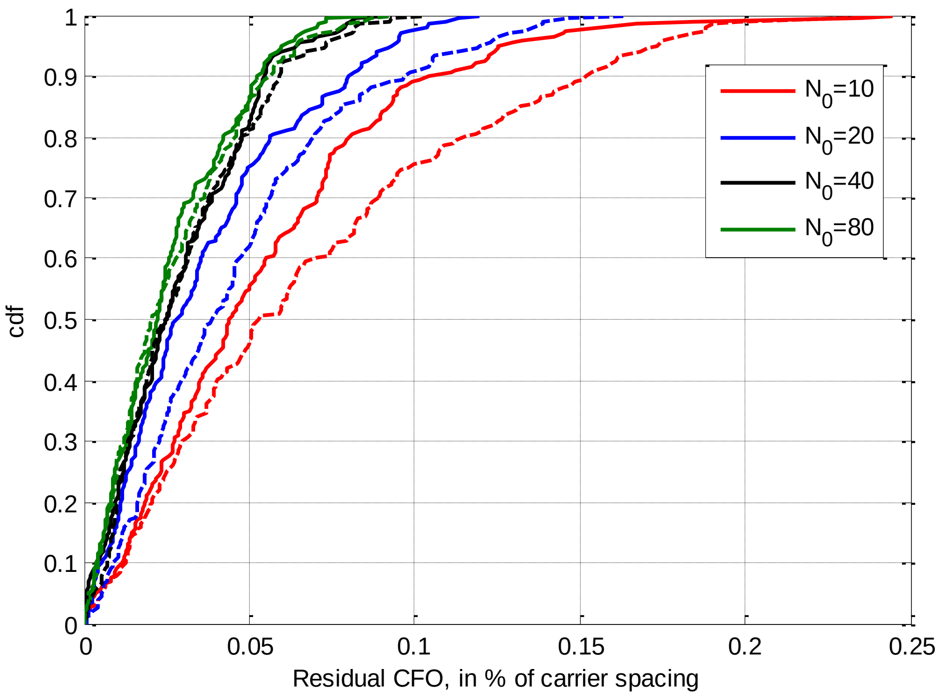

Figure 3.2.5. Residual CFO after step 2, in % of carrier spacing. $\delta_{\Delta f} = 12.5$ % (after step 1), $d = 160$ m.

Solid lines: $\tau = 220$ samples, dashed lines: $\tau = 0$ sample.

The compensation of the integer part of the CFO is simply realized by a carrier shifting while the compensation of the fractional part requires for each carrier a weighted sum of $2Q + 1$ carriers.The influence of the parameter Q was measured on Figure 3.2.6. Here $\delta_{\Delta f} = 12.5$ % and 6 %. It can be noted that few carriers are necessary to get a good BER: $Q = 3$ allows for an accurate correction of the CFO.

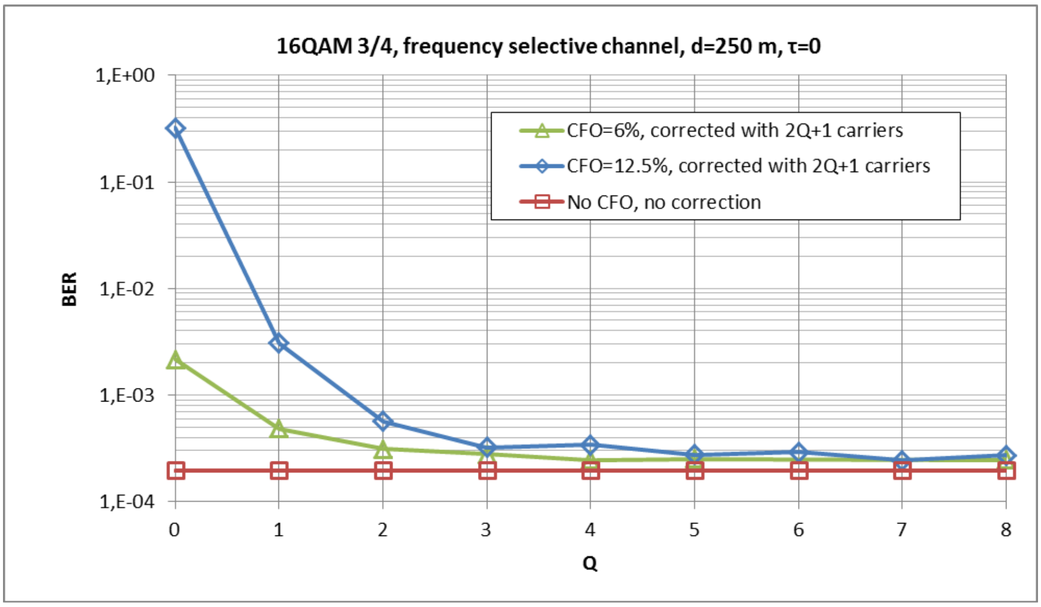

Figure 3.2.6. Influence of the parameter Q on the correction of the CFO.

Cooperative MIMO-OFDM deals with Inter Symbol Interference (ISI) thanks to the use of a CP: when delay difference between the cooperative BSs is shorter than the CP, all ISI that may deteriorate the quality of service at the receiver is suppressed. For cooperative MIMO-OFDM, due to high propagation distances, the CP must be longer than for non-cooperative OFDM. In LTE 10 MHz the short CP is 72 samples long and the long CP has a duration of 256 samples. Contrary to OFDM symbols [IBI08], FBMC symbols structurally overlap in the time domain at the transmitter, the use of a CP thus becomes useless. Figure 3.2.7 shows the influence of the delay on the BER at the UE, for 16QAM modulation with convolutional code of rate 3/4. The distance d is 250 m. The CFO is null and neither estimated nor corrected. At the UE, on each antenna j the equivalent channel $h_{eq,j}(t) = h_{1j}(t) + h_{2j}(t-\tau)$ is either supposed perfectly known (dotted line curve) or estimated (solid line curve). The estimation is realized thanks to preamble symbols with one carrier over four being a pilot carrier.

It first must be noted that with perfect channel estimation, performance does not decrease even for very high delays. It is then shown that FBMC, with real channel estimation, can cope with delays up to 120 times samples (7.8 µs) without any correction. For the parameters of LTE with 10 MHz channel bandwidth, this corresponds to a distance of 2340 m. FBMC modulation is thus demonstrated to be very resistant to time propagation differences between signals from the two BSs, due to its overlapping structure. Recalling that FBMC does not need any Cyclic Prefix to cope with time propagation differences; the spectral efficiency is then preserved without impact on time synchronization. Delays higher than 7.8 µs are unlikely to occur in most of cooperative systems; nevertheless it could be useful to decrease the virtual delay seen at the UE in order to keep the channel flat over a Resource Block.

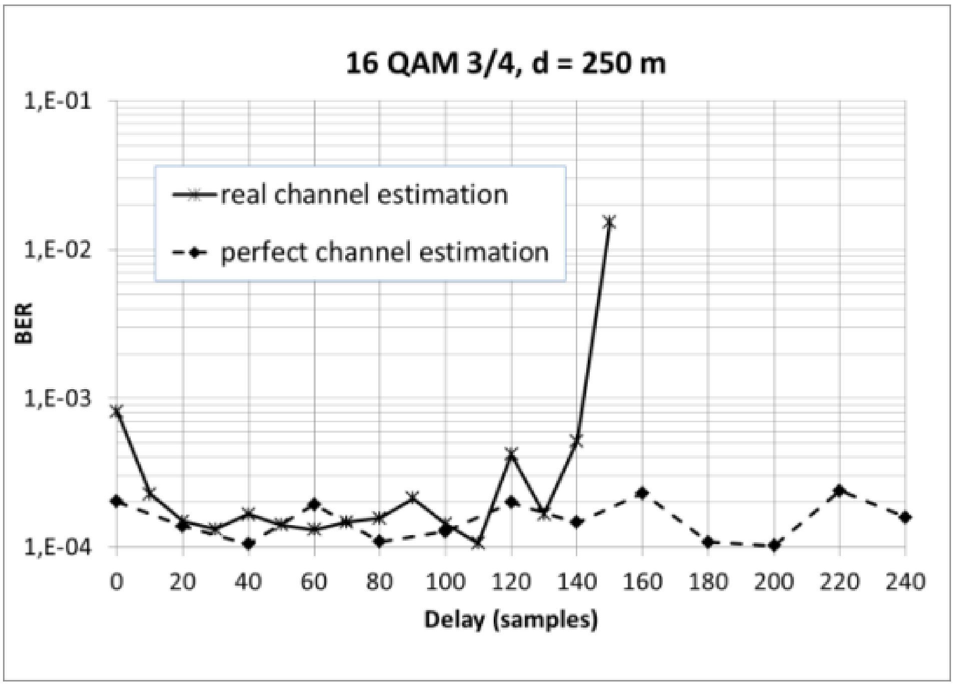

Figure 3.2.7. BER of CoMP FBMC with MRC at the receiver for different delays τ between BSs.

The deterioration of the BER for real channel estimation with high delays is due to the phase rotations introduced by the delay τ that increases the frequency selectivity of the equivalent channel $h_{eq,j}(t)$. Indeed when the coherence bandwidth of the channel is much smaller than the pilot spacing, channel interpolation cannot be reliably computed. In order to decrease the effects of phase rotations of the channel, the UE computes the estimate of the channel in the time domain (thanks to the IFFT of the estimate in the frequency domain) and seeks for the peak that corresponds to the delay. Figure 3.2.8 shows an example for two values of the delay. Note that range of the estimation is limited by the aliasing of the IFFT.

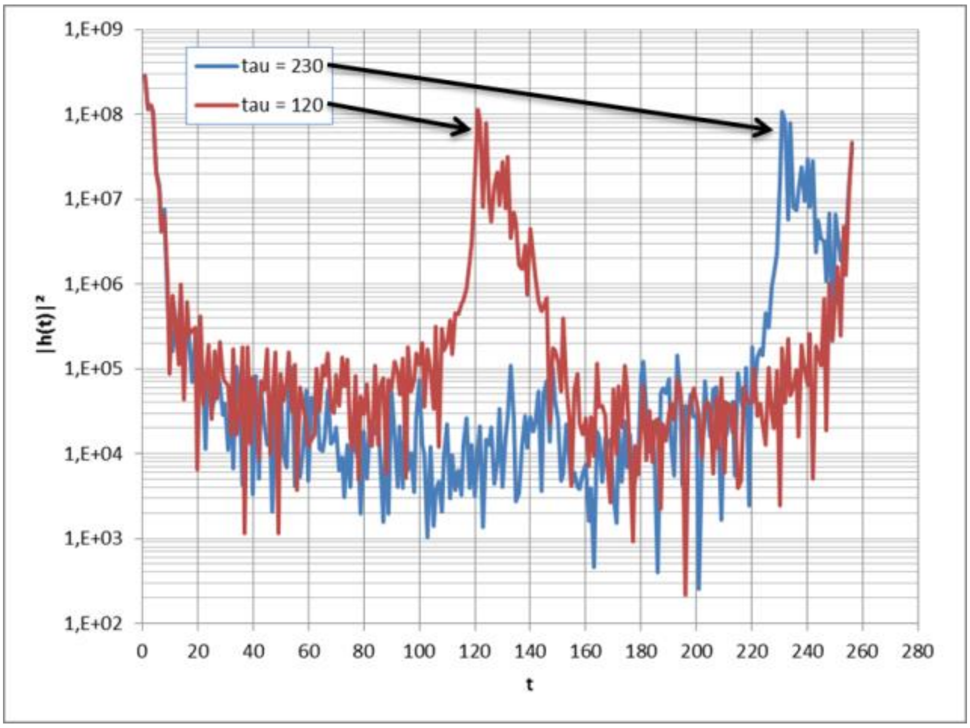

Figure 3.2.8. Time estimation of the equivalent channel. d=250m.

The goal of the delay detection algorithm is then to return a value $\tilde{\tau}$ such that $0 \leq \tau - \tilde{\tau} \leq 30$ with τ the actual delay. The choice of the value 30 for the maximum virtual delay $\hat{\tau} = \tau - \tilde{\tau}$ has been motivated by the study of the coherence bandwidth of the channel. Such a value indeed ensures that the channel is flat over 12 consecutive carriers (one PRB). The 'latter' BS is then asked to rotate each carrier of the transmitted data with a factor $\exp(\frac{j2\pi k\tilde{\tau}}{N})$, with N the number of carriers of the symbol. The set of values taken by $\tilde{\tau}$ must be as small as possible in order to limit the feedback from UE to BS.

The algorithm schematically consists in filtering $|h(n)|^2$ presented in Figure 3.2.8 and finding the index of the maximal value. Based on this index the algorithm outputs a value $\tilde{\tau}$ chosen in the set {0,20n+5}, n=1,2,…,11. This set is composed of 12 values; it then requires 4 bits of feedback, plus the identifier of the BS that must rotate the data. This algorithm is very robust to non-detections and false alarms with very limited feedback information [CKD13].

In Section 2.3 of this deliverable a hierarchical MAC structure was introduced to cope with LTE-A CoMP scenarios. It includes a multi-cell MAC, individual cell MACs connected through X2 interface, and an X2 interface extension in terms of signaling. The paragraph below highlights the impact of the FBMC scheme on MAC layer functionalities.

In [MP11], where OFDM is considered, the authors demonstrate that joint transmission among multiple cells can provide significantly large throughput gains at the users. Nevertheless, they point out the price to pay to achieve an efficient CoMP transmission; these identified drawbacks are below assessed against the assumptions and results of our study, which is based on FBMC:

- Pilot overhead in the downlink (reference signals overhead in DL, e.g. use of CSI RS for CoMP). Still in [MP11], it is stated that the number of pilots dedicated to the estimation of the channels in the downlink is increasing linearly with the number of cooperating BSs. This comes from the will of the CoMP UE to estimate all the channels from all the cooperating BSs. This assumption is no longer true in our study where the CoMP UE sees the signals from all cooperating BSs as multipath copies of the intended signal and estimates the equivalent point to point channel. The necessary number of pilots then only depends on the higher delay from the 'latter' BS. It was furthermore shown in [CKD13] that the estimation of the channel for FBMC can be realized the same way than for OFDM, i.e. based on preamble symbols with regularly spaced pilot tones.

- Precise synchronization of the oscillators (synchronous data exchange and clock synchronization between eNBs for proper timing of coordinated transmission). In our study cooperating BSs are considered synchronized in frequency but not a priori in phase. We show that both the CFO estimation and compensation can be realized at the UE side, in the frequency domain. These operations require no feedback from the UE to the BSs. We moreover demonstrate that FBMC allows an easier and more accurate estimation and compensation of the CFO than OFDM.
- Backhaul latency and capacity (need for fast exchange of scheduling information, CSI, BF weights, data). The backhaul link is the link on which cooperating BSs are exchanging, among other information, the data intended to the CoMP users. The rate on this link would be the same for OFDM and for FBMC. However one must have in mind that, as described in [MP11], the overall backhaul rate for two cooperating BSs can reach tens of Mbit/s/cell. BS sites thus need high-capacity backhaul (fibre or microwave).
- Need for potentially large CSI feedback (uplink CSI feedback overhead for radio channels' measurements to all cooperative points in the serving set). When dealing with MU-CoMP, most of the feedback is indeed devoted to providing to the BSs the necessary information for codeword and user selection. The robustness of FBMC to MAC related asynchronism such as outdated CSI will be investigated in the future.

One last issue that is not mentioned in [MP11] is the necessary feedback for time synchronization at the UEs. Indeed in this book, as OFDM is considered, no time synchronization is required because all the ISI are suppressed by the use of a CP. To do so and when dealing with large cooperating areas, the size of the cyclic prefix can reach high values, leading to high spectral efficiency loss. FBMC does not require CP but as expected we have shown that time synchronization then become necessary. An algorithm has been provided that minimizes the feedback rate for this synchronization: only 4 bits are necessary on the uplink to get to an acceptable synchronization. The refresh rate this information must be provided to the BSs depends on the speed of the UE.

On the other hand, uplink CoMP is implementation matter only meaning that it does not require any changes to radio interface. Simulations were performed in [5GNOWD3.1] in order to compare the capabilities of different waveforms to harvest on the gains UL CoMP is promising under realistic synchronization assumptions. Depending on the SNR operation point, performance gains of several dBs for UFMC (Universal Filtered Multicarrier) over OFDM can be observed, because of better inter-carrier interference suppression by the reduced side-lobe levels of the waveform. This demonstrates that UFMC, that applies filtering to subsets of the complete band instead of single subcarriers or the complete band, is a powerful candidate 5G waveform in the CoMP scenario in case of synchronization mismatch. This allows that synchronization requirements can be relaxed and in the case of MTC devices transmitting in CoMP joint reception systems, a better support of low-end devices with relaxed oscillator requirements can be provided by the help of UFMC.

3.3 CoMP under perfect CSI

There have been very recent approaches to deal with the limitations of the feedback link in a more robust manner [JCC+10, SP10, WS10, WS12]. Particularly, in [WS10, WS12] a new direction is developed which bears some great potential for the envisioned robustness framework. The main idea in this work is to use the structure of the transmit signals (in this case the spatial transmit codebook) and to incorporate as much information as possible in the design of the control channels. The collection of all information is the key to tailor the metrics used in the network to generate control messages as close as possible to the underlying performance indicators (rather than close to e.g. the mobile channel coefficients). This approach has been proven to drastically increase the rates [WS12] in a non-cooperative multi-cell network.

Recently this was generalized to CoMP including *joint transmission* and *coordinated beam-forming* schemes such as interference alignment using non-standard (and robust) alignment conditions [SWJ+13]. Let us look at these schemes first operating under perfect CSI.

A useful characterization of transmission schemes under perfect CSI in complex wireless networks where the exact capacity is unknown are the degrees of freedom (DoF), defined as

$$d = \log_{P\to\infty} \frac{C(P)}{\log(P)}.$$

For Multiuser MIMO [CJK+10], as well as for Network MIMO [KG12], or CoMP, the asymptotical capacity behaves as

$$C(P) = Bn_t \log P + c_2(B, n_t),$$

with *B* being the number of base stations. The slope of the curves in the asymptotic regime is determined by the pre-log factor which is identical to the DoFs of the system.

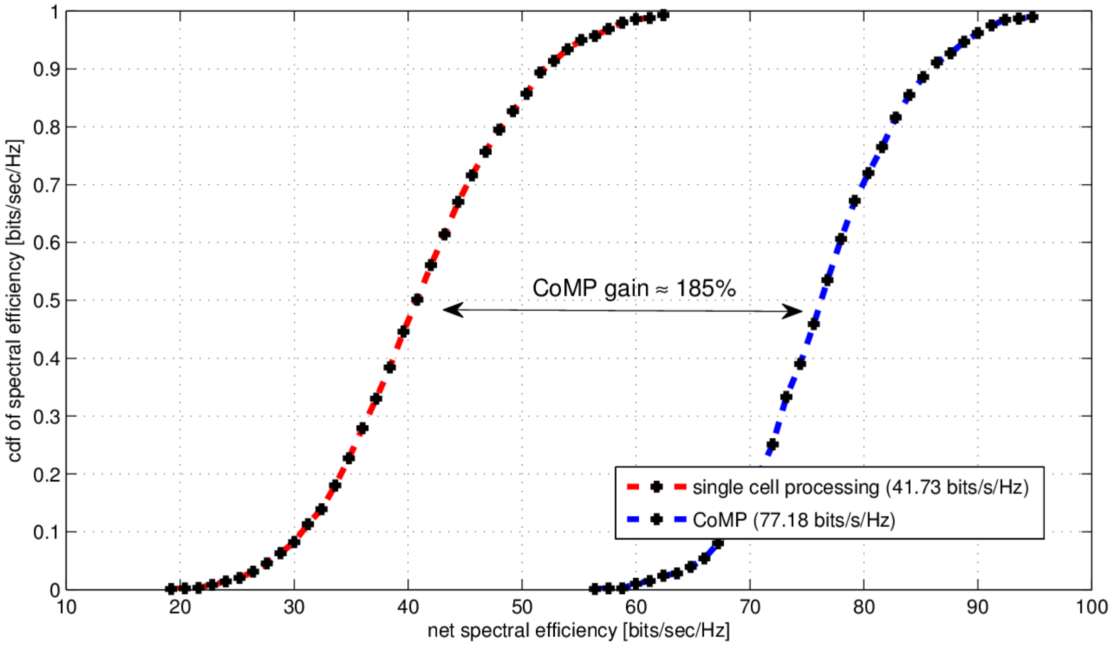

Figure 3.3.1: CoMP performance

To obtain more concrete numerical results, subsequently we assume 3 base stations equipped with 4 antennas and a total number of 30 single antenna users. We assume an SCME channel and perfect channel state information at the transmitter. The average SNR is set to 10 dB.

CoMP promises to achieve huge gains, see Figure3.3.1. However, it requires message sharing among the cooperating base stations. This raises the problem that real-world constraints on the backhaul induce delay and consequently we have to deal with frequency offsets, time synchronization issues, etc. A possible solution to this problem can be *Interference Alignment*. The key is that transmitters use linear precoding in a way, such that the interference signals end up in the same subspace at the receiver, i.e., multiple interferers appear as one single interferer.

In [SW11] the DoFs of a $((B,N)\times(K,M))$ cellular system are characterized by

$$d = \frac{BNKM}{KM+N}.$$

These DoFs are achieved by averaging over multiple fading slots. A possible scheme to achieve these rates is *Cellular Iterative Interference Alignment* presented in [SW12a], which is now briefly described.

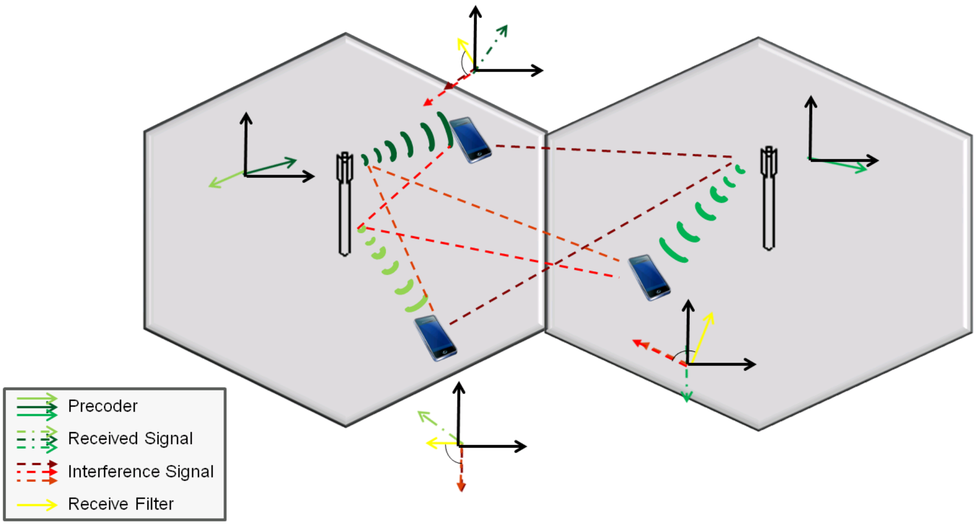

Figure 3.3.2: Iterative cellular interference alignment

The algorithm is based on *Alternating Optimization* of precoders and receive filters. Thereby the intra-cell interference is aligned in the receive subspace spanned by the out-of-cell interference. The algorithm has three basic components. First the algorithm performs a *receive filter optimization* where only the out-of-cell interference is considered. The optimization depends only on precoders used by the other base stations and not on the actual user selection. Second the algorithm performs a *Greedy user selection* which is based on the estimated rates. Users are added as long as the estimated sum rate increases. Third the precoders are optimized, where intra-cell interference is aligned in the receive subspace spanned by the out-of-cell interference. Thereby only the active users are considered. The outcome of the algorithm is illustrated in Figure3.3.2.

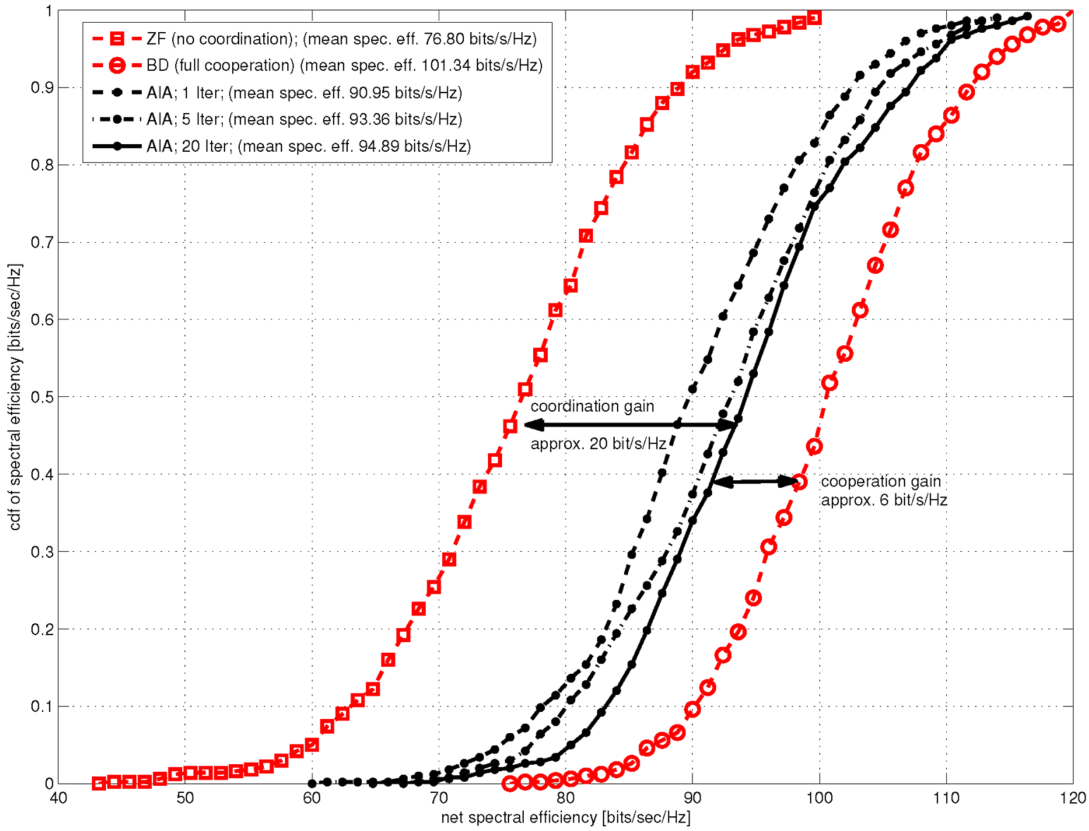

Figure 3.3.3: Performance with perfect CSI

In Figure 3.3.3 the algorithm's performance with perfect CSI is plotted using as baseline first joint coherent transmission with greedy user selection (i.e. block diagonalization (BD)), and second single cell processing with greedy user selection (i.e. zero forcing (ZF)). We use the following assumptions. We simulate an SCME channel with a user velocity of 3 km/h. We have 3 base stations and 15 users in the system and an average receive SNR of 25dB. Moreover we consider 5x5 MIMO. The overall bandwidth is 10 MHz, the carrier frequency is 2.1 GHz. A key observation is here that the proposed algorithm brings a coordination gain of roughly 20bit/s/Hz in the setting which is a remarkable result since no data sharing is required.

The situation is quite different with imperfect CSI. With limited feedback (Figure 3.3.4) the conclusion is that the algorithm performs close to joint transmission for a good fraction of feedback rates and hence the standard analysis using DoF does not reflect the true performance. Also the requirements on the backhaul network are significantly smaller than with block diagonalization. For the partial CSI each user quantizes the 6 most significant channel taps, assumed to lie within the first 100 samples, using a variable amount of bits. This required feedback for quantizing the channel in the time domain has to be afterwards multiplied with the number of transmit and receive antennas to obtain the overhead for each feedback message.

In the following we present a new robust version.

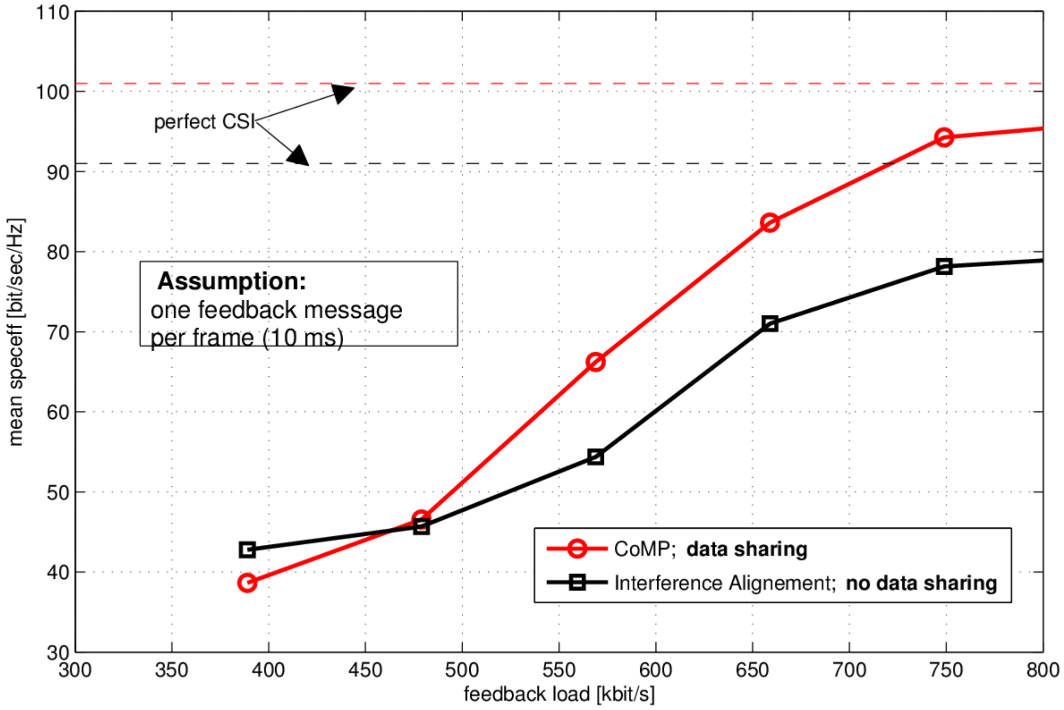

Figure 3.3.4: Limited feedback performance

3.4 Performance of CoMP under imperfect CSI

3.4.1 Algorithm

Let T be the number of base stations. Moreover we define S_b to be the set of users selected at basestation b. Furthermore π denotes a mapping from the set of scheduled users to the corresponding precoding vectors. With this notation the overall algorithm is given as follows.

Algorithm 3.4.1: Iterative Alignment Scheme

Begin of transmission frame:

- Transmit common pilots to all users and make an estimate of the channels from each user to each base station
- For each base station select a subset of users
- Set $\pi(k) = \frac{1}{\sqrt{n_t}}(1,1,\dots,1)^T$ for all $k \in \{S_1, S_2, \dots, S_T\}$

Repeat

- Transmit dedicated pilots

For b=1,2,…,T **do**

- Compute receive filter matrix u_k for all $k \in S_b$
- Quantize and feed back the effective channels

End for

For b=1,2,…,T do

- Compute precoding vectors $\pi(k)$ for all $k \in S_b$

End for

Until termination condition is satisfied

End of transmission frame

3.4.2 Analysis

The rate loss gap analysis needs to capture the following effects:
(1) the rate loss due to scheduling and beamforming based on partial CSI, and
(2) the rate loss due to link adaption based on partial CSI.
Therefore, we define the following per user performance metric:

$$\begin{aligned}\Delta r_m(\pi_H,\pi_V\,) &\coloneqq \max\{r_m(\pi_H,S_H;H)-r_m(\pi_V,S_V;H),r_m(\pi_H,S_H;H)-r_m(\pi_V,S_V;V)\}\\ &= r_m(\pi_H,S_H;H)-\min\{r_m(\pi_V,S_V;H),r_m(\pi_V,S_V;V)\}\end{aligned}$$

The rate loss gap captures the following effects:

i) The first part $r_m(\pi_H,S_H;H)-r_m(\pi_V,S_V;H)$, which is usually considered in the literature (see e.g. [CJK+10]), describes the rate loss due to beamforming based on partial CSI and assumes perfect link adaption, i.e., transmission with a rate equal to $r_m(\pi_V,S_V;H)$.

ii) ii) The second part, $r_m(\pi_H,S_H;H)-r_m(\pi_V,S_V;V)$ models the rate loss due to link adaption based on partial CSI, i.e., allocation of the rates $r_m(\pi_V,S_V;V)$. Even though $\Delta r_m(\pi_H,\pi_V)$ is still optimistic since it does not account for the case $r_m(\pi_H,S_H;H)<r_m(\pi_V,S_V;V)$ it is strong enough to address some of the drawbacks of the conventional analysis and leads to indeed very different results. Please note that, due to the per-user formulation, $\Delta r_m(\pi_H,\pi_V\,)$ is not necessarily positive for all H.

In [CJK+10], [Jin06, Thm.2] a broadcast channel with $|U|=n_t$ single antenna users and zeroforcing beamforming $\pi_{ZF,H}$, $\pi_{ZF,V}$ with respect to H,V respectively is considered. Then, limited feedback with B feedback bits per user incurs a throughput loss relative to ZF with perfect CSI according to

$$E\big[r_m(\pi_{ZF,H},U,H)-r_m(\pi_{ZF,V},U,H)\big]<\log(1+P2^{-\frac{B}{n_t-1}})$$

In [SWJ+13] it was shown that the scaling law is overly optimistic under the premises of the more realistic metric provided above. Furthermore the main result in [SWJ+13] is an upper and a lower bound on the expected rate gap.
The upper bound is given by the following relation. In any iteration of Algorithm 3.4.1 the average rate loss per user is upper bounded by

$$E[\Delta r_m(\pi_H,\pi_V)]\leq 3P\left(T^2n_r^2 2^{-\frac{B}{n_t-1}}+Tn_r2^{-\frac{B}{2(n_t-1)}}\right)$$

Moreover, the lower bound is given by the following relation. For some $c_2>0$ for sufficiently high SNR the average rate loss is lower bounded by

$$E[\Delta r_m(\pi_H,\pi_V)]\geq c_2\log\left(1+\frac{PE[\mu_{m,b}^2\,]}{|S_b|+\left(1+PE[\mu_{m,b}^2\,]\right)}2^{-\frac{B}{2(n_t-1)}}\right)+o\left(2^{-\frac{B}{2(n_t-1)}}\right).$$

3.4.3 Simulations

3.4.3.1 Baseline scheme

As a baseline scheme we consider centralized IA, which was proposed in [SW11b]. The baseline scheme requires a central processing unit which has global CSI. Each user m quantizes and feeds back the channel matrix $H_{m,l}$, for all *l = 1,..,T*, to all base stations. The base stations than computes the transmit precoders in an iterative manner similar to IA algorithm proposed in Paragraph 3.4.1. To quantize the channel matrices we use a component wise scalar quantization, i.e., each user maps each real element of the channel matrix to an element of a scalar feedback codebook with 2^B elements. Scalar quantization leads to $2Tn_tn_rB_s$ bits that need to be fed back by each user. As we will see, the feedback and control overhead is significantly larger than for the proposed distributed algorithm.

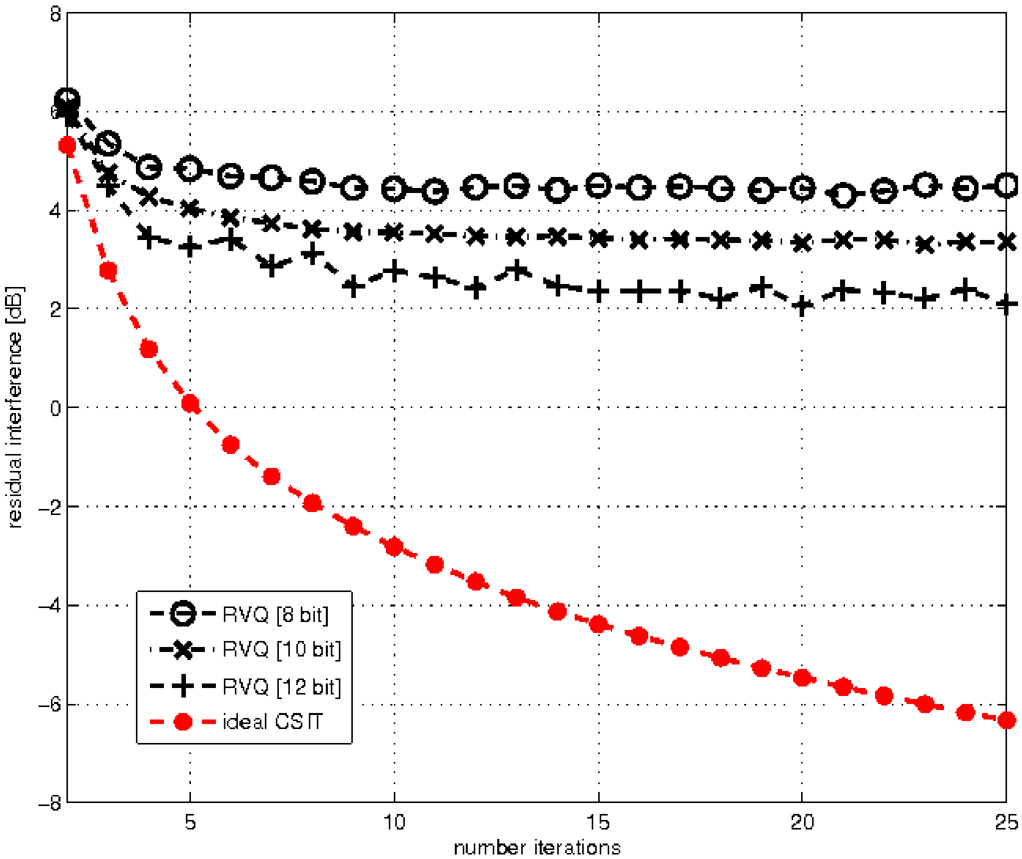

Figure 3.4.1: Residual interference over SNR. Convergence of Algorithm 3.4.1.

3.4.3.2 Transmit Protocol

The transmit protocol for the proposed algorithms can be summarized as follows. For simplicity, it is assumed that the channels stay constant during one transmission frame:

1) All base stations transmit orthogonal common pilots, such that each user m can estimate the channels $H_{m,b}$ for all *b = 1,…,T*. For brevity, we assume that all users can perfectly estimate their channels.

2) All users update their receive filters and feed back the effective channels.

3) All base stations perform (joint) user selection, update (locally) the transmit precoders and transmit dedicated (i.e. precoded) pilots.

4) Step 2 and 3 are repeated until some termination condition is satisfied (e.g. maximum number of iterations, minimum residual interference, etc.).

3.4.3.3 Simulation setup

In the simulations we consider a cellular network with T = 3 base stations and U = 9 users. Each node is equipped with nt = nr = 5 antennas. From [SW12b] we know that IA is feasible if each base station b serves $|S_b| = 3$ users. For the MIA (Algorithm 3.4.1) each base station is assigned randomly to three users. Power allocation is assumed to be uniform.

3.4.3.4 Simulation results

First, we investigate the convergence of the proposed MIA (Algorithm 3.4.1). Figure 3.4.1 depicts the residual interference of Algorithm 3.4.1. We observe that with partial CSI based on RVQ the residual interference converges rapidly to its minimum of approximately 4.5 dB, 3.5 dB and 2.5 dB for 8, 10 and 12 bit per user per iteration, respectively. In contrast, with ideal CSI the residual interference keeps decreasing with the number of iterations. Therefore, we conclude that with partial CSI the number of iterations can be kept low (5 iterations) without losing a significant part of the achievable performance. Figure 3.4.2 depicts the spectral efficiency over the SNR for the MIA (Algorithm 3.4.1). Each user uses an independent random codebook with 2B isotropic elements, where we chose *B = 16*. Again, we observe that the proposed IA algorithm converges rapidly, i.e., going from 2 to 6 iterations the performance is increased only slightly. This is a remarkable result since in each iteration, each user needs to feedback *TB = 48* bits and, therefore, a small number of iterations keeps the feedback load small.

Figure 3.4.2 also compares the proposed MIA (Algorithm 3.4.1) with the centralized baseline algorithm. For the centralized algorithm the number of bits per scalar is *Bs = 3*, which results in a feedback load of 450 bits per user per feedback message.

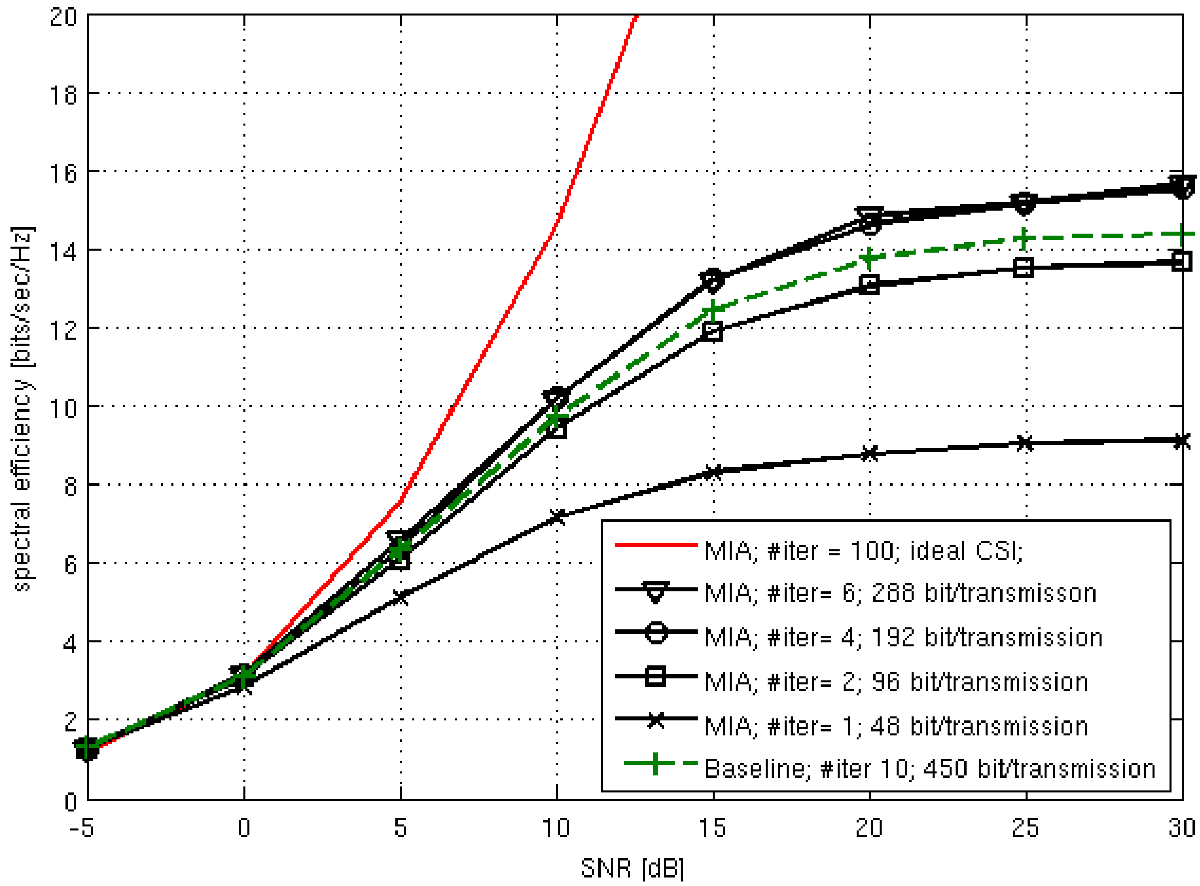

Figure 3.4.2: Spectral efficiency over SNR. Comparing Algorithm 3.4.1 with the centralized algorithm.

We observe that with 2 iterations and a codebook with 16 bit we already come very close to the centralized solution. Using a codebook with 16 bit and 6 iterations we clearly outperform the centralized solution.

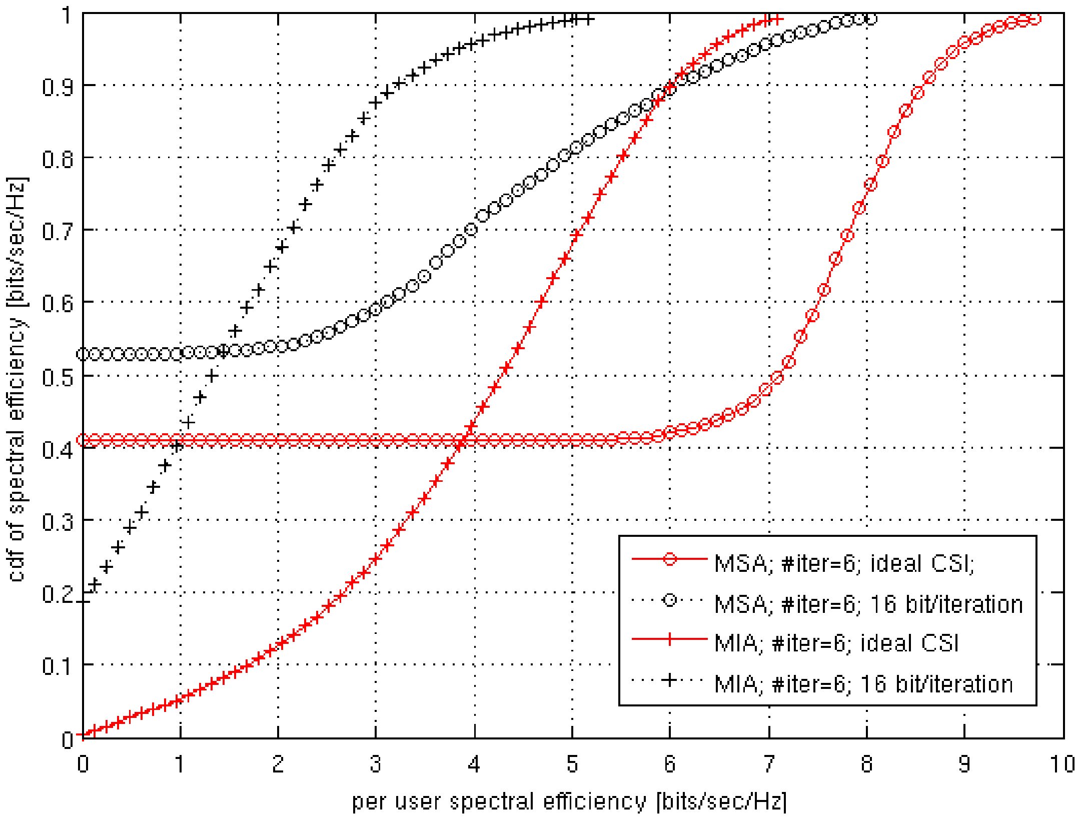

Figure 3.4.3: CDF of per user spectral efficiency at SNR= 20 dB.

Figure 3.4.3 depicts the CDF of the per user spectral efficiency at SNR= 20 dB. We compare the algorithm with a second algorithm, called MSA, which is presented in [SWJ+13]. We observe that the MSA schedules less users than the MIA but achieves a higher spectral efficiency for the scheduled users. For both algorithms, with partial CSI the mean spectral efficiency per user is approximately half of the mean spectral efficiency that can be achieved with ideal CSI. Figure 3.4.4 depicts the CDF of the network spectral efficiency at SNR= 20 dB. With partial CSI the MSA outperforms the MIA.

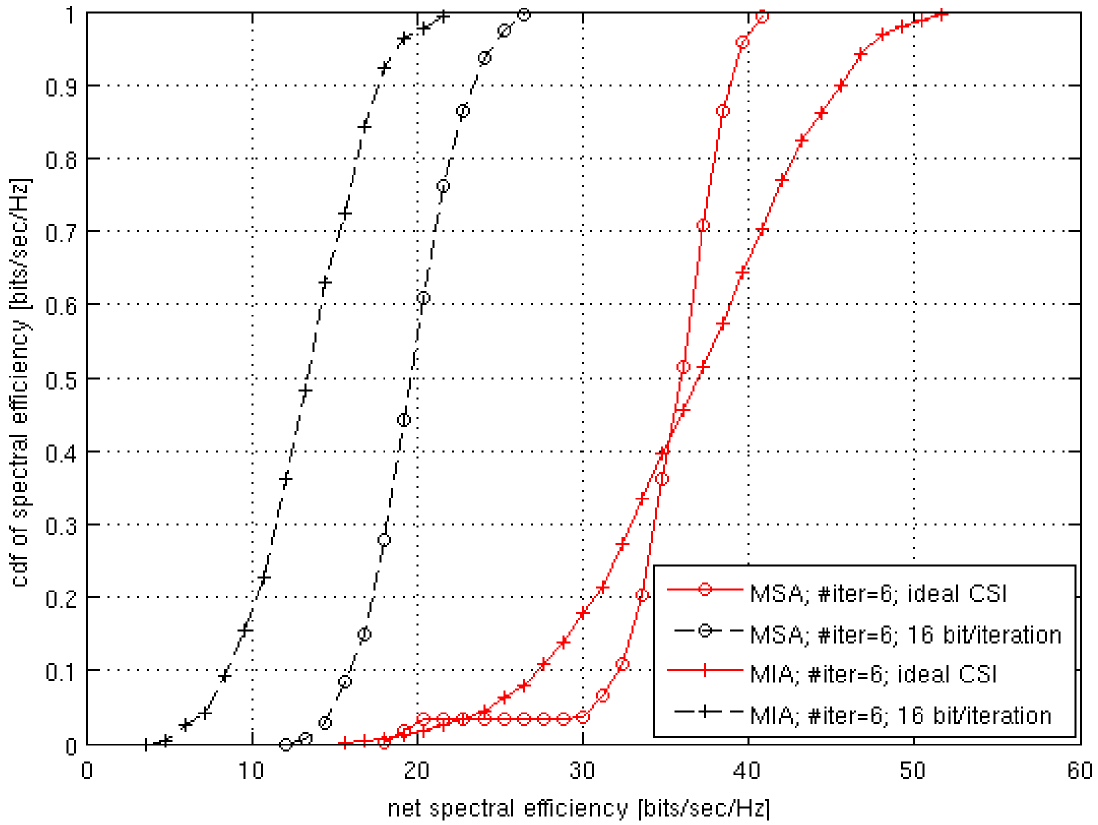

Figure 3.4.4: CDF of network spectral efficiency at SNR= 20 dB.

4 Conclusions

This deliverable provides a summary of intermediate MAC concepts, including gradual evolutions of the current LTE /LTE-A standardization together with new robustness concepts and corresponding performance evaluations.

The deliverable summarizes the state-of-the art in terms of signaling and MAC architecture for basic LTE/LTE-Advanced scenario. Moreover it describes concepts of ICIC and presents the X2 signaling related for interference management. Starting with the current LTE standard, new paths are evaluated e.g. for signaling reduction. As a first step in this direction, an optimization with respect to the current LTE standard is performed. This robust LTE mode is a transmission mode where synchronization, throughput, complexity and signaling requirements are relaxed.

Furthermore, the deliverable presents a multiple access vision, suitable for the requirements of inhomogeneous traffic types. The concept of a Unified Frame Structure allows handling e.g. of synchronous and asynchronous users within the same band. Relaxing synchronicity (and thus orthogonality) is an appealing feature to get rid of a growing signalling overhead, due to the larger number of devices which 5G systems have to handle in applications such as the Internet of Things (IoT) and Machine Type Communication (MTC). The potential of including multiple signal layers, in particular by using IDMA, is described and the impact of the FBMC waveform on MAC layer functionalities is investigated.

New directions are described which bear some great potential for the envisioned robustness framework. A major issue that is considered is the limited feedback problem and corresponding imperfect channel state information for CoMP scenarios. It is shown that the achieved gains by CoMP transmission are still far away from the theoretical limits while even constraining the potential services in the network due to extensive uplink capacity use for control signaling.

Novel concepts are presented to overcome the limitations of state-of-the-art systems under limited feedback. The main idea is to exploit the structure of the transmit signals (in this case the spatial transmit codebook) and to incorporate as much information as possible in the design of the control channels. The collection of all information is the key to tailor the metrics used in the network to generate control messages as close as possible to the underlying performance indicators (rather than close to e.g. the mobile channel coefficients).

5 Abbreviations and References

3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GNOW	5th Generation Non-orthogonal Waveforms for Asynchronous Signaling
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BER	Bit Error Ratio
BSR	Buffer status report
BW	Bandwidth
CB	Coordinated Beamforming
CC	Component Carrier
CCCH	Common Control Channel
CFI	Control Format Indication
CFO	Carrier Frequency Offset
CL	Closed Loop
CoMP	Cooperative Multipoint
CQI	Channel Quality Indication
CRS	Cell Specific Reference Signals
CS	Coordinated Scheduling
CSI	Channel State Information
CSI-RS	CSI Reference Signals
DCI	Downlink Control Information
DLSCH	Downlink Shared Channel
DM-RS	Demodulation Reference Signals (DL)
DoF	Degree of Freedom
DRB	Data Radio Bearer
DRS	Demodulation Reference Signals (UL)
DRX	Discontinuous Reception
DTCH	Dedicated Traffic Channel
FBMC	Filter Banks Multicarrier
HARQ	Hybrid ARQ
HI	HARQ Indications
HO	Handover
ICIC	Inter-Cell Interference Coordination
IE	Information Element
IoT	Internet of Things
JP	Joint Processing
JT	Joint Transmission
LWDF-PF	Largest Weighted Delay First PF
MAC	Medium Access Control

MCS	Modulation and Coding Scheme
MTC	Machine Type Communications
MTCD	MTC Device
NAS	Non-Access Stratum
OL	Open Loop
PBCH	Physical Broadcast Channel
PCC	Primary Component Carrier
PCCH	Paging Control Channel
PCFICH	Physical Control Format Indication Channel
PCH	Paging Channel
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PF	Proportional Fair
PHICH	Physical HARQ Indication Channel
PHR	Power Headroom Report
PHY	Physical Layer
PMI	Precoding Matrix Indication
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QoS	Quality of Service
RAP	Random Access Preamble
RAR	Random Access Response
RE	Resource Element
RI	Rank Indication
RLM	Radio Link Monitoring
RNTP	Relative Narrowband Transmit Power
RoHC	Robust Header Compresssion
RR	Round Robin
RRC	Radio Resource Control
RV	Redundancy Version
SCC	Secondary Component Carrier
SDU	Service Data Unit
SFN	System Frame Number
SFO	Sampling Frequency Offset
SNIR	Signal-to-Noise and Interference Ratio
SPS	Semi-Persistent Scheduling
SRB	Signaling Radio Bearer
SRS	Sounding Reference Signal
SSS	Secondary Synchronization Signal
T/F	Time / Frequency
TA	Timing Advance

TPC	Transmit Power Command
UCI	Uplink Control Information
UE	User Equipment
ULSCH	Uplink Shared Channel

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