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3GPP Procedures and Scenarios for CCSK

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Abstract
This deliverable describes the LTE-M procedures and scenarios where the usage of the CCSK modulation could be interesting by carrying data with sequences easy to detect.

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Glossary

Initials	Definition
ACK	ACKnowledgment
BL/CE UE	Bandwidth reduced Low complexity / Coverage Enhancement UE
CE	Coverage Enhancement
CIoT	Cellular Internet of Things
CP	Control Plane
CP-OFDM	Cyclic Prefix Orthogonal Frequency Division Multiplexing
CSI	Channel State Information
DC	Direct Current
DCI	Downlink Control Information
DL	DownLink
EDT	Early Data Transmission
eNB	4G base station
FDD	Frequency Division Duplex
FD-FDD	Full-Duplex Frequency Division Duplex
gNB	5G base station
HARQ	Hybrid Automatic Repeat Request
HD-FDD	Half-Duplex Frequency Division Duplex
IMT-2020	International Mobile Telecommunications-2020
ITU	International Telecommunication Union
LPWAN	Low Power Wide Area Network
MIB	Master Information Block
MME	Mobility Management Entit
mMTC	Massive Machine-Type Communications
MPDCCH	MTC Physical Downlink Control CHannel
MTC	Machine-Type Communications
NACK	Negative ACKnowledgment
NAS	Non-Access Stratum
NB	Narrow-Band
NR	New Radio
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PBCH	Physical Broadcast CHannel
PCI	Primary Cell Identity
PDCCH	Physical Downlink Control CHannel
PDSCH	Physical Downlink Shared CHannel
PRACH	Physical Random Access CHannel
PRB	Physical Resource Block
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control CHannel
PUSCH	Physical Uplink Shared CHannel

RA	Random Access
RACH	Random Access CHannel
RAN	Radio Access Network
RAPID	Radio Access Preamble ID
RAR	Random Access Response
RA-RNTI	Random Access - RNTI
RE	Resource Element
RF	Radio Frequency
RLC	Radio Link Control layer
RNTI	Radio Network Temporary Identifier
RRC	Radio Resource Control
RS	Reference Signal
RTD	Round-Trip Delay
SAE	System Architecture Evolution
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCS	SubCarriers Spacing
SFN	System Frame Number
SI	System Information
SIB	System Information Block
SN	Subframe Number
SSS	Secondary Synchronization Signal
S-TMSI	SAE - TMSI
TA	Timing Advance
TC-RNTI	Temporary Cell - RNTI
TDD	Time Division Duplex
TMSI	Temporary Mobile Subscriber Identity
TR	Technical Report
TS	Technical Specification
UCI	Uplink Control Information
UE	User Equipment
UL	UpLink
UP	User Plane
ZC	Zadoff-Chu

Contents

Introduction

The QCSP (Quasi-Cyclic Short Packet) project studies the efficiency of combining non-binary codes with CCSK (Cyclic Code Shift Keying) modulation in the context of LPWAN IoT (Low Power Wide Area Network Internet of Things), especially considering the transmission of short data packets. The CCSK modulation maps different binary words to a shifted version of a root binary sequence, which is then modulated by a standard modulation process, e.g. BPSK (Binary Phase Shift Keying). If well designed, this sequence and its shifted versions allow the receiver to commonly detect the signal, synchronize to it and demodulate the received binary words. Thus, there is no need to add a training / pilot sequence in addition to the payload. Yet the CCSK sequence can be long, and at constant bandwidth, it may take more time and energy to transmit the same amount of data, compared to a standard transmission including a shorter pilot sequence. Consequently, the CCSK modulation should be more efficient in the case of short data packets and / or in low to very low SNR (Signal to Noise Ratio) conditions, where higher redundancy is needed for reliable communications.

With the objective to contribute to the 3GPP standardization process, the performance of the CCSK need to be assessed with regard to some well-chosen 3GPP procedures. The combination of CCSK and non-binary codes may also be assessed for the same use cases for the sake of completeness. The introduction of novel error coding scheme in the 3GPP standard is however a nearly impossible task for a currently deployed technology, e.g. 5G. The results of this study may also help to define future 3GPP standards, as the next 6G technology.

This document provides relevant information regarding LTE and LTE-M air interface. Descriptions of 3GPP procedures are provided, in which using the CCSK modulation instead of the standardized approach would be interesting. 3GPP link level scenarios parameters from technical specification are used to inspire the definition of the actual test scenario for the CCSK.

1 Cellular IoT technologies

LPWA refers to IoT connectivity solutions and use cases, involving IoT devices communicating over wide area but with energy and complexity constraints. Typical LPWA use cases are small sensors, spread over a large area, a city for instance, and providing regular reports on temperature, wind and pollution metering. A high density of LPWA devices is (still) expected, and most of them are autonomous: working without human monitoring. Hence, these devices are expected to be cheap and have a battery life of several (tens of) years. Meeting the LPWA requirements is not an easy task for a communication system, especially when the devices are stationary and placed in a challenging communication environment, such as underground. Some requirements make the design of a connectivity solution easier, as these devices usually transmit small data packets, i.e. tens or hundreds of bytes, with relax latency requirements, i.e. in the order of (tens of) seconds. To solve this connectivity challenge, many dedicated solutions have appeared during the last decade. The novel air interfaces standardized by the 3GPP to support LPWA connectivity on cellular system (also known as Cellular IoT or CIoT) are LTE-M and NB-IoT.

Early work on LPWA was realized by the 3GPP during the Release 12 in 2014-15 with the introduction of the lower complexity device category[1]: Cat. 0. The same year, a Study Item was lead on the proposition of connectivity solution to address LPWA use cases. The requirements and proposed solutions are regrouped in TR (Technical Report) 45.820. Related Work Items the next year led to the creation of both LTE-M[2] (from the Cat. 0) and NB-IoT technologies in the Release 13. New related categories of devices also appeared: Cat. M1 for LTE-M and Cat. NB1 for NB-IoT. These novel categories were cheaper to produce thanks to low complexity requirements. Since then, both technologies have evolved through the different releases. Especially in Release 14, where two new devices categories were created: Cat. M2 and Cat. NB2. These categories are more complex than their first Release 13 counterpart, to address use cases requesting higher data-rates. Table 1 provides a technical description of LTE-M and NB-IoT in Release 13 and 14. Further improvements have been also provided to both technologies in Release 15 and 16 and the standardization of LTE-M and NB-IoT continues in the context of 5G. Actually, they have been branded as 5G standards. Both technologies comply with the 3GPP 5G IoT requirements in terms of coverage, message latency and battery life defined in the TR 38.913 and the capacity requirement defined by the ITU in the IMT-2020 requirements on capacity for massive Machine-Type Communications (mMTC) [1] [2] [3]. Regarding deployment conditions in a 5G-NR base station (gNB), LTE-M and NB-IoT can use NR in-band resources as in 4G LTE.

[1] A device category reflects the overall performance and capabilities of the UE (User Equipment) and therefor the complexity and cost. It states the support of MIMO operations, the minimal bandwidth, which high order modulations are supported, etc.
[2] The original name of LTE-M is eMTC.

	eMTC Cat. M1 (Rel. 13)	**NB-IoT Cat. NB1 (Rel. 13)**	**FeMTC Cat. M2 (Rel. 14)**	**eNB-IoT Cat. NB2 (Rel. 14)**
Bandwidth	1.4 MHz	180 kHz	5 MHz	180 kHz
Duplexing	HD-FDD, FD-FDD, TDD[3]	HD-FDD	HD-FDD, FD-FDD, TDD	HD-FDD
Deployment	Standalone, in LTE channel	Standalone, in LTE channel, LTE guard bands	Standalone, in LTE channel	Standalone, in LTE channel, LTE guard bands
Maximum Output Power	23, 20 dBm	23, 20 dBm	23, 20 dBm	23, 20, 14 dBm
Examples of peak data-rates	~800 kbps (FD-FDD), 300-375 kbps DL/UL (HD-FDD)	30/60 kbps DL/UL (HD-FDD)	4/~7 Mbps DL/UL (FD-FDD)	~127/~143 kbps DL/UL (HD-FDD)
Target coverage (MCL)[4]	155.7 dB	164 dB	155.7 dB	164 dB

Table 1: Overview of LTE-M and NB-IoT devices capacities in Release 13 and 14.

In the context of the QCSP project, a CIoT technology has to be chosen for the matter of performance comparison. Both LTE-M and NB-IoT constitute a wise choice. Originally, NB-IoT was seen as dedicated to the support of low-end LPWA use cases, with low data-rate, low energy consumption, low complexity and low cost. On the contrary, LTE-M was more flexible since it addressed medium- to high-end LPWA use cases, providing higher data-rates. But, because of the evolutions of both technologies over the 3GPP releases and also based on the results of some studies [2] [4], the gap between them shrunk and the boundary is now blurred. One clear difference stays true: LTE-M is an evolution of LTE whereas NB-IoT is an entirely new air interface.

LTE-M has been selected as the QCSP study case for the following reason:

- More flexible simulation / experimentation scenarios can be selected since LTE-M addresses a wider range of use cases, from low-end to high-end LPWA.
- For the purpose of future valorization, one can envision evolution of current LTE (or even 5G) features to fit LTE-M standard (e.g. LTE Sidelink). These evolutions may be seen as more straightforward than NB-IoT ones.

The interested reader can learn more on Release 13 and Release 14 CIoT technologies by reading this book [5].

[3] HD: Half-Duplex; FD: Full-Duplex; FDD: Frequency-Division Duplex; TDD: Time-Division Duplex
[4] Maximum Coupling Loss: a metric introduced in TR 45.820 to evaluate the coverage of a physical layer.

2 LTE-M Physical Layer

This section describes the general aspects of the LTE-M physical layer. The objective is to provide the information needed by the reader to be able to understand the hereafter presented use cases. Since the 4G cellular system is not presented as a whole, this document supposes that the reader already has some basic knowledge on the system. The interested reader can refer to [6] for more information.

As an evolution of LTE, LTE-M shares most of the LTE digital signal processing blocks [7]. The main differences are the following:

- For the sake of complexity reduction, some high modulation order and large user data packet size (transport block size) cannot be used in LTE-M.
- Because it is a broadband channel, the PDCCH (introduced later) cannot be received by LTE-M UE implementing lower system bandwidth. A dedicated channel, the MPDCCH, is added instead.
- Various numbers of blind repetitions are introduced to cope with the coverage extension. Contrary to repetitions due to negative acknowledgement (NACK), blind repetitions are considered as necessary for the transmission to be reliable. Consequently, they are transmitted without waiting for any acknowledgement (ACK). The UE and the eNB are expected to implement frame combining algorithms to take advantage of these repetitions, thus effectively improving the system coverage.

2.1 LTE-M transmission process blocks

Figure 1 provides an overview of the signal processing at the LTE-M transmitter side[5]. This constitutes a simplification of the TX block diagram. After identifying the suitable modulation and coding rate to use, the user data are first split into binary code-blocks. Each code-block is then fed to the selected channel encoder. The rate matching step adapts the number of bits of each code-word outgoing from the encoder, to match an expected value. The bits can thus be punctured (removed) or repeated, depending on the need to raise or lower the actual code rate. Finally, the bits are modulated, and the outgoing complex symbols are mapped by the OFDM (Orthogonal Frequency Division Multiplexing) block on the appropriate subcarriers and transmitted to the radio frequency block (RF).

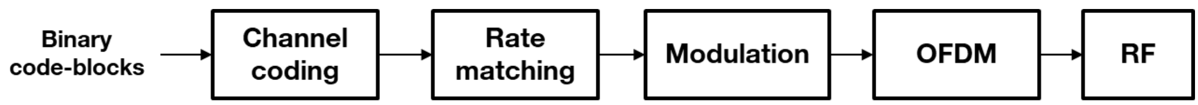

Figure 1: Simplified LTE-M transmission chain.

[5] Only the transmission side is standardized by the 3GPP, leaving the choice of the reception signal processing algorithms to the manufacturers. However, they still have to comply with well-defined performance requirements.

For the channel encoding block, several encoders are available. The choice depends on the kind of the data to transmit. For user data, usually involving large code-blocks, LTE-M uses a Turbo Code scheme. Regarding control data, the size of the code-blocks is smaller. In this case, a convolutional code or a block code (Reed-Muller code) is used, depending on the kind of control information to encode.

The modulation used depends on the direction of the data flow (uplink or downlink) and on the type of data. For user data, LTE-M can use the 4-QAM and 16-QAM modulations in uplink (PUSCH). In downlink (PDSCH), 4-QAM, 16-QAM and 64-QAM are available. The order of modulation is chosen by assessing the channel quality, to ensure reliable and efficient communications. The BPSK can also be used but is solely enabled for control information.

The modulation step described above is only a mapping from binary-words to complex symbols. This step is associated to the OFDM, which constitutes a “second” modulation step before the RF processing. To be precise, the CP-OFDM (Cyclic Prefix OFDM) is used in downlink, and the SC-FDMA (Single Carrier Frequency Division Multiple Access) in the uplink. The latter is a modulation scheme derived from the CP-OFDM that will be described subsequently. The general idea behind the OFDM is to split the information over N orthogonal subcarriers, each carrying $\frac{1}{N}$ of the total information. Since the shaping filter is usually rectangular, the spectrum of each sub-carrier is described as a sinc function. The signal is designed to enable orthogonality between the subcarriers, so the information carried by each sub-carrier can be recovered without suffering from other subcarriers interferences. Another advantage of this approach is the multiplexing flexibility, where each sub-carrier is a resource that can be attributed to a user. This constitutes an efficient multiple access scheme, the OFMDA, where inter-users interferences are theoretically avoided. Figure 2 describes a schematic view of the CP-OFDM modulator. The IFFT block directly maps one of the N complex data symbol on the related sub-carrier. It also makes the transition from the frequency plan to the temporal plan. The temporal signal is then serialized and can be sent to the RF block. The receiver can use a FFT block to recover the complex symbol carried by each sub-carrier. Regarding the Cyclic Prefix (CP) part of the CP-OFDM modulation, it is simply the repetition of the end of the temporal signal at the beginning. One can then split the final temporal signal into the CP followed by the OFDM symbol, as described on Figure 2. The presence of the CP provides two major advantages. First, if long enough, it absorbs the interferences from the previous OFDM symbol that can appear due to multipath propagation channel. Second, it makes the signal appear as periodic on the duration composed of the CP and the OFDM symbol. One can demonstrate [8] that this feature simplifies the equalization step, allowing a “one tap channel” equalization per sub-carrier in the frequency plan. The channel complex coefficient is then equal to the channel frequency response on that sub-carrier. At the receiver, the CP is removed before the FFT step.

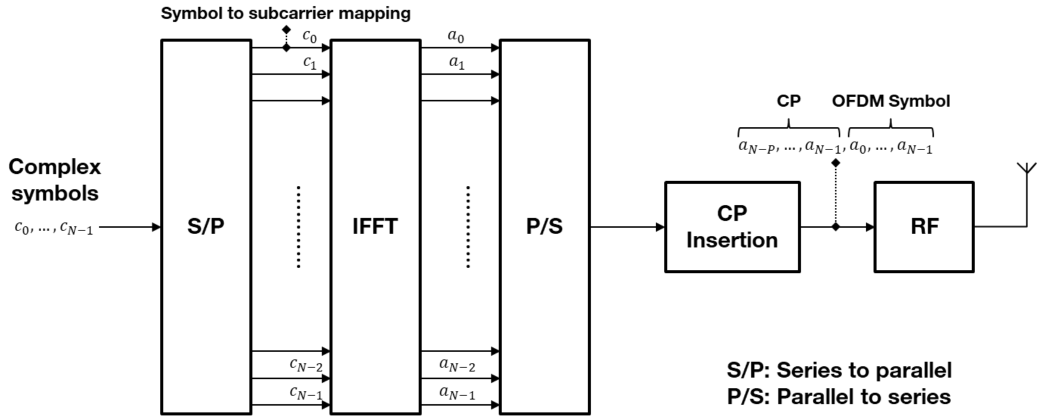

Figure 2: Schematic view of CP-OFDM modulation.

Nevertheless, the CP-OFDM presents also some disadvantages. In case of several users transmitting on the same system bandwidth, a good frequency and time synchronizations are necessary to avoid interferences. Moreover, the Peak to Average Power Ratio (PAPR) of the OFDM waveform is high. Hence, to avoid power amplifier (PA) saturation, the implementation of highly linear PA is needed, leading to a cost and a form factor increase. For these reasons, the CP-OFDM is not used in uplink. Instead, the UE uses a modulation scheme derived from it: the SC-FDMA. Figure 3 describes a SC-FDMA modulator. Based on the CP-OFDM one, a DFT operation is added before the IFFT. The size of the DFT, M, depends on the number of subcarriers attributed to the UE. If $M < N$ then the null symbol is attributed to the rest of subcarriers by the UE. The succession of the DFT and the IFFT removes the sinc aspect of the subcarriers spectrum and results instead in a standard one mono-carrier transmission, whose spectrum is localized on the attributed subcarriers. This modulation provides a PAPR reduction, which allows the implementation of cheaper PA in the UE. Moreover the SC-FDMA shares some of the OFDM flexibility, even if the attributed subcarriers have to be adjacent in frequency to maintain the mono-carrier spectrum. The CP still provides a protection against interferences from previous SC-FDMA symbol affected by multipath channel. But contrary to the OFDM, the equalization step cannot be done on a subcarrier basis, since the spectrum is spread over the attributed subcarriers spectrum. Hence a robust equalization is mandatory to ensure a reliable demodulation. Finally, it should be noted that the central subcarrier, called DC (Direct Current) subcarrier, is not used in downlink because of possible quantification noise issue. However, this subcarrier is used in uplink.

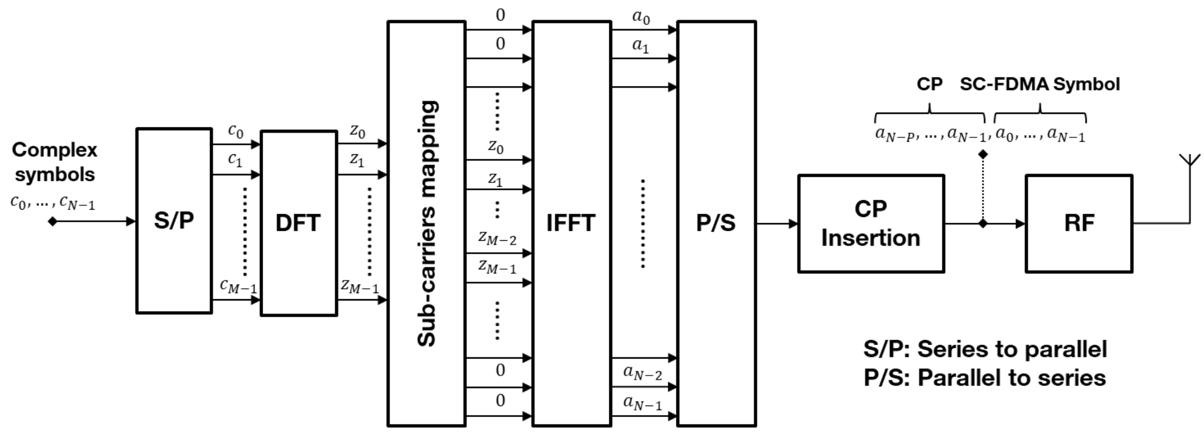

Figure 3: Schematic view of SC-FDMA modulation.

2.2 Numerology

LTE-M shares the most part of the LTE physical layer numerology, the system bandwidth being the only limitation. Thanks to this compatibility, LTE-M can be transmitted within a standard LTE spectrum, the number of allocated resources being dynamically adapted to the needs.

Despite their differences, the CP-OFDM and SC-FDMA share the same numerology. A subcarrier spacing (SCS) of 15 kHz is used. It represents the frequency gap between two adjacent subcarriers. The resources allocation is not done on a per subcarrier basis, but rather on a per block of subcarriers basis. A block of subcarriers is called a Physical Resource Block (PRB) and data transmission can be scheduled on several PRBs. One PRB regroups 12 adjacent subcarriers, spanning over 180 kHz (12*15 kHz) and the frequency location of the PRBs in the system spectrum is fixed. The LTE system bandwidth can take the following values: 1.4, 3, 5, 10, 15 and 20 MHz corresponding to 6, 15, 25, 50, 75 and 100 PRBs. On the contrary the system bandwidth supported by LTE-M is restricted to 1.4 MHz for Cat. M1 and 5 MHz for Cat. M2. This limitation has several consequences on the LTE physical layer to address compatibility issues. One of them is the definition of so-called Narrow-Bands (NBs) spanning over 6 contiguous PRBs. Depending on the LTE total system bandwidth, a fixed number of NBs are available for LTE-M communications. For instance, in a 20 MHz LTE system, 16 NBs are defined and 2 PRBs on each spectrum edge are not used. To still benefit from frequency diversity, LTE-M traffic can be scheduled of different NBs over the time, thanks to the NB frequency hopping.

The (time) frame structure of LTE and LTE-M is the same and is described by the Figure 4. The frame structure is organized in several sub-frame layers with decreasing time duration. Starting at the frame level, one frame consists in 10 subframes, lasting 1 ms each. A subframe is divided into 2 slots, each one lasting 0.5 ms. The slot is the lowest temporal level in LTE, but they are usually associated in a pair, constituting the subframe. Frame identification numbers, noted System Frame Number (SFN), range from 0 to 1023. On a same fashion, subframe identification numbers, noted Subframe Number (SN), range from 0 to 9.

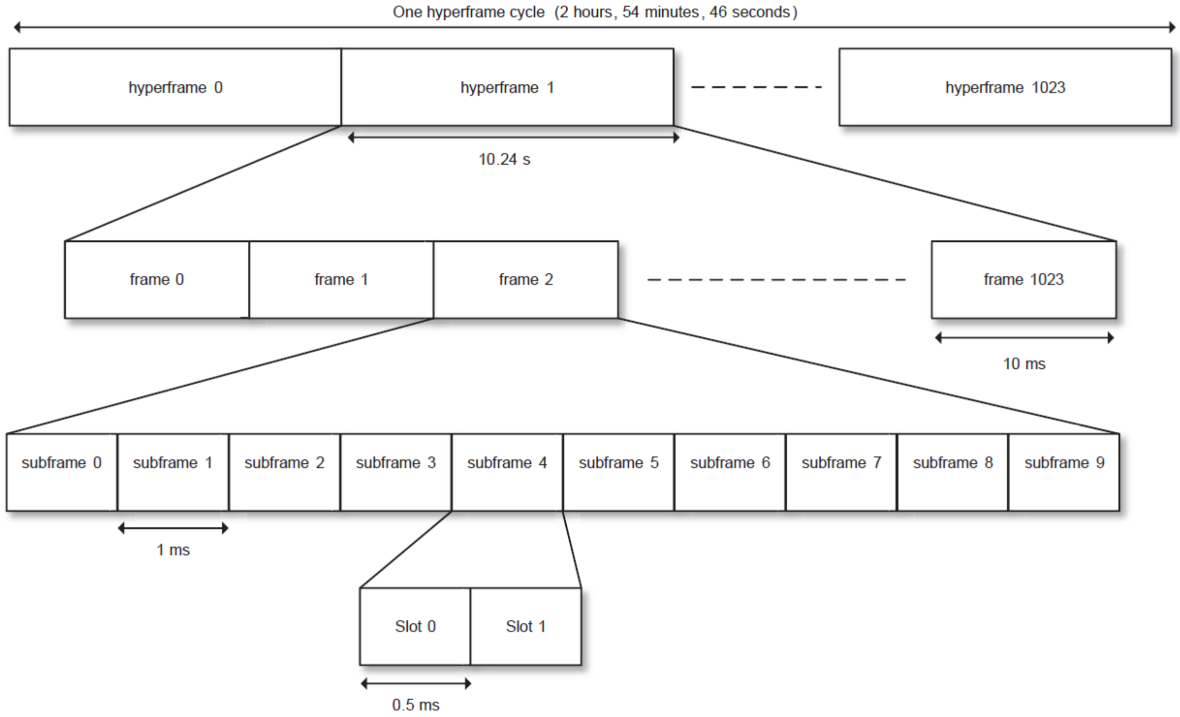

Figure 4: LTE-M frame structure [5].

The Figure 5 describes the coupling of frequency and time structures: a PRB during one subframe. On the frequency axis, the PRB is split into the 12 subcarriers of 15 kHz each. On the time axis, each slot is divided into 7 OFDM symbols, leading to a total of 14 OFDM symbols within a subframe. It should be noted that the actual number of OFDM symbols within a slot depends on the length of the CP. The normal CP lasts 5.21 μs for the symbol 0 and 4.69 μs for the symbol 1 to 6, conducting to the transmission of 7 OFDM symbols within a slot. The extended CP lasts 16.67 μs in each symbol and only 6 OFDM symbols can be transmitted within a slot. In both cases, the mean useful OFDM symbol lasts 66.67 μs during a slot. Despite the loss in capacity, the extended CP can handle channel delay profiles that are more spread. It is especially useful for cell with large covering radius. For the sake of simplicity and because it is the common case, we will only consider the normal CP for the rest of the document. Splitting resources in time and frequency, the smallest resource unit corresponds to a subcarrier during one OFDM symbol (a square on the figure) and is called a Resource Element (RE). The smallest resource that can be allocated to a transmission is one PRB mapped over two slots, which corresponds to 14 OFDM symbols. The PRB in the second slot doesn't have to be on the same frequency range than in the first one.

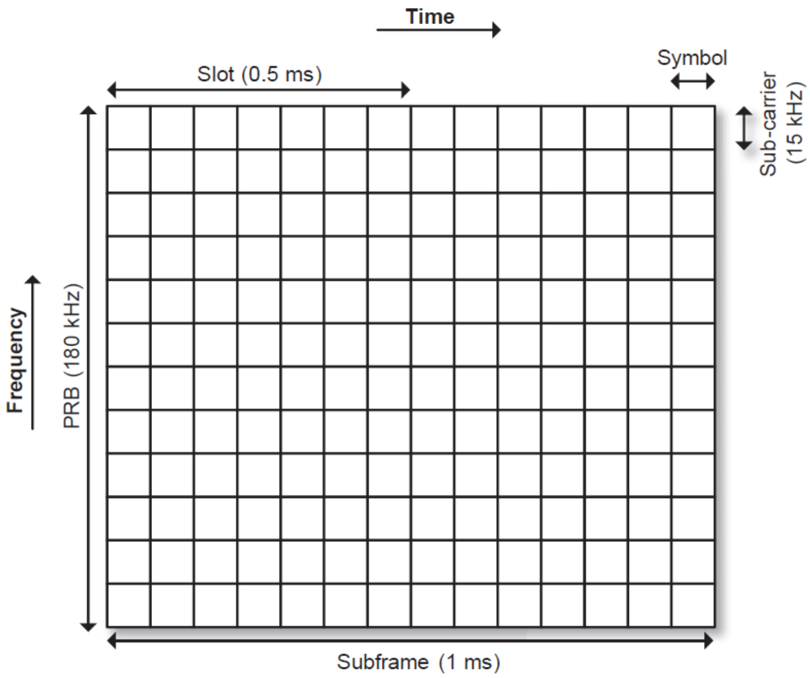

Figure 5: Subframe-PRB description [5]

Regarding duplexing schemes, LTE-M supports both standard LTE transmission modes: Full Duplex Frequency Division Duplex (FD-FDD) and Time Division Duplex (TDD). Moreover, to decrease cost and complexity of modems, LTE-M also supports a Half Duplex FDD (HD-FDD) type B. The type B allows a HD design with a single local oscillator. This further simplifies the radio block, but a guard subframe should be added when the UE is switching between downlink and uplink, to grant the time to retune the carrier frequency. In the following sections, we will only consider the FD-FDD duplexing scheme since it simplifies the procedures explanations without being less relevant for the project.

Finally, one of the main objectives of LTE-M is to provide Coverage Enhancement (CE) compared to the standard LTE coverage. To increase the coverage, LTE-M uses numerous repetitions. This is a simple and modular method which has a low impact on the system complexity. Two CE modes A and B are available, but only the CE mode A is mandatory. CE mode A supports at most 32 subframe repetitions, while CE mode B supports 2048 repetitions. The exact number of allowed repetitions depends on the type of data to transmit. Originally, these repetitions should have brought a coverage extension of 15 dB gain compared to traditional LTE coverage. However, recent studies [4] show that a 20 dB gain can be achieved with the standardized CE mode B.

2.3 DL channels

The concept of LTE channel is here not related to the propagation or communications channel. LTE channels constitute system features, which identify the kind of data to transmit and define the processing to apply. LTE-M downlink channels are presented on the Figure 6. These channels are separated in logical, transport and physical channels, depending on the LTE protocol layer concerned.

Logical channels are handled by the RLC layer. A logical channel is identified by the type of data it carries, e.g. user data or control information about the cell configuration.
Transport channels are related to the MAC layer and are defined by transport methods of the information over the physical resources, e.g. scheduling mode, HARQ process.
Finally the physical channels are managed by the Physical layer (PHY). A physical channel is characterized by a collection of information on the PHY processing and REs mapping, e.g. modulation and coding scheme, scrambling sequence. The only LTE-M downlink physical channel that is not common with LTE is the MPDCCH. In addition to the physical channels, the PHY layer also used purely physical signals. They are not related to upper layer information, but rather transport known symbol sequences for synchronization or channel estimation operations. The following analysis is focused on the downlink physical channels and signals:

- PSS and SSS: Primary and Secondary Synchronization Signals are used by the device to detect the cell, acquire the carrier frequency, frame timing and number, CP length, duplex mode and Physical Cell Identity (PCI).
- RS: Reference Signals regroup several preset sequences that allow the UE to estimate the downlink propagation channel, to demodulate downlink physical channels and to assess downlink reception quality.
- PBCH: The Physical Broadcast Channel transports the Master Information Block (MIB) which is the core part of the System Information (SI). The SI describes the different aspects of the system configuration; indicates which features are supported and their parameterization. The other System Information Blocks (SIBs) are transported by the PDSCH.
- PDSCH: The Physical Downlink Shared Channel usually carries the user data. This is the main channel carrying downlink data.
- MPDCCH: The MTC Physical Downlink Control Channel is the LTE-M counterpart of the PDCCH. It carries different Downlink Control Information (DCI) to the UE and is usually associated to a PDSCH. The information provided by the DCIs can be related to downlink scheduling information, uplink grant information, uplink power control and paging. Specific DCIs have been designed for LTE-M but they fulfill the same purpose as LTE DCIs on PDCCH.

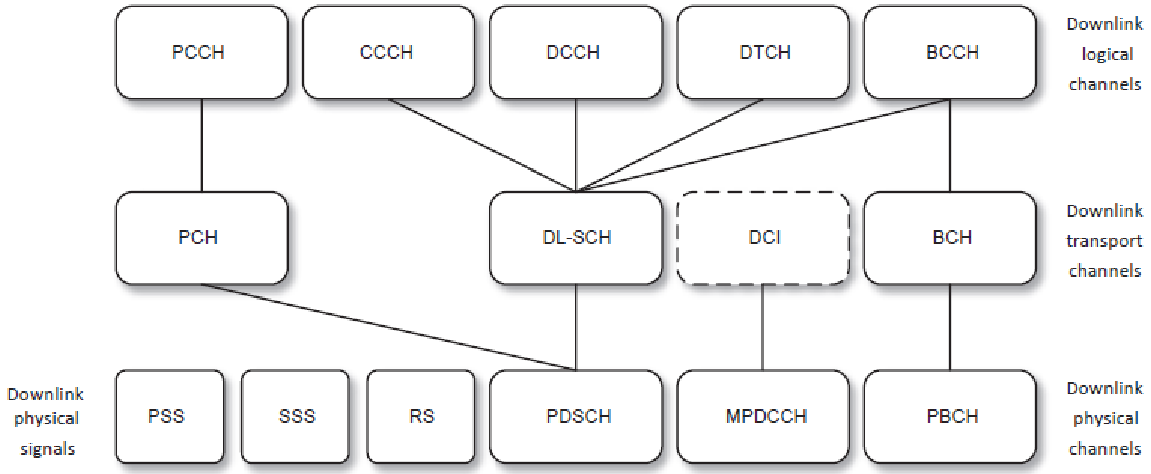

Figure 6 : Downlink channel structure [5]

The reason behind the definition of the MPDCCH lays in the PDCCH resource mapping. The LTE PDCCH is mapped on the first OFDM symbols of each subframe, in the LTE control region, as presented on the Figure 7. The number of OFDM symbols in the control region depends on the system configuration, system bandwidth and the actual system load. It is ranged from 1 to 3 OFDM symbols, and even 4 symbols in the case of the smallest system bandwidth 1.4 MHz. The PDCCH is sent on the whole system bandwidth, which means that if the bandwidth is 20 MHz, the UE needs to listen to the first OFDM symbols on 20 MHz to decode the PDCCH. Consequently, this scheme is not compatible with LTE-M, and a new channel was created for that purpose: the MPDCCH. The MPDCCH and PDSCH are transmitted together over the LTE data region (since the LTE control region is occupied by the PDCCH). The LTE-M starting symbol depends on the length of the PDCCH. Hence it can start in the second, third or fourth position, except for the smallest system bandwidth where it can be up to the fifth position.

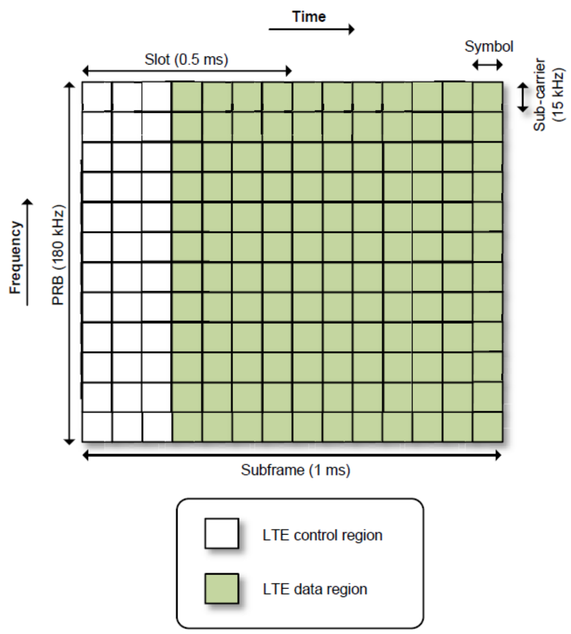

Figure 7: Control and data region in downlink [5]

Another specificity of LTE-M downlink channels is related to the authorized subframes for downlink transmissions (namely MPDCCH and PDSCH). They can only be transmitted on specified subframes identified thanks to a mapping sequence (bitmap) broadcasted in the SI. This mapping sequence has a periodicity of 10 or 40 ms, indicating the allowed subframes for 1 frame or 4 frames.

2.4 UL channels

An equivalent channel structure is also used in the uplink. It is described by the Figure 8. The same logical, transport and physical layers are present as well as reference signals not indicated on the figure. The following description focuses again on the physical channels:

- PRACH: The Physical Random Access Channel is used by the UE to initiate the communication with the base station when it has no granted resource for an uplink transmission. Typically the UE uses the PRACH during the first attach procedure to the cell.
- PUSCH: The Physical Uplink Shared Channel is the uplink counterpart of the PDSCH. Its main purpose is to transport user data to the base station.
- PUCCH: The Physical Uplink Control Channel is the uplink counterpart of the PDCCH or MPDCCH in the case of LTE-M. In the same way the MPDCCH carries DCI, the PUCCH carries Uplink Control Information (UCI). A UCI can transport a scheduling request, a HARQ feedback or a Channel State Information (CSI).
- RS: Reference Signals are also transmitted by the UE. They are used by the eNB to estimate the channel quality in uplink and to coherently demodulate the PUSCH and the PUCCH.

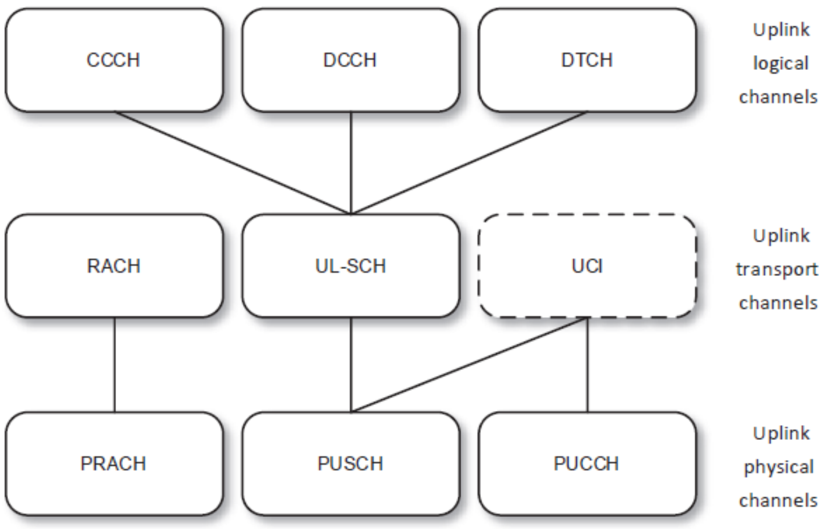

Figure 8: Uplink channel structure [5]

An uplink LTE-M bitmap sequence may also be broadcasted to indicate which subframes are allowed for LTE-M uplink transmissions (PUCCH/PUSCH). The periodicity is 10 ms, corresponding to 1 frame.

3 Use Cases for CCSK

This section describes the relevant use cases identified. The 3GPP procedures chosen to assess the performance of the CCSK modulation should focus on the advantages of this modulation: parallel transmission of data and a detection/synchronization sequence.

3.1 RACH

The Random Access Channel (RACH) is used by the UE to transmit the PRACH. As a reminder, the PRACH is used by the UE to initiate the communication with the base station when it doesn't already have allocated resources. The PRACH transmission is the first step of the Random Access (RA) procedure, which can be initiated simultaneously by several UEs in an unsynchronized manner. Consequently, collisions can occur on the PRACH and the RA procedure has been designed to solve these collisions. The RA procedure is said to be contention based.

3.1.1 PRACH

LTE-M uses the same PRACH as LTE. It is composed of a CP (Cyclic Prefix), a PRACH sequence (a preamble) and a guard time. The PRACH can span over several subframes denoted as the PRACH transmission occasion. Because of the unknown propagation delay between the UE and the eNB, the transmitted PRACH could interfere with synchronized transmissions in following subframes. To avoid this situation, a guard time (no transmission) is added at the end of the PRACH. The length of the guard time as well as the length of the CP and the preamble depend on the PRACH format and influence the maximum theoretical cell range. PRACH formats are described in Table 2. The actual maximum cell range may be smaller depending on the radio environment of the cell. The different PRACH formats are available to cope with different cell radius and multipath spreading. Longer CPs can absorb higher multipath propagation delays and are adapted to dense environments like urban areas. To calculate the PRACH sequence and CP durations, the 3GPP uses the basic LTE time unit $\mathrm{T_s}$, corresponding to the minimal sampling period (20 MHz system bandwidth):

$$\mathrm{T_s} = \frac{1}{15000 * 2048}\ \mathrm{s} = \frac{1}{30.72\ \mathrm{MHz}}$$

The durations in Table 2 are also approximated in µs for convenience. The table also provides the number of subframes used by one PRACH transmission occasion.

PRACH format	CP length ($\mathbf{T_s/\mu s}$)	Sequence length ($\mathbf{T_s/\mu s}$)	PRACH transmission occasion (ms)	Maximum theoretical cell range (km)
0	3168 / 103	24576 / 800	1	14
1	21024 / 684	24576 / 800	2	77
2	6240 / 203	2*24576 / 2*800	2	29

3	21024 / 684	2*24576 / 2*800	3	100

Table 2: LTE-M PRACH configurations.

The PRACH time and frequency resources are multiplexed with the PUSCH ones. On the frequency dimension, 6 PRBs (1.08 MHz) can be allocated in a subframe for PRACH transmission. To determine the PRACH format and the resources' location, the UE have to decode the SIB2. One should note that the resources for the PRACH do not have to be continuous in time.

Without prior information, the UE time reference for transmission is based on its reception time of eNB signal. Hence the UE synchronization is delayed by the one-way propagation from the eNB as presented in Figure 9. Consequently, UE transmissions are received by the eNB with a delay corresponding to the round-trip delay (RTD; equals two times the one-way propagation time). The eNB estimates this delay based on the PRACH reception instant and then calculates a corresponding Timing Advance (TA) value. As soon as the UE is informed of the TA value, it will anticipate its transmission starting time, so the eNB correctly receives the uplink message within the subframe timing. The TA is then constantly evaluated by the eNB by estimating the delay of arrival of PUCCH, PUSCH or uplink RS. TA commands can be sent to the UE to adjust the actual TA value.

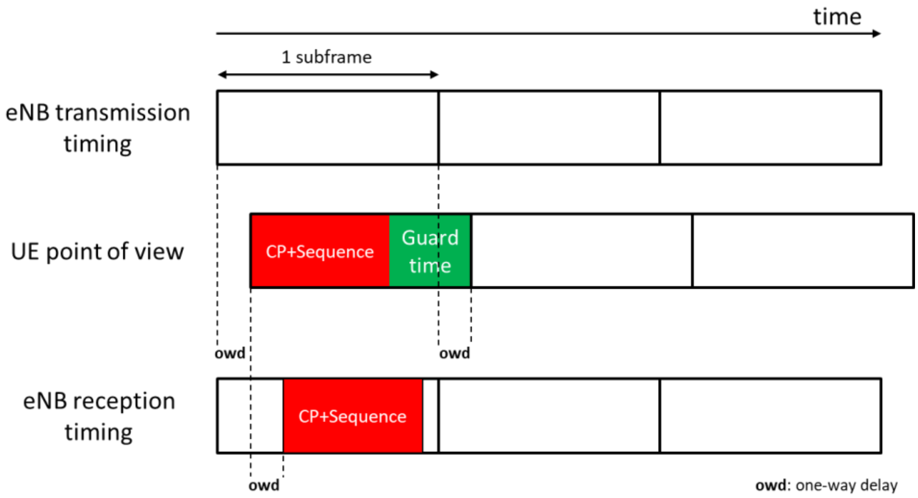

Figure 9: Propagation delay and guard time.

In each cell, there is a maximum of 64 sequences available for a PRACH transmission. During PRACH dedicated subframes, the UE randomly pick one of the sequences and make a PRACH attempt. Since the UE has no dedicated resources to transmit its PRACH, collisions between UE are possible. The sequences are Zadoff-Chu (ZC) sequences. In the following, relevant information on the ZC sequences are provided.

The elements of the ZC sequences used in uplink LTE(-M) are defined as [6]:

$$x_u(n) = e^{-\frac{j\pi un(n+1)}{N_{\mathrm{ZC}}}} \text{ for } 0 \le n \le N_{\mathrm{ZC}} - 1$$

with u the root sequence index and N_{ZC} the length of the ZC sequence. u and N_{ZC} should be relatively prime.

The ZC sequences share interesting properties:

- They have constant amplitude and their circular autocorrelation is null. They are said to be CAZAC (Constant Amplitude Zero Auto-Correlation) sequences.
- Considering two ZC sequences with two different sequence indexes but same length N_{ZC} as a prime number; their normalized circular inter-correlation is constant and equals to $\frac{1}{\sqrt{N_{\mathrm{ZC}}}}$. When N_{ZC} is not prime, there is no guarantee for the circular inter-correlation to be low.

The autocorrelation property is described by the following equation:

$$\frac{1}{N_{\mathrm{ZC}}} \sum_{n=0}^{N_{\mathrm{ZC}}-1} x_u(n) x_u^*(n+\alpha) = \begin{cases} 1 \text{ if } \alpha = 0 \\ 0 \text{ if } \alpha \neq 0 \end{cases}$$

Based on this property and the presence of the CP, the receiver can estimate the channel coefficients in multi-path channel conditions as described in Figure 10: Channel estimation based on ZC sequences.. Here the CP is the repetition of the end of the ZC sequence. Consequently the section studied for path 1 is a circularly shifted version of the original ZC sequence. On the Figure 10 the path 1 corresponds to a shift of one symbol.

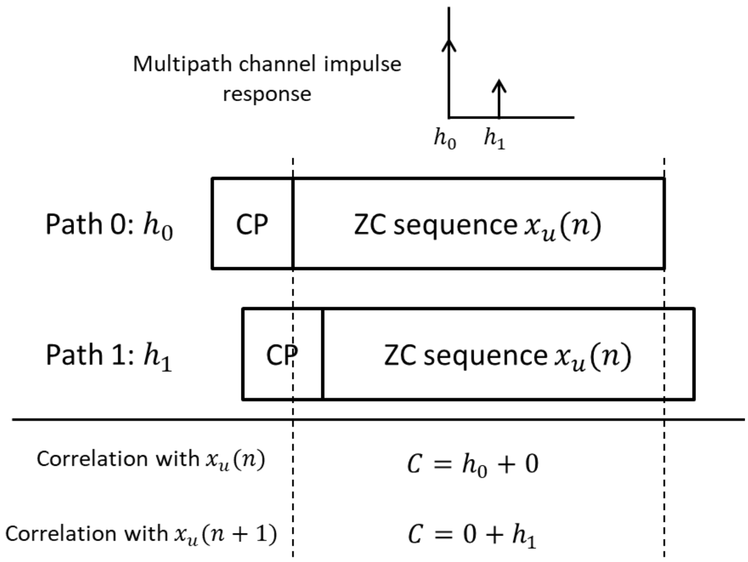

Figure 10: Channel estimation based on ZC sequences.

The ZC sequences are used in uplink for the reference signals. These signals, such as the PRACH, are transmitted on unallocated resources, resulting in possible interference between

UEs. To differentiate UEs in reception, one can assign circularly shifted versions of the same ZC sequence. The minimum shift value for reference signals sequences should then be greater than the delay spread of the channel. Otherwise, a delayed version of a ZC sequence from a UE may be considered as a transmission from another UE and interfere with the channel estimation process.

Another interesting property of the ZC sequence with prime length is that the DFT of a ZC sequence is also a ZC sequence (a time-scaled conjugate of the ZC sequence multiplied by a constant factor [9]). Consequently, the ZC symbol can be directly mapped in the frequency domain without the DFT step. The temporal shift becomes a phase ramp, so that each subcarrier symbol should be multiplied by $e^{j\alpha n}$ with α the temporal shift value and n the subcarrier index.

Coming back to the PRACH description, only one processing window within a PRACH transmission occasion is considered at the eNB to enable an efficient processing. The eNB use the CP and the property of circular autocorrelation of the ZC previously described to detect all the UEs. A consequence of this design is that the CP length of a PRACH format is equal to the maximum round trip delay ($\mathrm{RTD}_{\max}$) of the cell in addition to the multipath channel delay spread. Moreover, only the CP and the preamble length are standardized, leading to a guard time lasting the rest of the PRACH transmission occasion, which should be at least equal to the $\mathrm{RTD}_{\max}$. In case of the maximum expected delay ($\mathrm{RTD}_{\max} + \text{channel delay spread}$) the PRACH will interfere on the following subframe for a duration only equal to the channel delay spread, which is absorbed by the CP of the next subframe.

In a standard transmission, an OFDM symbol last 66.67 µs, leading to the subcarrier spacing of $\frac{1}{66.67} = 15$ kHz. Because a PRACH preamble lasts 800 µs, it uses a specific subcarrier spacing of $\frac{1}{800} = 1.25$ kHz. The 6 PRBs can then contain 864 subcarriers instead of the standard 72 subcarriers. The PRACH itself spans over 839 subcarriers and 25 subcarriers are null at the edge of the 6 PRBs.

There is a total of 64 ZC sequences available per cell. The sequence selection by the UE is random and done for each PRACH attempt. Among the 64 sequences there may be several sequences and their circularly shifted versions if one shifted sequence is not enough. The shift value should be above $\frac{\mathrm{RTD}+\Delta}{\mathrm{T_e}}$ where Δ is the channel delay spread and $\mathrm{T_e}$ is the duration of a sequence element. If UEs select different ZC sequences, the intercorrelation is not perfect but remains sufficiently low for the eNB to detect all UEs. If several UEs chose the same sequence, a collision (contention) occurs. This contention will be solved later during the Random Access (RA) procedure. This step is called contention resolution.

For LTE-M to provide CE to the PRACH, up to 128 repetitions can be used. The available repetitions values are 1, 2, 4, 8, 16, 32, 64 and 128. Since high repetition values can drastically reduce the capacity of the system and create collisions with UE in better coverage, frequency, time and sequences resources can be dedicated to a PRACH CE level, associated to a PRACH repetition value. An eNB supporting CE mode B can have up to 4 PRACH CE levels (2 for mode A and 2 for mode B), and 2 PRACH CE levels if the eNB supports only CE mode A.

3.1.2 Random Access procedure

The RA procedure is used by the UE to contact the eNB when it doesn't have uplink allocated resources or when it does not achieve to contact the eNB by other ways (loose of synchronization for instance). An example of RA procedure is described in Figure 11. Similar procedures can be found in GSM (2G), UMTS (3G) and even 5G-NR.

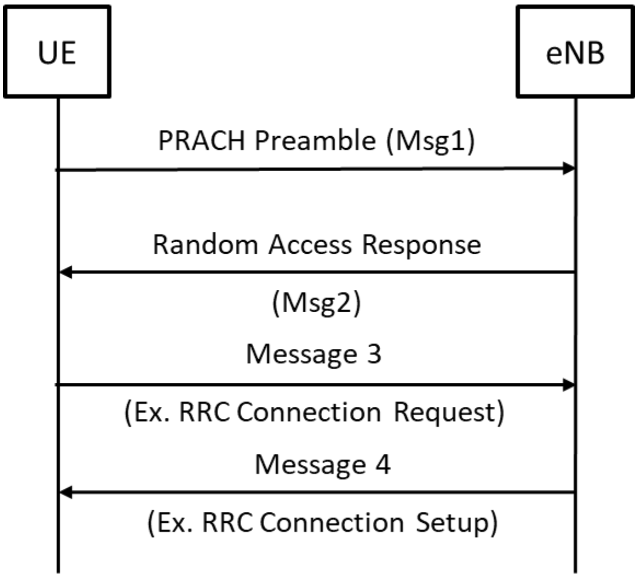

Figure 11: Example of Random Access Procedure.

Strictly speaking, the procedure is composed of 4 messages:
<u>Message 1:</u> The first message is the PRACH preamble (see section
PRACH) transmitted by the UE. To determine the time-frequency and ZC sequence resources to use, the UE has to decode the SIB2.
<u>Message 2:</u> The Random Access Response (RAR) is carried by the MPDCCH scrambled by the RA-RNTI (Random Access - Radio Network Temporary Identifier). The RA-RNTI value depends only on the frame and subframe index carrying the PRACH. Thus, the UE listen to the MPDCCH in a configured timing window and try to decode it using the RA-RNTI. If successful, the UE has to look for the RAPID (Random Access Preamble ID) contained in the corresponding PDSCH. One of the RAPID should match the chosen ZC sequence index. In this case, it means the UE PRACH transmission has been detected and acknowledge by the eNB. The RAR then contains a TC-RNTI (Temporary Cell - RNTI), the timing advance value and a resource allocation for the uplink message 3 transmission. In case of two UEs selecting the same ZC sequence and transmitting on the same PRACH resources (collision case), they will look for the same RA-RNTI and RAPID values. Consequently, they will both consider their PRACH acknowledged. The contention resolution will occur at the next step.
<u>Message 3:</u> From this point the messages are carried on allocated resources. There are several message 3 possibilities depending on the RA triggering reason. To illustrate the RA process,

the message is here a *RRCConnectionRequest*. This message is commonly transmitted on the PUSCH, when the UE was in Idle mode (RRC Idle mode) and need to activate a RRC connection (RRC Connected mode). Within the message 3, the UE will include a unique NAS (Non Access Stratum) identifier, the S-TMSI (SAE[6]-Temporary Mobile Subscriber Identity), previously provided by the network. If the UE does not have an S-TMSI, it has to choose a random number between 2^{40} possibilities.
Message 4: The corresponding message 4 is the *RRCConnectionSetup*. The UE listens to the MPDCCH looking for a scrambling with the TC-RNTI provided in the message 2. The message 4 carried by the PDSCH contains the S-TMSI or the random number provided by the UE in the message 3. This step should act as a contention resolution since the S-TMSI is unique. There is still a minute possibility of not resolving the contention, if both UEs had to choose a random number and choose the same one.

Officially the message 4 closes the random access procedure. Here the next message that properly ends the exchange is the *RRCConnectionSetupComplete* message.

As explained in the section PRACH, several PRACH CE levels are available: 2 for the CE mode A and 2 for the CE mode B if supported. To select an appropriate CE level, the UE evaluates first the channel quality. Based on this evaluation and on threshold values defined in the SIB2, the UE can select the PRACH CE level. Since the CE level is associated to a CE mode, the following messages (2, 3 and 4) are configured with the corresponding parameters (modulation, repetitions, etc.). These parameters are derived from the CE mode A and B configuration parameters with some adaptations for the RA procedure. If the UE can’t detect a RAR, it can retry a PRACH transmission with improved detectability thanks to power ramping and CE level ramping techniques.

3.1.3 Data transmission during RA procedure

The 3GPP proposes some features that enable small data transmission within the RA procedure. The following sections provide an overview of these features. The main objective is to point out the way data transmissions are enable and also the quantity of data transferred.

3.1.3.1 Early Data Transmission (EDT)

The EDT allows one uplink data transmission optionally followed by one downlink data transmission during the RA procedure. Early data transmission refers to both Control Plane EDT (CP-EDT) and User Plane EDT (UP-EDT). In both cases, UL data are transferred within the message 3 of the RA procedure and DL data within the message 4. Moreover, the UE never switch to RRC Connected state. This procedure is reserved to LTE-M UE, NB-IoT UE and UE in coverage enhancement situation.

CP-EDT is based on the possibility to transfert data in an RRC signaling message, introduced by the Control Plane CIoT EPS optimisation. The RRC message type used by the UE is a *RRCEarlyDataRequest*. Hence, the data are encapsulated within the signaling plane and

[6] SAE or System Architecture Evolution is the name of the 4G core network architecture.

transferred to the network equipment responsible for the control plane of the radio access network (RAN): the Mobility Management Entity (MME). The MME forwards then the data into the 4G core network. The eNB will close the CP-EDT procedure with a *RRCEarlyDataComplete* message. This message can optinally contain DL data.

UP-EDT is based on the possibility to suspend and resume the RRC connection, introduced by the User Plane CIoT EPS optimization. After the suspension of the RRC connection (UE is in RRC Idle), the UE has the possibility to quickly resume its RRC context with a message *RRCConnectionResumeRequest*, instead of the message *RRCConnectionRequest*. With this procedure, the security and cyphering of the communication is resumed, avoiding further dedicated exchange between the UE and the eNB, hence providing lower latency and lower energy consumption. In the context of the UP-EDT, UL data are multiplexed with the *RRCConnectionResumeRequest* message. These data are on the user plane and cyphered. The eNB will close the UP-EDT procedure with a message *RRCConnectionRelease* optionally containing cyphered DL data.

When the EDT is closed, the UE is still in RRC Idle mode and it can go back to sleep if possible.

The quantity of data (Transport Block Size or TBS) that can be transferred in UL in the message 3 depends on the eNB configuration. The highest maximum allowed value is 1000 bits. The exact way to compute the allowed TBS depending on the CE mode is described in TS 36.213, section 8.6.2.

3.1.3.2 2-step RACH (5G-NR)

In Release 16, the 2-step RACH feature is only available for the new 5G physical layer: 5G New Radio or 5G-NR. Hence, it cannot be used (for the moment) by LTE-M users. Nevertheless, the approach of this feature is interesting, and it will be concisely described. The 5G-NR RA process is almost identical to the LTE one and no new information is needed to understand the following description.

In 5G-NR, a new RA procedure has been created, in addition to the traditional 4-step (type-1) RA procedure. The 2-step RA procedure, also known as type-2 RA procedure, allows the UE to send the PRACH preamble (Msg1) directly followed by the PUSCH (Msg3) data. This combination is known as the message A (MsgA). Then, the UE waits for the gNB answer, the MsgB. This message content is similar to the concatenation of Msg2 and Msg4, which resolves the contention. The Figure 12 describes the 2-step RA.

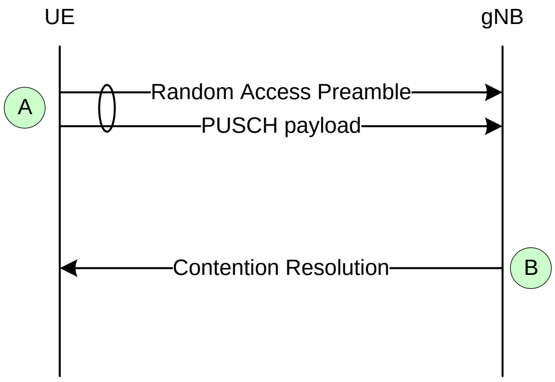

Figure 12: 2-step RA [TS 38.300]

Since type 1 and type 2 RA can be supported in parallel by the gNB, different PRACH resources (for ex. time, frequency, sequences) are allocated to each RA type. Moreover, the MsgA PUSCH uses PUSCH resources which are also dedicated to the type 2 RA and mapped with a corresponding PRACH resource. Several PRACH resources can be mapped to the same PUSCH occasion. This also means that PUSCH resources are reserved in case of 2-step RA attempt, decreasing the capacity of the system. To limit this drawback and the failure of the RA due to collision, a threshold is used to allow only UEs in good coverage conditions to use the 2-step RA.

If the PRACH preamble is correctly detected, but the PUSCH is not correctly decoded, the MsgB should contain a fallback RAR. The UE will then fallback to the type 1 RA and (re-)transmit the Msg3 as in the 4-step RA case.

In conclusion, the 2-step RA is used to decrease the latency and the signaling overhead compared to a standard 4-step RA. The sole objective of the MsgA PUSCH is to contain the same information as the Msg3. For instance the *RRCConnectionRequest* message. The 3GPP does not consider user data transmission within MsgA PUSCH. But combined with EDT, one can easily imagine user data transmitted within the RRC message or multiplexed with the RRC message in MsgA PUSCH.

3.2 Other Use Cases

Other procedures and sequences could be of interest for a CCSK use case. The Wake-Up Signal (WUS), the Positioning Reference Signals (PRS), Primary Synchronization Signal (PSS) and Secondary Synchronization Signal (SSS) are potential candidates but are not further described here.

4 Simulations

4.1 Scenarios

All the documentation quoted here are from the 3GPP Release 16 Technical Specifications (TS), frozen in July 2020. The TS can easily be found online for further information.

The propagation channel models are described in the project document Channel Model and are also provided in the Annex Propagation channel models. No MIMO operations are considered at the moment. In case they are needed (for further study), definition of MIMO models and correlation matrices are provided in annex B.5 of TS 36.104.

4.1.1 RACH

This section describes the simulation scenarios kept for the RACH case. Information from the standardization is first provided, and then simulation scenarios are detailed.

The objective is to use the CCSK to define a new PRACH allowing a data transmission in parallel to the preamble. The CCSK-PRACH should also accomplish the role of the standard PRACH: detection of the UE request by the eNB and potentially TA estimation.

4.1.1.1 3GPP minimum requirements

The eNB minimum requirements for PRACH processing are described in section 8.4 of TS 36.104. They concern the PRACH false alarm probability and detection requirements.

The false alarm probability should be equal to 0.1% for any system parameters (bandwidth, number of antenna and frame structure). It is defined as: “the conditional total probability of erroneous detection of the preamble (i.e. erroneous detection from any detector) when input is only noise.”

The detection probability is defined as: “the conditional probability of correct detection of the preamble when the signal is present. There are several error cases – detecting different preamble than the one that was sent, not detecting a preamble at all or correct preamble detection but with the wrong timing estimation. For AWGN, a timing estimation error occurs if the estimation error of the timing of the strongest path is larger than 1.04us. For ETU70 and EPA1, a timing estimation error occurs if the estimation error of the timing of the strongest path is larger than 2.08us. The strongest path for the timing estimation error refers to the strongest path (i.e. average of the delay of all paths having the same highest gain = 310ns for ETU) in the power delay profile.”
The detection probability should be ≥ 99% for the SNR levels listed in the following tables, copied from the TS. The *Low* notation in the propagation channel parameters refers to the MIMO correlation matrix type.

Table 8.4.2.1-1 PRACH missed detection requirements for Normal Mode

Number of TX antennas	Number of RX antennas	Propagation conditions and correlation matrix (Annex B)	Frequency offset	SNR [dB]				
				Burst format 0	Burst format 1	Burst format 2	Burst format 3	Burst format 4
1	2	AWGN	0	-14.2	-14.2	-16.4	-16.5	-7.2
		ETU 70 Low*	270 Hz	-8.0	-7.8	-10.0	-10.1	-0.1
	4	AWGN	0	-16.9	-16.7	-19.0	-18.8	-9.8
		ETU 70 Low*	270 Hz	-12.1	-11.7	-14.1	-13.9	-5.1
	8	AWGN	0	-19.8	-19.4	-21.5	-21.3	-11.8
		ETU 70 Low*	270 Hz	-16.3	-15.9	-17.8	-17.5	-8.6
Note*: Not applicable for Local Area BS and Home BS.								

Table 8.4.2.1-3 PRACH missed detection requirements for coverage enhancement (PRACH frequency hopping OFF)

Number of TX antennas	Number of RX antennas	Propagation conditions and correlation matrix (Annex B)	Frequency offset	Number of Repetitions	SNR [dB]			
					Burst format 0	Burst format 1	Burst format 2	Burst format 3
1	2	AWGN	0	4	-	-	-21.3	-21.1
				8	-21.7	-21.3	-	-
				16	-	-	-25.1	-25.0
				32	-25.6	-25.3	-	-
		EPA1 Low	270 Hz	4	-	-	-12.1	-11.7
				8	-13.0	-12.3	-	-
				16	-	-	-17.2	-17.2
				32	-19.0	-18.6	-	-
Note 1: Under fading channels, the PRACH detection performance may be significantly different with different PRACH Configuration Indexes. The requirements in this table are defined based on the simulation results with PRACH Configuration Indexes (3, 19, 35, 51) for Format 0, Format 1, Format 2, and Format 3 respectively.								

Table 8.4.2.1-4 PRACH missed detection requirements for coverage enhancement (PRACH frequency hopping ON)

Number of TX antennas	Number of RX antennas	Propagation conditions and correlation matrix (Annex B)	Frequency offset	Number of Repetitions	SNR [dB]			
					Burst format 0	Burst format 1	Burst format 2	Burst format 3
1	2	EPA1 Low	270 Hz	4	-	-	-15.5	-15.3
				8	-16.2	-15.8	-	-
				16	-	-	-20.1	-20.2
				32	-21.3	-21.1	-	-

Note 1: Under fading channels, the PRACH detection performance may be significantly different with different PRACH Configuration Indexes. The requirements in this table are defined based on the simulation results with PRACH Configuration Indexes (3, 19, 35, 51) for Format 0, Format 1, Format 2, and Format 3 respectively.

Note 2: The requirements in this table are defined under the assumption that UE RF tuning during PRACH frequency hopping has no impact on the symbols in PRACH subframes and thus all symbols in PRACH subframes are available for the transmission of PRACH preambles.

Note 3: The requirements in this table are defined under the assumption that the PRACH frequency offset (prach-FreqOffset-r13) is 0 and frequency hopping offset is N_{RB}^{UL} -6, where N_{RB}^{UL} is defined in TS36.211 [12].

Note 4: The requirements in this table apply for channel bandwidth of 5MHz, 10MHz, 15MHz or 20MHz. For channel bandwidth of 3MHz, the requirements in Table 8.4.2.1-3 apply.

4.1.1.2 3GPP Experiment Proceeding

In case of an experimental setup (testbench in a lab), the TS 36.141 defines the test proceedings and relaxed requirements. The section 8.4 of this TS provides the updated requirement tables.

Table 8.4.1.5-1: PRACH missed detection test requirements for Normal Mode

Number of TX antennas	Number of RX antennas	Propagation conditions and correlation matrix (Annex B)	Frequency offset	SNR [dB]				
				Burst format 0	Burst format 1	Burst format 2	Burst format 3	Burst format 4
1	2	AWGN	0	-13.9	-13.9	-16.1	-16.2	-6.9
		ETU 70 Low*	270 Hz	-7.4	-7.2	-9.4	-9.5	0.5
	4	AWGN	0	-16.6	-16.4	-18.7	-18.5	-9.5
		ETU 70 Low*	270 Hz	-11.5	-11.1	-13.5	-13.3	-4.5
	8	AWGN	0	-19.5	-19.1	-21.2	-21	-11.5
		ETU 70 Low*	270 Hz	-15.7	-15.3	-17.2	-16.9	-8.0

Note*: Not applicable for Local Area BS and Home BS.

Table 8.4.1.5-3: PRACH missed detection requirements for coverage enhancement (PRACH frequency hopping OFF)

Number of TX antennas	Number of RX antennas	Propagation conditions and correlation matrix (Annex B)	Frequency offset	Number of Repetitions	SNR [dB]			
					Burst format 0	Burst format 1	Burst format 2	Burst format 3
1	2	AWGN	0	4	-	-	-21.0	-20.8
				8	-21.4	-21.0	-	-
				16	-	-	-24.8	-24.7
				32	-25.3	-25.0	-	-
		EPA1 Low	270 Hz	4	-	-	-11.5	-11.1
				8	-12.4	-11.7	-	-
				16	-	-	-16.6	-16.6
				32	-18.4	-18.0	-	-
Note 1: Under fading channels, the PRACH detection performance may be significantly different with different PRACH Configuration Indexes. The requirements in this table are defined based on the simulation results with PRACH Configuration Indexes (3, 19, 35, 51) for Format 0, Format 1, Format 2, and Format 3 respectively.								

Table 8.4.1.5-4: PRACH missed detection requirements for coverage enhancement (PRACH frequency hopping ON)

Number of TX antennas	Number of RX antennas	Propagation conditions and correlation matrix (Annex B)	Frequency offset	Number of Repetitions	SNR [dB]			
					Burst format 0	Burst format 1	Burst format 2	Burst format 3
1	2	EPA1 Low	270 Hz	4	-	-	-14.9	-14.7
				8	-15.6	-15.2	-	-
				16	-	-	-19.5	-19.6
				32	-20.7	-20.5	-	-
Note 1: Under fading channels, the PRACH detection performance may be significantly different with different PRACH Configuration Indexes. The requirements in this table are defined based on the simulation results with PRACH Configuration Indexes (3, 19, 35, 51) for Format 0, Format 1, Format 2, and Format 3 respectively. Note 2: The requirements in this table are defined under the assumption that UE RF tuning during PRACH frequency hopping has no impact on the symbols in PRACH subframes and thus all symbols in PRACH subframes are available for the transmission of PRACH preambles. Note 3: The requirements in this table are defined under the assumption that the PRACH frequency offset (prach-FreqOffset-r13) is 0 and frequency hopping offset is $N_{\mathrm{RB}}^{\mathrm{UL}}$ -6, where $N_{\mathrm{RB}}^{\mathrm{UL}}$ is defined in TS36.211 [12]. Note 4: The requirements in this table apply for channel bandwidth of 5MHz, 10MHz, 15MHz or 20MHz. For channel bandwidth of 3MHz, the requirements in Table 8.4.1.5-3 apply.								

4.1.1.3 PRACH generation process

This section provides a concise version of the information needed for the ZC sequence selection and generation, based on the eNB configuration.

4.1.1.3.1 PRACH resources

The section 5.7 of TS 36.211 provides all the information needed to determine the PRACH resources selection. The following table reminds the available preamble formats (FDD, see section
PRACH).

Table 5.7.1-1: Random access preamble parameters

Preamble format	T_{CP}	T_{SEQ}
0	$3168 \cdot T_s$	$24576 \cdot T_s$
1	$21024 \cdot T_s$	$24576 \cdot T_s$
2	$6240 \cdot T_s$	$2 \cdot 24576 \cdot T_s$
3	$21024 \cdot T_s$	$2 \cdot 24576 \cdot T_s$

To determine the actual time and frequency resources where to transmit the PRACH, some calculation are needed. "For BL/CE UEs[7], for each PRACH coverage enhancement level, there is a PRACH configuration configured by higher layers with a PRACH configuration index (*prach-ConfigurationIndex*), a PRACH frequency offset $\bar{n}^{\mathrm{RA}}_{\mathrm{PRBoffset}}$ (*prach-FrequencyOffset*), a number of PRACH repetitions per attempt $N^{\mathrm{PRACH}}_{\mathrm{rep}}$ (*numRepetitionPerPreambleAttempt*) and optionally a PRACH starting subframe periodicity $N^{\mathrm{PRACH}}_{\mathrm{start}}$ (*prach-StartingSubframe*). PRACH of preamble format 0-3 is transmitted $N^{\mathrm{PRACH}}_{\mathrm{rep}} \geq 1$ times. [...] If frequency hopping is not enabled for the PRACH configuration then $n^{\mathrm{RA}}_{\mathrm{PRBoffset}} = \bar{n}^{\mathrm{RA}}_{\mathrm{PRBoffset}}$. [...] The first physical resource block $n^{\mathrm{RA}}_{\mathrm{PRB}}$ allocated to the PRACH opportunity considered for preamble formats 0, 1, 2 and 3 is defined as $n^{\mathrm{RA}}_{\mathrm{PRB}} = n^{\mathrm{RA}}_{\mathrm{PRBoffset}}$." The next table presents the mapping between the broadcasted PRACH configuration index (*prach-ConfigurationIndex*) and the PRACH format associated to the authorized subframes for starting a PRACH transmission.

[7] BL/CE UE stands for Bandwidth reduced Low complexity / Coverage Enhancement UE. It is the name of the LTE-M UE in the 3GPP specifications.

Table 5.7.1-2: Frame structure type 1 random access configuration for preamble formats 0-3

PRACH Configuration Index	Preamble Format	System frame number	Subframe number	PRACH Configuration Index	Preamble Format	System frame number	Subframe number
0	0	Even	1	32	2	Even	1
1	0	Even	4	33	2	Even	4
2	0	Even	7	34	2	Even	7
3	0	Any	1	35	2	Any	1
4	0	Any	4	36	2	Any	4
5	0	Any	7	37	2	Any	7
6	0	Any	1, 6	38	2	Any	1, 6
7	0	Any	2 ,7	39	2	Any	2 ,7
8	0	Any	3, 8	40	2	Any	3, 8
9	0	Any	1, 4, 7	41	2	Any	1, 4, 7
10	0	Any	2, 5, 8	42	2	Any	2, 5, 8
11	0	Any	3, 6, 9	43	2	Any	3, 6, 9
12	0	Any	0, 2, 4, 6, 8	44	2	Any	0, 2, 4, 6, 8
13	0	Any	1, 3, 5, 7, 9	45	2	Any	1, 3, 5, 7, 9
14	0	Any	0, 1, 2, 3, 4, 5, 6, 7, 8, 9	46	N/A	N/A	N/A
15	0	Even	9	47	2	Even	9
16	1	Even	1	48	3	Even	1
17	1	Even	4	49	3	Even	4
18	1	Even	7	50	3	Even	7
19	1	Any	1	51	3	Any	1
20	1	Any	4	52	3	Any	4
21	1	Any	7	53	3	Any	7
22	1	Any	1, 6	54	3	Any	1, 6
23	1	Any	2 ,7	55	3	Any	2 ,7
24	1	Any	3, 8	56	3	Any	3, 8
25	1	Any	1, 4, 7	57	3	Any	1, 4, 7
26	1	Any	2, 5, 8	58	3	Any	2, 5, 8
27	1	Any	3, 6, 9	59	3	Any	3, 6, 9
28	1	Any	0, 2, 4, 6, 8	60	N/A	N/A	N/A
29	1	Any	1, 3, 5, 7, 9	61	N/A	N/A	N/A
30	N/A	N/A	N/A	62	N/A	N/A	N/A
31	1	Even	9	63	3	Even	9

4.1.1.3.2 ZC sequence

Section 5.7 of TS 36.211 provides the details of the 64 ZC sequences set generation: “The set of 64 preamble sequences in a cell is found by including first, in the order of increasing cyclic shift, all the available cyclic shifts of a root Zadoff-Chu sequence with the logical index […] RACH_ROOT_SEQUENCE, where […] RACH_ROOT_SEQUENCE [is] broadcasted as part of the System Information. Additional preamble sequences, in case 64 preambles cannot be generated from a single root Zadoff-Chu sequence, are obtained from the root sequences with the consecutive logical indexes until all the 64 sequences are found. The logical root sequence order is cyclic: the logical index 0 is consecutive to 837. The relation between a logical root sequence index and physical root sequence index u is given by Tables 5.7.2-4 for preamble formats 0 – 3.”

“The u^{th} root Zadoff-Chu sequence is defined by

$$x_u(n) = e^{-j\frac{\pi u n(n+1)}{N_{ZC}}}, \quad 0 \le n \le N_{ZC} - 1$$

where the length N_{ZC} of the Zadoff-Chu sequence is [839]. From the u^{th} root Zadoff-Chu sequence, random access preambles with zero correlation zones of length $N_{CS} - 1$ are defined by cyclic shifts according to

$$x_{u,v}(n) = x_u((n + C_v) \bmod N_{ZC})$$

where the cyclic shift is given by [only consider unrestricted sets case for the CCSK-PRACH testing]

$$C_v = \begin{cases} vN_{CS} & v = 0,1,\ldots,\lfloor N_{ZC}/N_{CS} \rfloor - 1, N_{CS} \neq 0 & \text{for unrestricted sets} \\ 0 & N_{CS} = 0 & \text{for unrestricted sets} \\ d_{start}\lfloor v/n_{shift}^{RA} \rfloor + (v \bmod n_{shift}^{RA})N_{CS} & v = 0,1,\ldots,w-1 & \text{for restricted sets type A and B} \\ \bar{\bar{d}}_{start} + (v - w)N_{CS} & v = w,\ldots,w + \bar{\bar{n}}_{shift}^{RA} - 1 & \text{for restricted sets type B} \\ \bar{\bar{\bar{d}}}_{start} + (v - w - \bar{\bar{n}}_{shift}^{RA})N_{CS} & v = w + \bar{\bar{n}}_{shift}^{RA},\ldots,w + \bar{\bar{n}}_{shift}^{RA} + \bar{\bar{\bar{n}}}_{shift}^{RA} - 1 & \text{for restricted sets type B} \end{cases}$$

$$w = n_{shift}^{RA} n_{group}^{RA} + \bar{n}_{shift}^{RA}$$

and N_{CS} is given by Tables 5.7.2-2 for preamble formats 0-3, […] where the higher-layer parameters *zeroCorrelationZoneConfig* shall be used for PRACH preamble Set 1 […].

Table 5.7.2-2: N_{CS} for preamble generation (preamble formats 0-3)

zeroCorrelationZoneConfig, zeroCorrelationZoneConfigHighSpeed	N_{CS} value		
	Unrestricted set	Restricted set type A	Restricted set type B
0	0	15	15
1	13	18	18
2	15	22	22
3	18	26	26
4	22	32	32
5	26	38	38
6	32	46	46
7	38	55	55
8	46	68	68
9	59	82	82
10	76	100	100
11	93	128	118
12	119	158	137
13	167	202	-
14	279	237	-
15	419	-	-

Table 5.7.2-4: Root Zadoff-Chu sequence order for preamble formats 0 – 3

Logical root sequence number	Physical root sequence number u (in increasing order of the corresponding logical sequence number)
0–23	129, 710, 140, 699, 120, 719, 210, 629, 168, 671, 84, 755, 105, 734, 93, 746, 70, 769, 60, 779 2, 837, 1, 838
24–29	56, 783, 112, 727, 148, 691
30–35	80, 759, 42, 797, 40, 799
36–41	35, 804, 73, 766, 146, 693
42–51	31, 808, 28, 811, 30, 809, 27, 812, 29, 810
52–63	24, 815, 48, 791, 68, 771, 74, 765, 178, 661, 136, 703
64–75	86, 753, 78, 761, 43, 796, 39, 800, 20, 819, 21, 818
76–89	95, 744, 202, 637, 190, 649, 181, 658, 137, 702, 125, 714, 151, 688
90–115	217, 622, 128, 711, 142, 697, 122, 717, 203, 636, 118, 721, 110, 729, 89, 750, 103, 736, 61, 778, 55, 784, 15, 824, 14, 825
116–135	12, 827, 23, 816, 34, 805, 37, 802, 46, 793, 207, 632, 179, 660, 145, 694, 130, 709, 223, 616
136–167	228, 611, 227, 612, 132, 707, 133, 706, 143, 696, 135, 704, 161, 678, 201, 638, 173, 666, 106, 733, 83, 756, 91, 748, 66, 773, 53, 786, 10, 829, 9, 830
168–203	7, 832, 8, 831, 16, 823, 47, 792, 64, 775, 57, 782, 104, 735, 101, 738, 108, 731, 208, 631, 184, 655, 197, 642, 191, 648, 121, 718, 141, 698, 149, 690, 216, 623, 218, 621
204–263	152, 687, 144, 695, 134, 705, 138, 701, 199, 640, 162, 677, 176, 663, 119, 720, 158, 681, 164, 675, 174, 665, 171, 668, 170, 669, 87, 752, 169, 670, 88, 751, 107, 732, 81, 758, 82, 757, 100, 739, 98, 741, 71, 768, 59, 780, 65, 774, 50, 789, 49, 790, 26, 813, 17, 822, 13, 826, 6, 833
264–327	5, 834, 33, 806, 51, 788, 75, 764, 99, 740, 96, 743, 97, 742, 166, 673, 172, 667, 175, 664, 187, 652, 163, 676, 185, 654, 200, 639, 114, 725, 189, 650, 115, 724, 194, 645, 195, 644, 192, 647, 182, 657, 157, 682, 156, 683, 211, 628, 154, 685, 123, 716, 139, 700, 212, 627, 153, 686, 213, 626, 215, 624, 150, 689
328–383	225, 614, 224, 615, 221, 618, 220, 619, 127, 712, 147, 692, 124, 715, 193, 646, 205, 634, 206, 633, 116, 723, 160, 679, 186, 653, 167, 672, 79, 760, 85, 754, 77, 762, 92, 747, 58, 781, 62, 777, 69, 770, 54, 785, 36, 803, 32, 807, 25, 814, 18, 821, 11, 828, 4, 835
384–455	3, 836, 19, 820, 22, 817, 41, 798, 38, 801, 44, 795, 52, 787, 45, 794, 63, 776, 67, 772, 72 767, 76, 763, 94, 745, 102, 737, 90, 749, 109, 730, 165, 674, 111, 728, 209, 630, 204, 635, 117, 722, 188, 651, 159, 680, 198, 641, 113, 726, 183, 656, 180, 659, 177, 662, 196, 643, 155, 684, 214, 625, 126, 713, 131, 708, 219, 620, 222, 617, 226, 613
456–513	230, 609, 232, 607, 262, 577, 252, 587, 418, 421, 416, 423, 413, 426, 411, 428, 376, 463, 395, 444, 283, 556, 285, 554, 379, 460, 390, 449, 363, 476, 384, 455, 388, 451, 386, 453, 361, 478, 387, 452, 360, 479, 310, 529, 354, 485, 328, 511, 315, 524, 337, 502, 349, 490, 335, 504, 324, 515
514–561	323, 516, 320, 519, 334, 505, 359, 480, 295, 544, 385, 454, 292, 547, 291, 548, 381, 458, 399, 440, 380, 459, 397, 442, 369, 470, 377, 462, 410, 429, 407, 432, 281, 558, 414, 425, 247, 592, 277, 562, 271, 568, 272, 567, 264, 575, 259, 580
562–629	237, 602, 239, 600, 244, 595, 243, 596, 275, 564, 278, 561, 250, 589, 246, 593, 417, 422, 248, 591, 394, 445, 393, 446, 370, 469, 365, 474, 300, 539, 299, 540, 364, 475, 362, 477, 298, 541, 312, 527, 313, 526, 314, 525, 353, 486, 352, 487, 343, 496, 327, 512, 350, 489, 326, 513, 319, 520, 332, 507, 333, 506, 348, 491, 347, 492, 322, 517
630–659	330, 509, 338, 501, 341, 498, 340, 499, 342, 497, 301, 538, 366, 473, 401, 438, 371, 468, 408, 431, 375, 464, 249, 590, 269, 570, 238, 601, 234, 605
660–707	257, 582, 273, 566, 255, 584, 254, 585, 245, 594, 251, 588, 412, 427, 372, 467, 282, 557, 403, 436, 396, 443, 392, 447, 391, 448, 382, 457, 389, 450, 294, 545, 297, 542, 311, 528, 344, 495, 345, 494, 318, 521, 331, 508, 325, 514, 321, 518

708–729	346, 493, 339, 500, 351, 488, 306, 533, 289, 550, 400, 439, 378, 461, 374, 465, 415, 424, 270, 569, 241, 598
730–751	231, 608, 260, 579, 268, 571, 276, 563, 409, 430, 398, 441, 290, 549, 304, 535, 308, 531, 358, 481, 316, 523
752–765	293, 546, 288, 551, 284, 555, 368, 471, 253, 586, 256, 583, 263, 576
766–777	242, 597, 274, 565, 402, 437, 383, 456, 357, 482, 329, 510
778–789	317, 522, 307, 532, 286, 553, 287, 552, 266, 573, 261, 578
790–795	236, 603, 303, 536, 356, 483
796–803	355, 484, 405, 434, 404, 435, 406, 433
804–809	235, 604, 267, 572, 302, 537
810–815	309, 530, 265, 574, 233, 606
816–819	367, 472, 296, 543
820–837	336, 503, 305, 534, 373, 466, 280, 559, 279, 560, 419, 420, 240, 599, 258, 581, 229, 610

4.1.1.3.3 Discrete time signal generation

From section 5.7 of TS 36.211:

"The time-continuous random access signal $s(t)$ is defined by

$$s(t)=\beta_{\text{PRACH}}\sum_{k=0}^{N_{\text{ZC}}-1}\sum_{n=0}^{N_{\text{ZC}}-1}x_{u,v}(n)\cdot e^{-j\frac{2\pi nk}{N_{\text{ZC}}}}\cdot e^{j2\pi\left(k+\varphi+K\left(k_0+\frac{1}{2}\right)\right)\Delta f_{\text{RA}}\left(t-T_{\text{CP}}\right)}$$

where $0\leq t<T_{\text{SEQ}}+T_{\text{CP}}$, β_{PRACH} is an amplitude scaling factor in order to conform to the transmit power P_{PRACH} specified in clause 6.1 in 3GPP TS 36.213 [4], and $k_0=n_{\text{PRB}}^{\text{RA}}N_{\text{sc}}^{\text{RB}}-N_{\text{RB}}^{\text{UL}}N_{\text{sc}}^{\text{RB}}/2$. The location in the frequency domain is controlled by the parameter $n_{\text{PRB}}^{\text{RA}}$ is derived from clause 5.7.1. The factor $K=\Delta f/\Delta f_{\text{RA}}$ accounts for the difference in subcarrier spacing between the random access preamble and uplink data transmission. The variable Δf_{RA}, the subcarrier spacing for the random access preamble, and the variable φ, a fixed offset determining the frequency-domain location of the random access preamble within the physical resource blocks, are both given by Table 5.7.3-1."

Table 5.7.3-1: Random access baseband parameters

Preamble format	Δf_{RA}	φ
0 – 3	1250 Hz	7
4	7500 Hz	2

4.1.1.4 CCSK-PRACH Scenario: common configuration

4.1.1.4.1 Test proceeding

The section 8.4 of TS 36.141 proposes a testing proceeding for the PRACH performances estimation:

"The test signal generator sends a preamble and the receiver tries to detect the preamble. This pattern is repeated as illustrated in figure 8.4.1.4.2-1. The preambles are sent with certain timing offsets as described below. The following statistics are kept: the number of preambles detected in the idle period and the number of missed preambles.

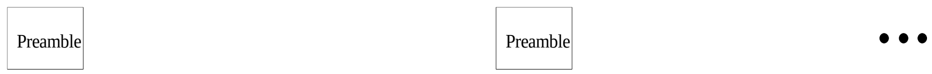

Figure 8.4.1.4.2-1: PRACH preamble test pattern

The timing offset base value is set to 50% of Ncs. This offset is increased within the loop, by adding in each step a value of 0.1us, until the end of the tested range, which is 0.9us. Then the loop is being reset and the timing offset is set again to 50% of Ncs. The timing offset scheme is presented in Figure 8.4.1.4.2-2."

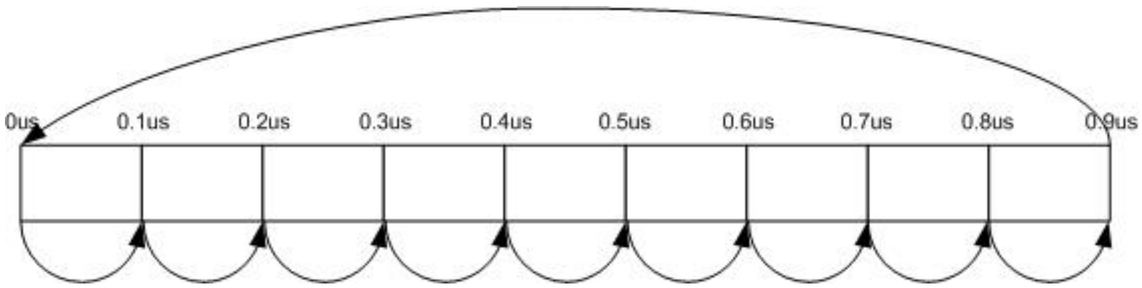

Figure 8.4.1.4.2-2: Timing offset scheme

We propose to follow this testing process to assess the CCSK-PRACH performances. In the test process, one preamble also contains all the needed repetitions.

4.1.1.4.2 Formats, resources and preambles

The annex A.6 of TS 36.104 provides the tested preambles considered to assess the performances of the PRACH false alarm and detection by the eNB. They are listed in the following tables:

Table A.6-1 Test preambles for Normal Mode

Burst format	Ncs	Logical sequence index	v
0	13	22	32
1	167	22	2
2	167	22	0
3	0	22	0

Table A.6-3 Test preambles for coverage enhancement

Burst format	Ncs	Logical sequence index	v
0	13	22	32
1	167	22	2
2	167	22	0
3	0	22	0

The CCSK-PRACH may not be able to use the same ZC sequences compared to the standard PRACH. To inspire the CCSK-PRACH design and to be able to provide comparative performance studies, we provide here the physical root sequences used for PRACH generation based on the cases above:

- Format 0: root sequence index $u = 1$; cyclic sequence shift $C_v = 416$
- Format 1: root sequence index $u = 1$; cyclic sequence shift $C_v = 334$
- Format 2: root sequence index $u = 1$; cyclic sequence shift $C_v = 0$

- Format 3: root sequence index $u = 1$; cyclic sequence shift $C_v = 0$

Moreover, some notes in the tables describing the minimum requirements in section 3GPP minimum requirements indicate the use of specific PRACH configuration index. The corresponding time resources are:

- Format 0 and index 3: system frame number Any; subframe number 1
- Format 1 and index 19: system frame number Any; subframe number 1
- Format 2 and index 35: system frame number Any; subframe number 1
- Format 3 and index 51: system frame number Any; subframe number 1

According to this setting, we propose a similar time resource allocation for the CCSK-RACH. The transmission can start in any frame but only from subframe 1.

Finally, from the PRACH signal equation:

$$s(t) = \beta_{\text{PRACH}} \sum_{k=0}^{N_{\text{ZC}}-1} \sum_{n=0}^{N_{\text{ZC}}-1} x_{u,v}(n) \cdot e^{-j\frac{2\pi nk}{N_{\text{ZC}}}} \cdot e^{j2\pi\left(k+\varphi+K\left(k_0+\frac{1}{2}\right)\right)\Delta f_{\text{RA}}\left(t-T_{\text{CP}}\right)}$$

In our case we will consider that:

$$\beta_{\text{PRACH}} = 1;\ \phi + \frac{K}{2} = 13;\ n_{\text{PRB}}^{\text{RA}} = 0$$

Considering a 1536 points FFT, with 336 zeros on both sides, the central 864 points represent the 6 PRBs for the PRACH transmission. The 839 points representing the ZC sequence are then mapped from index -419 to index 419 with index 0 as the central FFT index (from -768 to 767). The term Kk_0 locates the PRACH transmission on a PRB within the total uplink bandwidth configured in the cell. As presented in the next section, this uplink bandwidth configured in the cell is 5 MHz.

4.1.1.4.3 Other common configuration and requirements

The UE is assumed to have a 1TX/1RX antenna configuration with 1.4 MHz of bandwidth (Cat. M1). The advised FFT size is 128 points for 15 kHz subcarriers spacing and 1536 points for 1.25 kHz subcarriers spacing. The sampling frequency is 1.92 MHz. The uplink central frequency is 2560 MHz [2557.5; 2562.5], corresponding to LTE band 7. LTE-M communications are considered authorized in every frames and subframes.

The eNB is assumed to have a 1TX/1RX antenna configuration with 5 MHz of bandwidth. The advised FFT size is 512 points for 15 kHz subcarriers spacing and 6144 points for 1.25 kHz subcarriers spacing. The sampling frequency is 7.68 MHz. The downlink central frequency is 2680 MHz [2677.5; 2682.5], corresponding to LTE band 7. LTE-M communications are considered authorized in every frames and subframes.

The requirements in terms of false alarm and detection probability are the same as the ones presented in section 3GPP minimum requirements.
No frequency hopping is considered for the moment, so the table with activated frequency hopping (8.4.2.1-4) should be ignored.

No MIMO operation is considered for the moment, so a relaxed 3 dB value on the SNR levels should be considered.

Since data can also be transmitted according to the CCSK modulation, correct decoding requirement should be added. A requirement level equivalent to the detection level can be considered: correct decoding of the frame ≥ 99% for the indicated SNR levels (-3 dB with 1RX eNB configuration).

4.1.1.5 Scenario 1

For the moment, we need more information on the possibilities of the CCSK-PRACH design. Hence, it does not have to be restricted to the same time or frequency resources, even if it would be better for the matter of comparison and standard compliance.
Even if there is no data size expected for the moment, one could think of transmitting the S-TMSI or random number within the PRACH, which would solve the contention at RA message 2. The S-TMSI is 40 bits long.

5 Conclusion

Because of a modification of the objective of the study, a more general CP-OFDM system has been considered in the simulation presented in Deliverable 2.5b. Nevertheless, the use cases presented in this document are valid scenarios to use the CCSK modulation. The property to have a modulation carrying data while allowing an easy detection or synchronization represent a great advantage in numerous LTE-M procedures. It could improve the system capacity and decrease the energy consumption, especially for very small data packets.

6 Annex

6.1 Propagation channel models

In the Technical Specification (TS) 36.104 “Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception”, all radio performance requirements for the BS are provided. The same information are provided for the UE in the TS 36.101 “Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception”.

The multipath radio propagation channels provided are described in TS 36.104 and TS 36.101 annexes B.2:
The multipath propagation conditions consist of several parts:

- A delay profile in the form of a "tapped delay-line", characterized by a number of taps at fixed positions on a sampling grid. The profile can be further characterized by the r.m.s. delay spread and the maximum delay spanned by the taps.
- A combination of channel model parameters that include the Delay profile and the Doppler spectrum that is characterized by a classical spectrum shape and a maximum Doppler frequency

The delay profiles are selected to be representative of low, medium and high delay spread environments. The resulting model parameters are defined in Table B.2.1-1 and the tapped delay line models are defined in Tables B.2.1-2, B.2.1-3 and B.2.1-4.

Table B.2.1-1 Delay profiles for E-UTRA channel models

Model	Number of channel taps	Delay spread (r.m.s.)	Maximum excess tap delay (span)
Extended Pedestrian A (EPA)	7	43 ns	410 ns
Extended Vehicular A model (EVA)	9	357 ns	2510 ns
Extended Typical Urban model (ETU)	9	991 ns	5000 ns

Table B.2.1-2 Extended Pedestrian A model (EPA)

Excess tap delay [ns]	Relative power [dB]
0	0.0
30	-1.0
70	-2.0
90	-3.0
110	-8.0
190	-17.2
410	-20.8

Table B.2.1-3 Extended Vehicular A model (EVA)

Excess tap delay [ns]	Relative power [dB]
0	0.0
30	-1.5
150	-1.4
310	-3.6
370	-0.6
710	-9.1
1090	-7.0
1730	-12.0

2510	-16.9

Table B.2.1-4 Extended Typical Urban model (ETU)

Excess tap delay [ns]	Relative power [dB]
0	-1.0
50	-1.0
120	-1.0
200	0.0
230	0.0
500	0.0
1600	-3.0
2300	-5.0
5000	-7.0

The propagation conditions used for the performance measurements in multi-path fading environment are indicated as EVA[number], EPA[number] or ETU[number] where ‘number’ indicates the maximum Doppler frequency (Hz).

All taps have classical Doppler spectrum, defined as:

(CLASS) $$S(f) \propto 1/(1-(f/f_D)^2)^{0.5}$$ for $f \in -f_D, f_D$.

Hence, the channel used can be named as ETU70, based on the ETU delay profile and with a maximum Doppler frequency of 70 Hz. The higher the Doppler frequency, the shorter the channel coherence time: the channel evolves faster.

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