LTE- Advanced (3GPP Rel.12) Technology Introduction

White Paper

This white paper summarizes significant additional technology components based on LTE, which are included in 3GPP Release 12 specifications. The LTE technology as specified within 3GPP Release was first commercially deployed by end 2009. Since then the number of commercial networks is strongly increasing around the globe. LTE has become the fastest developing mobile system technology ever. As other cellular technologies, LTE is continuously worked on in terms of improvements. 3GPP groups added technology components according to so-called releases. Initial enhancements were included in 3GPP Release 9, followed by more significant improvements in 3GPP Release 10, also known as LTE-Advanced. Beyond Release 10 a number of different market terms have been used. However, 3GPP reaffirmed that the naming for the technology family and its evolution continues to be covered by the term LTE-Advanced. Therefore LTE-Advanced remains the correct description for specifications defined from Release 10 onwards, including 3GPP Release 12.

White Paper
A. Roessler, J. Schlienz,
S. Merkel, M. Kottkamp
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ROHDE&SCHWARZ

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1 Introduction

The LTE (Long Term Evolution) technology was standardized within the 3GPP (3rd Generation Partnership Project) as part of the 3GPP Release 8 feature set. Since end 2009, LTE mobile communication systems are deployed as an evolution of GSM (Global system for mobile communications), UMTS (Universal Mobile Telecommunications System) and CDMA2000. An easy-to-read LTE technology introduction can be found in [1]. Existing mobile technologies have always been enhanced over a significant time period. This holds true for the LTE technology with further enhancements specified in 3GPP Release 9, 10 and 11 (see [2], [3] and [4]). In particular IMT-Advanced requirements set by the ITU (International Telecommunication Union) were satisfied applying technology components in 3GPP Release 10, also known as LTE-Advanced. LTE has proven to be the fastest growing cellular technology. The first commercial network was launched in December 2009 and by end 2014 this number grew to 360 commercial networks deployed in more than 100 countries globally. Built on this success one can expect many more years of LTE / LTE-Advanced improvements to come.

This white paper summarizes significant additional technology components based on LTE, which are included in 3GPP Release 12 specifications. Each illustrated technology component is described in detail in section 2. The technology component dependencies from LTE Release 8 to 12 are illustrated in Fig. 1-1 below. Note that at the time of writing the 3GPP Release 12 specifications were not completely finalized. Future modifications and corrections will be updated as soon as completed in 3GPP. Please check for new versions of this white paper on the Rohde & Schwarz internet presence.

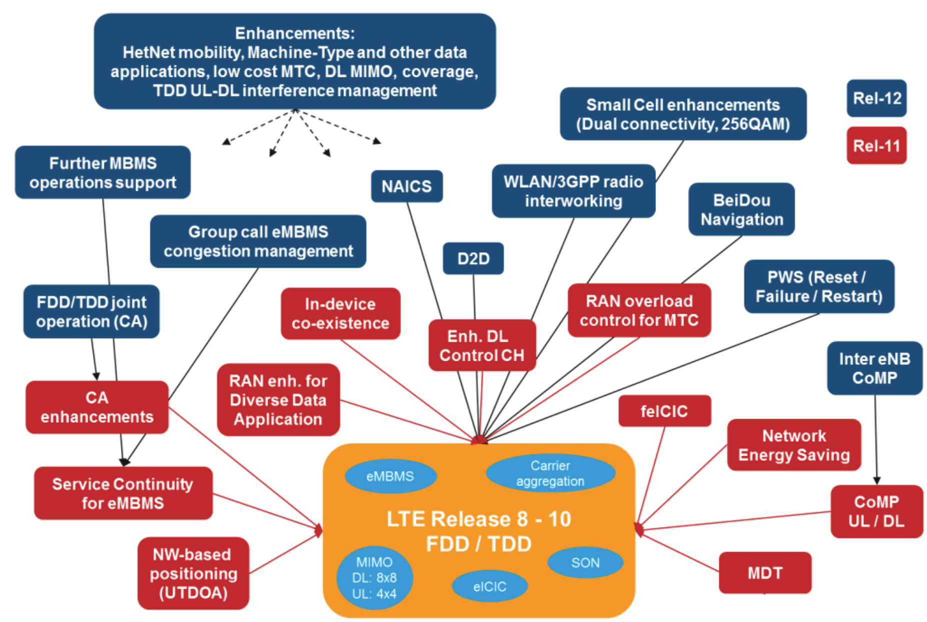


Fig. 1-1: 3GPP Release 8 to 12 technology component dependencies

Section 3 concludes this white paper. Section 4, 5 and 6 provide additional information including a summary of LTE frequency bands and literature references.

2 Technology Components of LTE-Advanced Release 12

Naturally the LTE/LTE-Advanced technology is continuously enhanced by adding either new technology components or by improving existing ones. LTE-Advanced as specified in 3GPP Release 12 comprises a number of these enhancements or additions. The following sections describe significant modifications in more detail.

Independent of a specific technology component added, 3GPP used the UE category concept since the initial specification of the LTE technology. From LTE specified in Release 8 up to Release 11 a single UE category describes an overall capability while only partly referring to single technology components in each 3GPP Release (see Table 2-1). On top of this basic categorization additional parameter signaling is used to inform about detailed support for individual technology components as specified in [10]. This includes physical layer parameters (e.g. support for Tx antenna selection), RF parameters (e.g. supported frequency bands), measurement parameters (e.g. *interFreNeedForGaps*), inter-RAT parameters (e.g. FDD and/or TDD) and many more.

Table 2-1: LTE/LTE-A UE categories 3GPP Release 8 - 11

<table>
<tr><th colspan="2" rowspan="2">UE category</th><th colspan="2">Max data rate in Mbps</th><th rowspan="2">Min. number of DL CCs</th><th rowspan="2">DL MIMO layer(s)</th><th colspan="2">Highest Modulation Scheme</th></tr>
<tr><th>DL</th><th>UL</th><th>DL</th><th>UL</th></tr>
<tr><td rowspan="5">Rel8</td><td>1</td><td>~10</td><td>~5</td><td rowspan="5">1</td><td>1</td><td rowspan="12">64QAM</td><td rowspan="4">16QAM</td></tr>
<tr><td>2</td><td>~50</td><td>~25</td><td rowspan="3">2</td></tr>
<tr><td>3</td><td>~100</td><td rowspan="2">~50</td></tr>
<tr><td>4</td><td>~150</td></tr>
<tr><td>5</td><td>~300</td><td>~75</td><td>4</td><td>64QAM</td></tr>
<tr><td rowspan="3">Rel10</td><td>6</td><td>~300</td><td>~50</td><td rowspan="2">1 or 2</td><td rowspan="2">2 or 4</td><td rowspan="2">16QAM</td></tr>
<tr><td>7</td><td>~300</td><td>~100</td></tr>
<tr><td>8</td><td>~3000</td><td>~1500</td><td>5</td><td>8</td><td>64QAM</td></tr>
<tr><td rowspan="4">Rel11</td><td>9</td><td rowspan="2">~450</td><td>~50</td><td rowspan="2">2 or 3</td><td rowspan="4">2 or 4</td><td rowspan="4">16QAM</td></tr>
<tr><td>10</td><td>~100</td></tr>
<tr><td>11</td><td rowspan="2">~600</td><td>~50</td><td rowspan="2">2, 3 or 4</td></tr>
<tr><td>12</td><td>~100</td></tr>
</table>

From 3GPP Release 12 onwards it was decided to decouple DL and UL capabilities, i.e. the fields *ue-CategoryDL* and *ue-CategoryUL* define downlink/uplink capability respectively. DL Category 0 / UL category 0 was specifically added designed for support of MTC applications. Table 2-2 shows the basic capabilities in downlink and uplink, respectively and Table 2-3 provides the mapping to existing UE categories.

Table 2-2: Downlink / Uplink physical layer parameter values set by the field ue-CategoryDL / ue-CategoryUL

<table>
<tr><th colspan="3">Downlink</th><th colspan="3">Uplink</th></tr>
<tr><th>DL Category</th><th>Max data rate in Mbps</th><th>DL MIMO layer(s)</th><th>UL Category</th><th>Max data rate in Mbps</th><th>64QAM support</th></tr>
<tr><td>0</td><td>~1</td><td>1</td><td>0</td><td>~1</td><td rowspan="2">No</td></tr>
<tr><td>6</td><td rowspan="2">~300</td><td rowspan="7">2 or 4</td><td>3</td><td>~50</td></tr>
<tr><td>7</td><td>5</td><td>~75</td><td>Yes</td></tr>
<tr><td>9</td><td rowspan="2">~450</td><td>7</td><td>~100</td><td>No</td></tr>
<tr><td>10</td><td>8</td><td>~1500</td><td rowspan="2">Yes</td></tr>
<tr><td>11</td><td rowspan="2">~600</td><td>13</td><td>~150</td></tr>
<tr><td>12</td><td colspan="3" rowspan="3"></td></tr>
<tr><td>13</td><td>~390</td></tr>
<tr><td>14</td><td>~3900</td><td>8</td></tr>
</table>

Table 2-3: Supported DL/UL Categories combinations set by the fields ue-CategoryDL and ue-CategoryUL and UE categories to be indicated

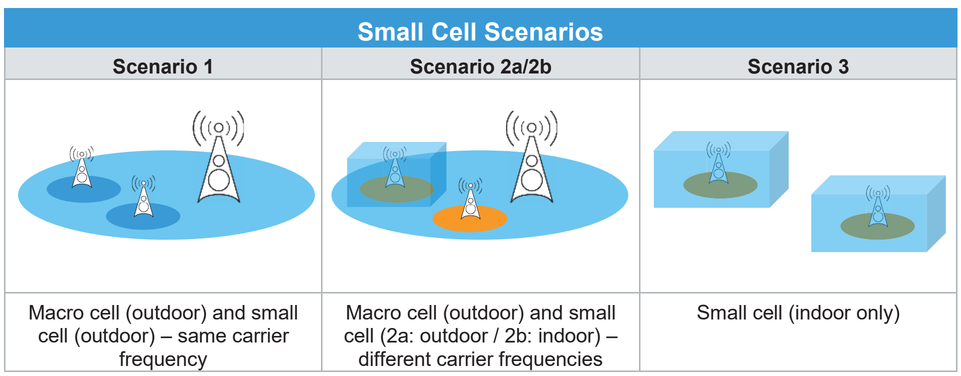
UE DL Category	UE UL Category	UE categories
0	0	N/A
6	5	Category 6, 4
7	13	Category 7, 4
9	5	Category 9, 6, 4
10	13	Category 10, 7, 4
11	5	Category 11, 9, 6, 4
12	13	Category 12, 10, 7, 4
13	3	Category 6, 4
13	5	Category 6, 4
13	7	Category 7, 4
13	13	Category 7, 4
14	8	Category 8, 5

2.1 Small Cell Enhancements

At the time when cellular networks were initially deployed based on GSM the deployment scenarios considered cells with similar cell size, i.e. homogeneous network topologies were used. However, soon different cell sizes were needed to address various capacity requirements. In today's 3G/4G networks heterogeneous network deployments are widely applied. They may include scenarios with small cells deployed within a macro umbrella cell. Small cell scenarios pose challenges in real life networks. Potential improvements for LTE small cells have been investigated throughout a study item phase in 3GPP (see [17], [19] and [20]). In particular the following design goals were addressed in [17]:

- Improve mobility robustness
- Reduce signaling load
- Enhance per-user throughput

Throughout the analysis phase three scenarios were investigated as shown below:



2.1.1 Higher Order Modulation (256QAM)

Up to 3GPP Release 10 the LTE technology applies QPSK, 16QAM and 64QAM (optional in uplink) modulation. Obviously small cell scenarios are characterized by small cell sizes and thus result into high signal to noise/interference potentially available at the end user device. Simulation campaigns showed potential gain by adding 256QAM modulation to the LTE technology. Many different aspects were addressed in [19]. One example result considers realistic scenarios of cell specific reference symbol interference modelling, 3% and 4% Tx EVM and 1.5%~4% Rx EVM. With these assumptions the following throughput gains (UPT) were obtained.

- 0%~5% gain on cell average UPT is observed for the scenarios 2a.
- 5%~13% gain on cell average UPT is observed for the scenarios 2b.
- 7%~30% gain on cell average UPT is observed for scenario 3.

Based on these investigations 256QAM was considered beneficial in selected small cell scenarios and added to the LTE feature set of Release 12 (see [6], section 6.3.2 and section 7.1.5). Independently from the supported UE category, the user device indicates the support for 256QAM reception as part of the radio capability signaling using the RF parameter field *dl-256QAM-r12.* A new modulation and coding scheme index table has been added to [8] in order to allow signaling 256QAM modulation to be used at the end user device. Table 2-4 and Table 2-2 show the difference how to interpret the MCS index (changes relevant to 256QAM are marked in orange). Higher layer signaling is used to distinguish the use of the two tables.

Table 2-4: Modulation and TBS table for PDSCH

MCS Index	Modulation Order	TBS Index
0	2	0
1	2	1
2	2	2
3	2	3
4	2	4
5	2	5
6	2	6
7	2	7
8	2	8
9	2	9
10	4	9
11	4	10
12	4	11
13	4	12
14	4	13
15	4	14
16	4	15
17	6	15
18	6	16
19	6	17
20	6	18
21	6	19
22	6	20
23	6	21
24	6	22
25	6	23
26	6	24
27	6	25
28	6	26
29	2	reserved
30	4	
31	6	

Table 2-5: Modulation and TBS table 2 for PDSCH

MCS Index	Modulation Order	TBS Index
0	2	0
1	2	2
2	2	4
3	2	6
4	2	8
5	4	10
6	4	11
7	4	12
8	4	13
9	4	14
10	4	15
11	6	16
12	6	17
13	6	18
14	6	19
15	6	20
16	6	21
17	6	22
18	6	23
19	6	24
20	8	25
21	8	27
22	8	28
23	8	29
24	8	30
25	8	31
26	8	32
27	8	33
28	2	reserved
29	4	
30	6	
31	8	

Likewise the CQI reporting from the user device distinguishes between use of QPSK/16QAM/64QAM only according to earlier 3GPP Releases or the additional use of 256QAM as shown below. Precisely, if higher layer parameter *altCQI-Table-r12* is set to *allSubframes, csi-SubframeSet1* or *csi-SubframeSet2*. Value *allSubframes* means the alternative CQI table applies to all the subframes and CSI processes, if configured. Value *csi-SubframeSet1* means the alternative CQI table applies to CSI subframe set1, and value *csi-SubframeSet2* means the alternative CQI table applies to CSI subframe set2. EUTRAN sets the value to *csi-SubframeSet1* or *csi-SubframeSet2* only if transmission modes TM1 up to TM9 are used.

Table 2-6: 4-bit CQI Table

CQI Index	Modulation	Code rate x 1024
0	Out of range	
1	QPSK	78
2	QPSK	120
3	QPSK	193
4	QPSK	308
5	QPSK	449
6	QPSK	602
7	16QAM	378
8	16QAM	490
9	16QAM	616
10	64QAM	466
11	64QAM	567
12	64QAM	666
13	64QAM	772
14	64QAM	873
15	64QAM	948

Table 2-7: 4-bit CQI Table 2

CQI Index	Modulation	Code rate x 1024
0	Out of range	
1	QPSK	78
2	QPSK	193
3	QPSK	449
4	16QAM	378
5	16QAM	490
6	16QAM	616
7	64QAM	466
8	64QAM	567
9	64QAM	666
10	64QAM	772
11	64QAM	873
12	256QAM	711
13	256QAM	797
14	256QAM	885
15	256QAM	948

2.1.2 Dual Connectivity for LTE

As introduced in section 2.1 comprehensive small cell studies were conducted. The study focusing on high layer aspects resulted into the definition of the dual layer connectivity feature [17]. This essential modification allows a UE to consume radio resources from two different network nodes. This is in principle similar to the CoMP feature (see [4]), however there are important differences as described below. These are essentially that DC assumes different carrier frequencies in macro and pico cell, that the UE runs two MAC entities, i.e. it utilizes radio resources provided by two distinct schedulers, and that the UE needs to support two UL carriers.

2.1.2.1 Deployment scenarios, eNodeB roles and network interfaces

eNBs involved in DC for a certain UE assume two different roles. An eNB either acts as a Master eNB (MeNB) or as a Secondary eNB (SeNB). A Master Cell Group (MCG) / Secondary Cell Group (SCG) is defined as a group of serving cells associated with the MeNB/SeNB, comprising of the Primary Cell (PCell) / Primary SCell (PSCell) and optionally of one or more Secondary Cells (SCells). In DC a UE is connected to one MeNB and one SeNB, i.e. the UE operates two MAC entities and two separate RLC entities for each data flow on each of the MeNB and SeNB. This is an essential difference compared with the CoMP feature introduced in 3GPP Release 11. The underlying assumption is that two eNBs involved in DC are connected via a non-ideal backhaul X_2 interface. Note that the eNBs may have different roles for different UEs, i.e. a SeNB to one particular UE may be the MeNB or the only eNB to another UE. The study in [17] concluded that the technology potential of inter-node radio resource aggregation for scenario #2 was justified in terms of all the design goals, where f_1 and f_2 correspond to different carriers in different frequency bands. To be precise the work in 3GPP RAN2 does not preclude applying the concept in scenarios with the same frequency in macro and pico cells. However in 3GPP RAN4 UE requirements are only specified assuming the scenario shown in Fig. 2-1.

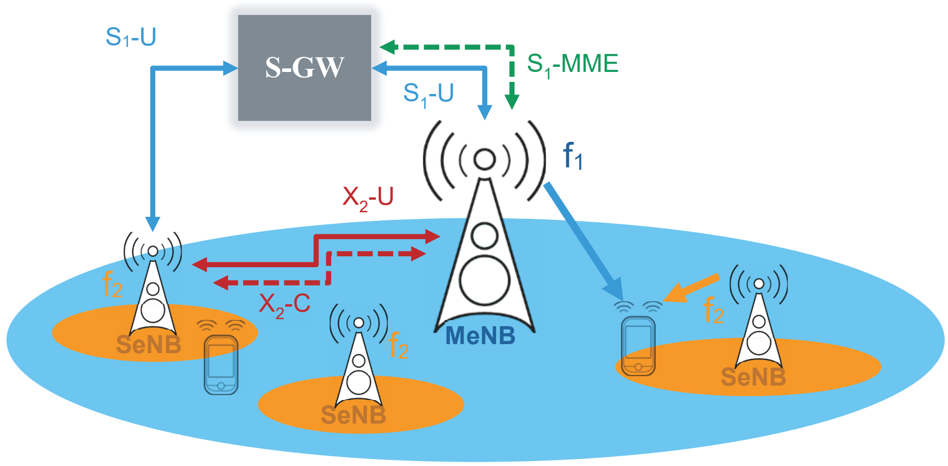


Fig. 2-1: Deployment scenario for small cells within macro coverage

As illustrated control plane signaling is realized via the X_2 interface and only one S_1-MME connection per UE exists. In contrast u-plane connections exist towards the MeNB and the SeNB depending on the bearer type used (see section 2.1.2.2 below).

For Dual Connectivity, two operations are defined; synchronous and asynchronous DC because of the assumed non-ideal backhaul connection between eNodeBs. In synchronous DC operation the requirements are the same as for carrier aggregation. I.e. the UE can cope with a delay spread of at least up to 33µs among any serving cells of all cell groups (CG) monitored at the receiver and can cope with a delay spread of at least up to 30.26µs among the serving cells belonging to the same CG monitored at the receiver. In asynchronous DC operation, the range for monitoring any serving cell out of all cell groups is extended to 500µs.

When DC is deployed, frame timing and SFN are aligned among the component carriers to be aggregated within a CG. However they may or may not be aligned among the component carriers to be aggregated between the different CGs.

2.1.2.2 Protocol architecture and split bearer

In DC, the radio protocol architecture that a particular bearer uses depends on how the bearer is setup. Three alternatives have been defined as follows:

- Master Cell Group (MCG) bearer
- Secondary Cell Group (SCG) bearer
- Split bearer

The three bearer alternatives are illustrated in the radio protocol architecture in Fig. 2-2. RRC is located in the MeNB and signaling (SRBs) is always of the MCG bearer and therefore only use the radio resources provided by the MeNB. The MCG bearer can be seen as the legacy bearer that transports both data and signaling. Split bearer and SCG bearer are data only bearers. The main difference between the latter two is that for split bearer the S1-U interface terminates in the MeNB whereas for SCG bearer the S1-U interface terminates at the SeNB.

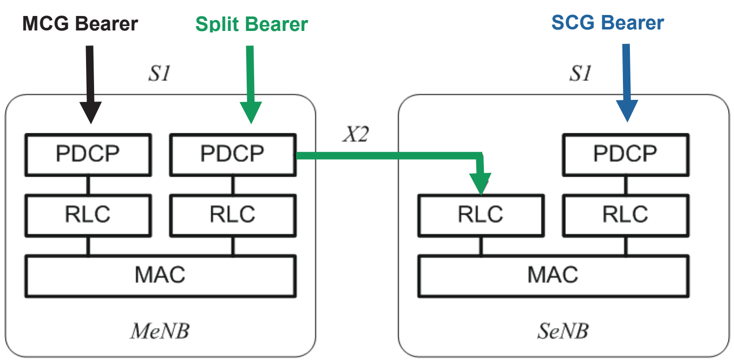


Fig. 2-2: Radio Protocol Architecture for Dual Connectivity

The MeNB essentially maintains the radio resource management (RRM) configuration of the UE and therefore may ask the SeNB to provide additional resources. In the downlink, for the split bearer case the decision whether to route a packet via MeNB or the SeNB is done in the MeNB. This decision depends on various parameters like measurement reports provided by the UE, traffic conditions, cell load, and used bearer types. In the uplink, the UE always only uses one of the two links for PDCP PDU transmission – switching between MeNB and SeNB for uplink data requires layer 3 messaging (sending of *RrcConnectionReconfiguration*). Recalling the scenario in Fig. 2-1, the MeNB becomes – at least to certain extent - the radio resource controller for a limited network area, since it may ask for additional resources from the SeNB. However each eNB owns its radio resources and is primarily responsible for allocating resources. The information exchange / coordination between MeNB and SeNB takes place using RRC container via the X_2 interface. See the specification [5] for detailed procedure descriptions with respect to SeNB addition, SeNB modification and SeNB release.

2.1.2.3 Power control, timing advance and RACH

For DC, two types of power control modes are defined, mode 1 and mode 2. Mode 1 is mandatory and mode 2 may be supported as an option. In both modes, the UE is configured with a minimum guaranteed power for each cell group (CG). In power control mode 1, UE allocates up to the minimum guaranteed power to each CG and any remaining power is shared across MCG and SCG on a per transmission basis according to a priority order based on Uplink Control Information (UCI) type. In power control mode 2, the UE reserves the minimum guaranteed power to each CG and any remaining power is first made available to the CG that starts the earliest in time. For detailed description of these power control modes refer to [8]. Another important difference compared with the CoMP as well as with the carrier aggregation feature used in downlink only is that a DC capable UE has to support two uplink carriers. As mentioned in [5] at least one cell in the SCG has a configured UL and this Primary SCell (PSCell) is configured with PUCCH resources. Therefore PUCCH is transmitted on PCell and PSCell in DC. The random access procedure is also performed on at least the PSCell upon SCG addition/modification, if instructed, or if UL/DL data arrives while the UE is in RRC_CONNECTED state. Accordingly the UE uses the PCell in MSG and the PSCell in SCG as timing references for timing advance. With respect to neighbor cell measurements the same principles as for carrier aggregation apply for intra-frequency and inter-frequency measurements. The configured set of serving cells includes all the cells from MCG and SCG. Note that there is only a single measurement gap configuration for the UE, which is informed by the MeNB.

2.2 Device to Device communication (D2D)

Up to now there are typically two separate systems in place to serve commercial communication requirements and critical communication requirements. Example for commercial communication systems are the technologies standardized by 3GPP, 3GPP2 or IEEE with LTE/LTE-Advanced, CDMA2000®1xRTT and 1xEV-DO or the various 802.11xx standards. For critical communications systems, often summarized as public safety, two different standards are in use dependent on the geographical region. In Europe and parts of Asia it is TETRA and its successor TETRA2 where in North, Latin and South America it is Project 25, short P25 also referred to as APCO-25.

With the worldwide success of LTE as the technology of choice for the majority of network operator to deliver mobile broadband data, high-definition video and advanced voice services to its subscriber base, governmental authorities have started to consider LTE as a candidate for critical communications. In June 2009 the National Public Safety Telecommunications Council (NPTSC), the Association of Public Safety Communication Officials (APCO) and the National Emergency Number Association (NENA) in the US decided to endorse LTE as a the platform for the next-generation public safety network with broadband capabilities. As a result of this effort 10 MHz of paired spectrum was set aside by the FCC for public safety purposes during the 700 MHz auction that took place in February 2008. In 2012 President Obama signed a law in that mandates to transfer this spectrum to an authority called First Responder Network Authority, short FirstNet. FirstNet has also the task to oversee the build out of a single nationwide broadband network for public safety throughout the country to ensure interoperability between states, counties and authorities. The organization is represented within the 3rd Generation Partnership Project (3GPP) by the U.S. Department of Commerce and took a leading role in providing requirements and input to enhance all relevant technical specifications of the LTE standard to support requirements for critical communications. These requirements are as follows:

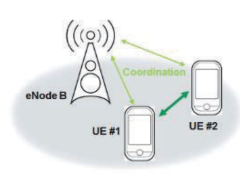
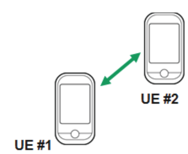
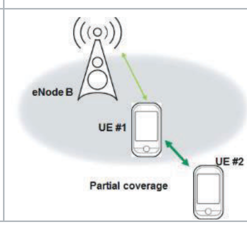
- Reliability and Resilience. Functioning satisfactorily over periods and under adverse circumstances
- Direct Communication between terminals
- Group Communication
- Off network communication
- Mission Critical Push-To-Talk (MCPTT) including group call communication with low call setup time

3GPP has taken on this challenge. A dedicated 3GPP SA working group was created to address mission critical applications, namely 3GPP SA6. In 3GPP RAN the first set of features is added to Release 12 namely LTE Device-to-Device (D2D) Proximity Services and Group Call System Enablers (GCSE) for LTE. Off network communication and MCPTT will follow as part of Release 13. The objective for Proximity Services (ProSe) is to allow devices in close proximity to detect each other and to communicate directly with each other with the goal to reduce the network load, increase capacity in a given bandwidth and allow communication in areas without network coverage. The latter applies only to the public safety use case, where the first two are also interesting for commercial consumer applications. GCSE will be defined to enable an efficient communication between mobile users and dispatchers (one-to-many). The general requirements call for a low latency to add users and obtain channels, a flexible group size and the support of flow control. There is a clear split between application and LTE layers. The application layer will be in control of the group management, floor control decisions and legacy interoperability. LTE will provide mobility and service continuity plus air interface efficiency. Both, application and LTE will impact overall performance and service integration. Proximity Services specifically exclude GSM and UMTS and will only be defined for LTE.

2.2.1 LTE D2D ProSe Scenarios

Before standardizing these two functionalities as part of Release 12 it was important to decide on scenarios, use cases and find a definition for in-coverage and out-of-coverage. In-coverage in this context means, that the device considers itself in-coverage when the ProSe carrier fulfils the S-criteria in SIB Type 1 of that cell. The following agreements were made in 3GPP and are summarized in the following table.

Table 2-8: LTE Device-to-Device (D2D) Proximity Services (ProSe) scenarios

	Within network coverage (Intra-/Inter-cell)	Outside network coverage	Partial network coverage
Non-public safety use case	Discovery	-	-
Public safety use case	Discovery, Communication	Communication	Communication
			

Based on the above it is obvious that ProSe will consist of two main elements. First, network-assisted discovery of users in close proximity to each other and second direct communication between these users with, or without supervision from the network. The latter is only applicable for the public safety use case. With 3GPP Release 12 network-assisted discovery is possible and only for the in-coverage scenario for commercial and public safety applications. Direct Communication is limited to public safety applications. In 3GPP Release 13 the ProSe functionality will be further enhanced.

2.2.2 Overall ProSe Network Architecture

With Release 12 the following functionality is defined:

- EPC-level ProSe Discovery
- EPC support for WLAN direct discovery and communication
- Direct Discovery
- Direct Communication
- UE-to-Network Relay

Fig. 2-3 shows the reference architecture for proximity-based services for the non-roaming case. Both UE's are connected to the same service providers' network, to the same PLMN.

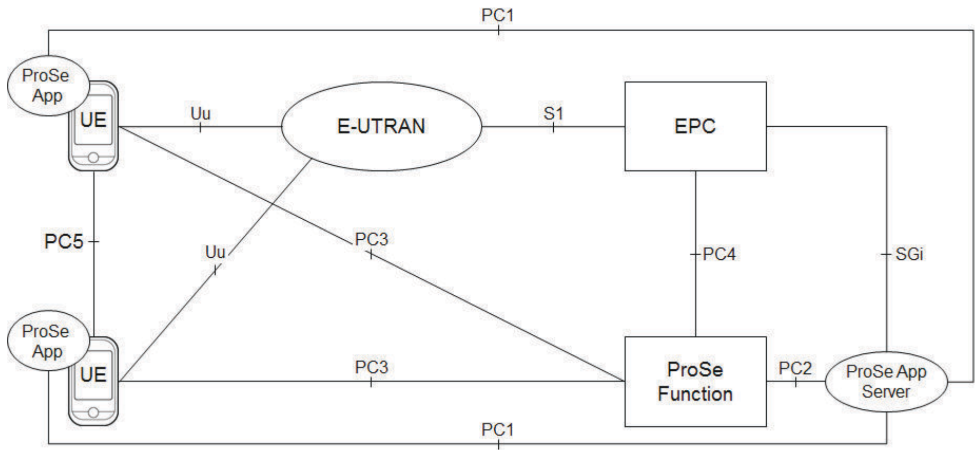


Fig. 2-3: Simplified Reference Architecture for ProSe (Non-Roaming case)

Several new reference points have been introduced to enable the standardization of the listed functionalities. For a detailed definition of all reference points please refer to [24], [26]. Most important reference points are the interface between the two devices, PC5 and between each device and the so called Proximity Service (ProSe) Function, PC3. The ProSe Function is one of the most relevant functional entity shown in Fig. 2-3 and shall be discussed in the following.

ProSe Function. The ProSe Function has a very important role in the entire process of Direct Discovery and Direct Communication. It actually provides three sub-functions: Direct Provisioning Function (DPF), Direct Discovery Name Management Function and EPC-level Discovery Function. As the name implies the DPF provisions the UE with all required parameters for Direct Discovery and Direct Communication for this particular network (PLMN). The task for the Direct Discovery Name Management Function is to allocate and process ProSe Application ID's and ProSe Application Codes that are used for Direct Discovery. This sub-function maintains a table that lists the mapping between the Application Identity (App ID) and Prose Application Code (ProSe App Code). In addition the function generates filter to enable a terminal to know whether an application code is interesting for a given ProSe application running on the device. Both, App ID and ProSe App Code will be explained in more detail in the next sections. An additional task for this sub-function is to contact the Home Subscriber Server (HSS) to check if the device is authorized to do Direct Discovery and if so, authorizes the device by synchronizing a ProSe Policy. Finally, it provides the device with integrity parameters to protect discovery messages that are transmitted over the air.

2.2.3 PHY and MAC layer for ProSe: New logical, transport and physical channels

Before starting to standardize ProSe features like direct discovery and direct communication some fundamental decisions had to be taken by 3GPP. First, it was decided, that for ProSe in general uplink resources are being used. In case of FDD uplink spectrum is utilized by the announcing device and the monitoring device. For

TDD correspondingly uplink subframes are being used. Next was the decision about which multiple access scheme to be used for transmission and reception. Here it was decided to use SC-FDMA, which is the scheme that is used in today's LTE networks for any uplink transmission. It was also decided to reuse the current uplink structure as much as possible. In that context the notation for LTE D2D ProSe was also changed to **"Sidelink"** when referring to D2D/ProSe's PC5 interface. This name change is reflected in the naming of newly introduced transport and physical channels [Fig. 2-4].

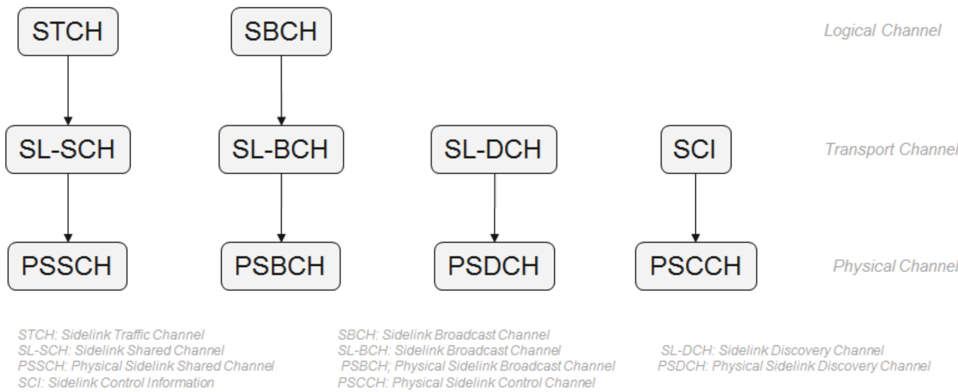


Fig. 2-4: New Transport and Physical Channels for Sidelink

2.2.4 Direct Discovery

The network is informed during the initial attach procedure if the device supports Proximity Services and in particular if Direct Discovery and Direct Communication are supported. This information is encoded in the UE network capability information element that is always part of the Attach Request message [29].

Direct Discovery and Direct Communication are defined as standalone services. Direct Discovery is not necessarily followed by Direct Communication. And Direct Communication does not require Direct Discovery as a pre-requisite.

For security and privacy reasons this feature is divided into open discovery and restricted discovery. In the latter case explicit permission is required from the device that is being discovered [Fig. 2-5].

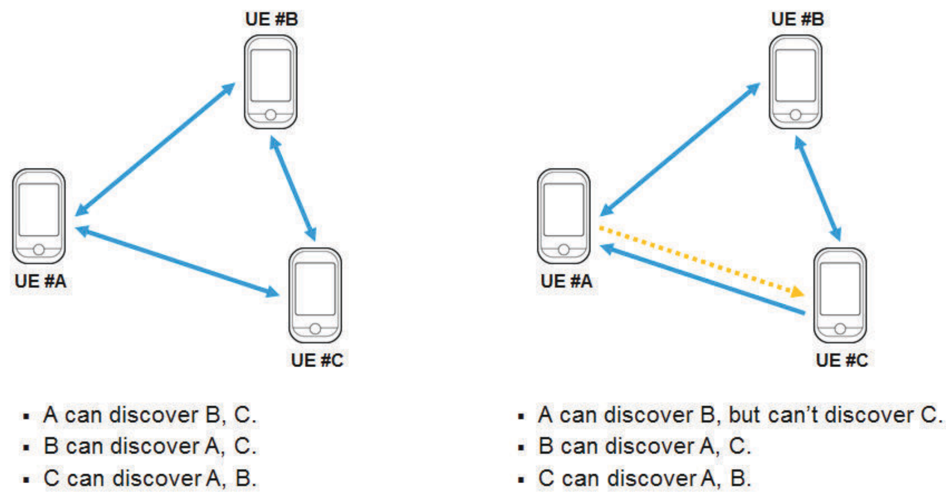


Fig. 2-5: Open and restricted Direct Discovery

As indicated earlier, ProSe Direct Discovery is from a commercial point of view only enabled for the in-coverage scenario and is therefore under full control by the serving network. In other words the network has to authorize a device on a "per UE" basis or a "per UE per application" basis to use Direct Discovery. There are two modes defined how discovery is being used. First, as an announcing terminal ("Here I am!" corresponds to Model A), where a device broadcasts information about itself. In this model a monitoring device is only looking for certain information of interest in its proximity. The announcing device sends out a discovery message that contains a ProSe Application Code. A discovery message is sent at pre-defined and network-controlled occasions. A monitoring device would monitor these occasions, receive the discovery message and process it. The second model can be described with the phrase "Who is out there?" or "Are you out there?" The 'Discoverer UE' sends out a request containing certain information about what it is interested in to discover. The 'Discoveree UE', that receives this message, can respond with some info related to the discoverers request. However, this model has not become part of Release 12 version of the specification. It is currently under discussion if this model is being standardized and supported with Release 13 as part of 'enhanced D2D ProSe'.

2.2.4.1 Service Authorization and Provisioning

For a device that is intended to be used for public safety (= Public Safety ProSe-enabled UE) the required service authorization may be already pre-configured in the device. The authorization may be stored in the device (Mobile Equipment, ME) itself or on the USIM that is part of the UICC card. Non-public safety and thus commercial devices have to be authorized by the network to use Direct Discovery. Therefore the device sends an authorization request to the ProSe function. All details of this procedure are described in [25]. In order to contact the ProSe function the IP address of the function needs to be revealed by the device. There are two possibilities. Option #1 is that the IP address to connect to the ProSe function is stored in the device. In case the IP address is not available on the terminal, the device needs to perform a DNS lookup according to IETF RFC 1035 to resolve the IP address of the ProSe function.

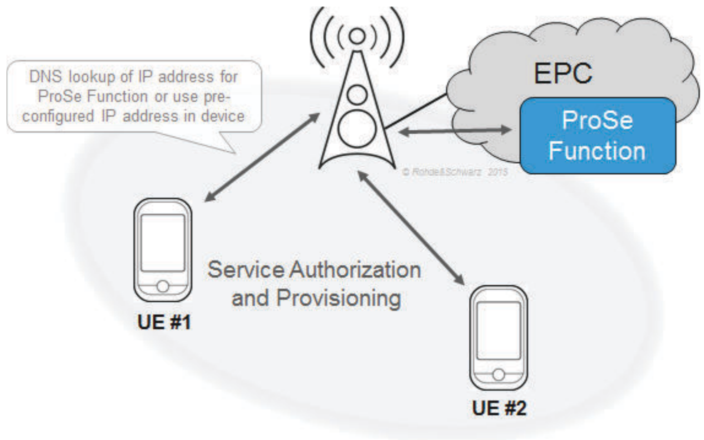


Fig. 2-6: Service Authorization and Provisioning

The UE uses the PLMN ID (= MCC, MNC) of the network that it is attached to, to construct the Fully Qualified Domain Name, short FQDN, for the ProSe function. This could be for example prose.mnc123.mcc456.3gppnetwork.org. With the earlier establishment of a PDN connection the device knows the DNS servers IP address and sends the FQDN to the DNS server to resolve the ProSe functions IP address. With the response of the DNS server, providing this IP address, the UE is capable to communicate and register with the ProSe function of that particular network. Depending on its interest, the device will now be provisioned by this networks ProSe function. The communication between the device and ProSe function via the PC3 interface is based on HTTP that is used as the transport protocol. The ProSe messages are embedded in the body of the HTML request or response message.

A non-public safety device would request a so called **ProSe Direct Service Management Object** (MO) [28] from the ProSe function[1]. Depending on the request the returned MO parameters are combined as either an ‘Announcing Policy’ or ‘Monitoring Policy’. The monitoring policy may include a list of networks (PLMNs) where the device is allowed to perform monitoring on. An ‘Announcing UE’ could only announce a discovery message on its serving cell (serving PLMN). In terms of roaming multiple ‘Announcing Policy’ could be assigned to a device for different PLMNs. Each policy includes a validity timer (T4005[2]), which defines how long each policy – announcing policy and monitoring policy – is valid. The announcing policy contains in particular an information about the ‘authorized announcing range’, defined as short, medium and long. This information has an impact on the actual transmission power with which the device could send its announcement as a discovery message. The maximum allowed transmission power for each of the three range classes is signaled in the network with help of System Information Block (SIB) Type 19 [see section 2.2.7.2]. The MO could further provide information whether the device is authorized to perform announcing and monitoring when it is not served by a network (out of

[1] The time the terminal has to wait to receive a response as well as how many (re-)attempts it undertakes if it doesn’t receive a response is implementation specific. The device shall not consider being authorized until it has received a valid response from the network.

[2] The timers unit is given in minutes. The maximum value is 525600 corresponding to 365 days (1 year). Upon expiration of this timer the device shall consider the authorization to be no longer valid.

coverage) and in this case it provides the relevant radio parameters for announcement and monitoring without being served by the E-UTRAN.

2.2.4.2 Discovery Request and Response for Announcing and Monitoring UE

The next step after authorization and provisioning by the network through the ProSe function is to send a Discovery Request to the network. The ProSe function processes this request. The following procedure depends on the interest of the device, i.e. announcing or monitoring specific information. In addition to the Discovery Request, which could be either sent for announcement or monitoring, there is also the match report, which is discussed in section 2.2.4.5.

An ‘Announcing UE’ (= UE #1 in Fig. 2-7) uses the Discovery Request procedure to obtain a ProSe Application Code that it uses for its announcements via the Discovery Message over the PC5 interface [see Fig. 2-3]. The Discovery Request message includes a (new) Transaction ID, the command is set to *‘Announce’*, the UE’s identity in form of its IMSI, the ProSe Application Identity (ID) and the Application ID, and both are coming from higher layers[3]. In case the device would like to monitor specific information, the Discovery Request message contains the very same information, with the difference that the command is set to *‘Monitor’* [see UE #2 in Fig. 2-7]. The Application ID is a unique identifier for the application that has triggered the transmission of the Discovery Request message. In both cases, announcing and monitor, the ProSe function contacts the Home Subscriber Server (HSS) to verify that the application, represented by the Application Identity, is authorized for Direct Discovery. If positive, the ProSe function checks if the device is authorized to use the ProSe Application Code either for announcement (UE #1) or for monitoring (UE #2). Afterwards, the network sends a Discovery Response message to the device. For the ‘Announcing UE’ the network returns the ProSe Application Code plus a validity timer for this specific code. In case this timer expires, the device needs to request a new code from the network. For the ‘Monitoring UE’, the Discovery Response message contains one (or more) discovery filter and related filter IDs.

After receiving this information UE #1 is configured and ready to announce, where UE #2 is configured and ready to monitor desired information [Fig. 2-7].

[3] Multiple transaction for example for different ProSe Application IDs can be included in just one Discovery Request message.

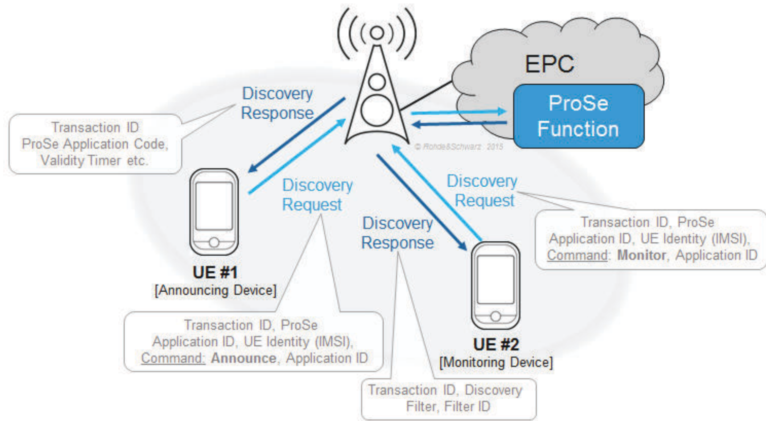


Fig. 2-7: Discovery Request and Response for Announcing and Monitoring UE

2.2.4.3 What is transmitted (announced) or received (monitored) during Direct Discovery?

Once authorized and provisioned, the 'Announcing UE' will transmit the Discovery Message(s) via the PC5 interface. The Discovery Message has the following structure.

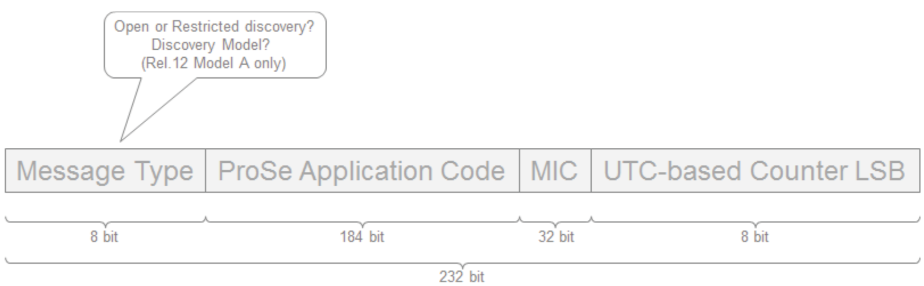


Fig. 2-8: Structure of Discovery Message

As shown in Fig. 2-8 the Discovery Message is comprised of the ProSe Application Code combined with some supporting information. The 'Announcing UE' has received via the Discovery Response message the ProSe Application Code from the network. The terminal computes and adds a Message Integrity Check (MIC) to this code [30]. This 32-bit check sum based on the Coordinated Universal Time (UTC), derived for example by acquiring SIB Type 16, which is provided by the network.

A 'Monitoring UE' will filter for Discovery Messages transmitted on defined resources on the physical layer that satisfies its Discovery Filter which was assigned via the Discovery Response message.

ProSe Application Code

The ProSe Application Code [Fig. 2-9] is composed of two parts, first the PLMN ID, second a Temporary Identity for the ProSe Application ID Name [26].

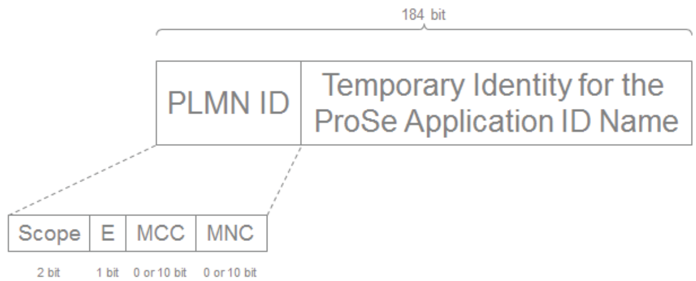


Fig. 2-9: ProSe Application Code

The PLMN ID is in this particular case not just defined through the Mobile Country Code (MCC) and Mobile Network Code (MNC). Some more specific information is added. The first two bits are defining the scope of this PLMN ID, whether it has a global scope, is country-specific or PLMN-specific. The next bit determines if the MCC, MNC of the ProSe function that has assigned this particular code is included in the overall code or not. Last the respective MCC and MNC, which are represented by the binary representation of their decimal values. The internal structure for the temporary identity of the ProSe Application ID Name is not within the scope of the 3GPP specification and may be specified by the service provider and is therefore network operator specific.

ProSe Application Identity

The ProSe Application Code is provided by the network based on its mapping to the ProSe Application Identity (ID). How is the ProSe Application Code linked to the ProSe Application Identity (ID)? In case the device is authorized to announce the ProSe Application ID sent with the Discovery Request message, the network shall allocate the corresponding ProSe Application Code via a Discovery Response message including a validity timer. Also the ProSe Application ID consists of two parts: the PLMN ID and ProSe Application ID Name. In contrast to the way in which the PLMN ID is used for the ProSe Application Code, here the PLMN ID is purely comprised of the MCC and MNC. The PLMN ID is followed by the ProSe Application ID Name, which consists of up to n so called Labels. The very first label is always named ‘ProSe App’. Labels are separated by dots. The hierarchical structure of the content is not part of the 3GPP specification and could be defined by the network operator. Relevant examples for the ProSe Application ID can be found in [26].

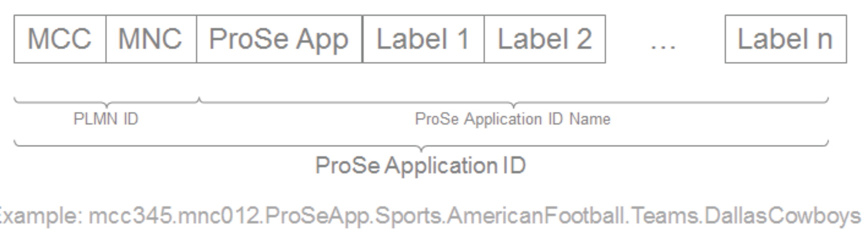


Fig. 2-10: ProSe Application ID

2.2.4.4 Announcing and monitoring of Discovery Message(s)

The Discovery Message is the information an announcing device transmits in the Discovery Resources, where a monitoring terminal would screen these resources to filter for information of interest. The Discovery Resources are either configured by the network or could pre-configured in the device.

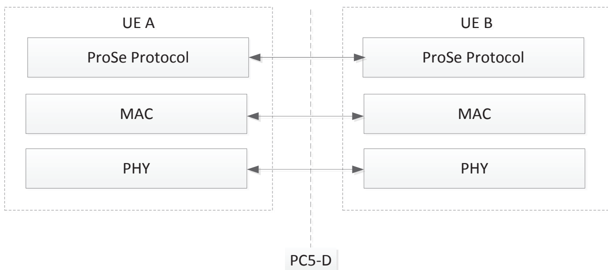


Fig. 2-11: PC-5 Interface for Direct Discovery [24]

As shown in Fig. 2-11 discovery messages are transparent to RLC / PDCP / RRC. This means there is no RRC layer involved no dedicated signaling procedure between two devices using direct discovery, nor direct communication. The MAC layer receives the discovery message directly from higher layers and uses the Sidelink Discovery Channel (SL-DCH) to map the discovery message to the Physical Sidelink Discovery Channel (PSDCH, compare Fig. 2-4). There are different ways how the ‘Announcing UE’ determines the radio resources to be used for transmitting the discovery message. First, the connection state with the network is important. It depends if the device is RRC_IDLE or RRC_CONNECTED since discovery is supported in both RRC states. For RRC_IDLE there are two options. A base station (eNB) that is part of a network that supports Direct Discovery broadcasts System Information Block Type 19 [see section **2.2.7.2**]. If the device is in idle mode it could use the provided resource pool in SIB Type 19 to announce the discovery message. However, with SIB Type 19 the base station and thus the network may only intend to indicate the support of direct discovery. Instead of the device autonomously selecting the radio resources from a resource pool to transmit the discovery message, the network would require the device to receive this via a dedicated resource allocation. In that case, the terminal has to transfer from idle mode into connected state in order to request the allocation of radio resource. The prerequisite is that the UE performs the NAS service request procedure as described in [29]. A device that is already in RRC_CONNECTED state may be configured by the eNB via dedicated RRC signaling for autonomous resource selection after authorization has been verified by the eNB. Alternatively, the eNB may provide a dedicated resource allocation to the terminal. A resource allocation is valid until the eNB reconfigures this allocation or the device moves into RRC_IDLE state. The service request is always accompanied by a *Prose UE Information Indication* sent by the UE. With this message, the device will request the assignment of dedicated resources as specified in [12]. Ultimately, the network will answer the request by sending an *RRCConnectionReconfiguration* message to the device, which includes the resource allocation to transmit the discovery message. Fig. 2-12 shows the message flow for Direct Discovery in case there is no valid transmission resource pool coming with SIB Type 19, which triggers the device to move to RRC_CONNECTED state in order to acquire radio resources for transmitting the discovery message.

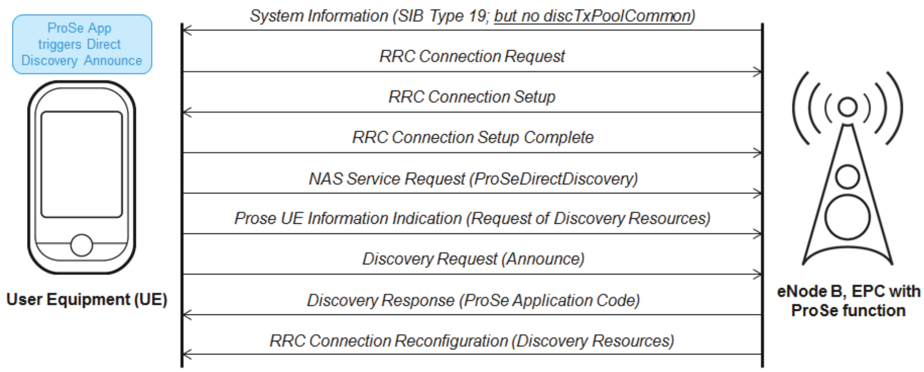


Fig. 2-12: Direct Discovery (Announce) message flow

The radio resource allocation distinguishes between two different types of discovery. In Type 1, resources are allocated on a non-UE specific basis. In Type 2, resources are allocated on a UE-specific basis. For the latter, two sub-modes A and B were identified during the standardization phase. However, only Type 2B became relevant. Type 2B defines a semi-persistent allocation of radio resources for discovery message transmission. The two discovery types 1 and 2B have an impact how the resources for the Physical Sidelink Discovery Channel (PSDCH) are identified and used [8].

2.2.4.5 Match Report

In case the ‘Monitoring Device’ receives a ProSe Application Code that matches the assigned discovery filter, but has no corresponding ProSe Application ID, the device is required to forward a match report including (new) Transaction ID, ProSe Application Code, UE identity, PLMN ID, UTC-based counter information, corresponding MIC to the ProSe function. In this Match Report the device shall indicate if it wishes to receive meta data about the related ProSe Application ID. The ProSe Function uses the provided information for validation and verification and in case this operation is successful it sends an acknowledgement to the device.

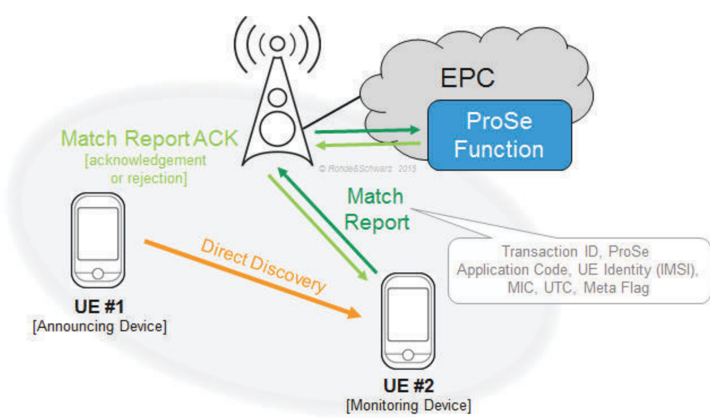


Fig. 2-13: Direct Discovery and Match Report

2.2.5 ProSe Direct Communication

Direct Communication between two devices in close proximity is defined for in-coverage scenario as well as for out of coverage and partial coverage scenario. However, only devices authorized for public safety can perform this type of communication. This assumes the public safety device camps on a carrier that allows and supports direct communication. In case not, cell reselection needs to be performed by the device, or, if in RRC_CONNECTED state a handover to the so called ProSe carrier needs to be initiated by the network. In the out of coverage case, the UE uses predetermined values (stored in the device or on the USIM).For the partial coverage case either predetermined values are applied or the latest values received from a network for a UE that was in coverage briefly before it lost the coverage.

Provisioning is also a pre-requisite for communication. All devices that want to participate in direct (group) communication need to be provisioned. Provisioning can be done by the network (in-coverage case) or a device could be pre-provisioned (e.g. for out-of-coverage case), meaning the related information is stored in either the device (Mobile Equipment, ME) or on the UICC card. The following parameters are included when provisioning a device:

- PLMN(s) the device is allowed to perform direct communication in when “served by E-UTRAN” (= in coverage).
- Information if UE is authorized to perform Direct Communication if the device is “not served by E-UTRAN” (= out-of-coverage).
- ProSe Layer-2 Group ID,
- ProSe Group IP multicast address,
- Indication if the device shall use IPv4 or IPv6 for that group,
- Security parameter for group communication,
- Radio parameters when UE is “not served by E-UTRAN”.

The radio resources for Direct Communication can be selected by the device autonomously or will be scheduled by the network. In case the device has acquired System Information Block (SIB) Type 18 and has further a passive connection with the network (RRC_IDLE) the device would select radio resource from the broadcasted resource pool in SIB Type 18 [see section 2.2.7.1]. Similar to Direct Discovery a UE would have to move into RRC_CONNECTED state in case no valid (transmit) resource are provided by SIB Type 18. In that case, also a *Prose UE Information Indication* is sent by the terminal to the network [compare Fig. 2-12], indicating the wish to use the Direct Communication feature. In response, the network will assign a Sidelink Radio Temporary Network Identifier (SL-RNTI) to the device. Now the network uses this SL-RNTI and the downlink control channel ((E)-PDCCH) to assign a transmission grant to the device with the new defined Downlink Control Information (DCI) Format 5. Table 2-9 shows the content of DCI Format 5.

Table 2-9: DCI Format 5 content

DCI Format 5	
Resource for PSCCH	6 bit
TPC command for PSCCH and PSSCH	1 bit
Frequency hopping flag	1 bit
Resource Block Assignment and hopping allocation	5-13 bit
Time Resource Pattern	7 bit

The device will use the provided information to determine when to transmit the Sidelink Control Information (SCI) Format 0 on the Physical Sidelink Control Channel (PSCCH). SCI Format 0 content is shown in Table 2-10. As it can be seen, some content of DCI Format 0 and SCI Format 0 overlap.

Table 2-10: SCI Format 0

SCI Format 0	
Modulation and Coding Scheme (MCS)	5 bit
Time Resource Pattern (T-RPT)	7 bit
Timing Advance Indication	11 bit
Group Destination ID	8 bit
Resource Block Assignment and Hopping Flag	5-13 bit
Frequency hopping flag	1 bit

The parameters provided by the SCI Format 0, in the early phase of standardization referred to as Scheduling Assignment (SA), will be used by the receiving device to determine when the transmitting device is sending its data on the Physical Sidelink Shared Channel (PSSCH) [Fig. 2-14].

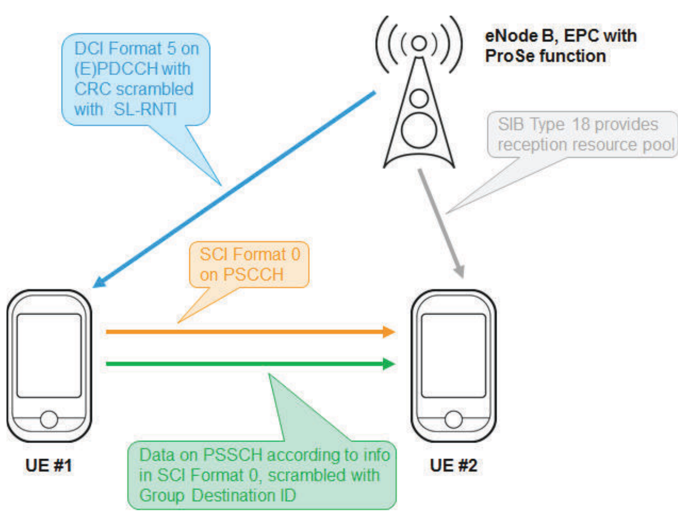


Fig. 2-14: Scheduling Transmission Resources for Direct Communication, Mode 1

The PSCCH, carrying the SCI Format 0 is transmitted in two subframes out of the configured resource pool occupying only one resource block pair. The exact procedure how to determine subframe and resource block is defined in [8]. The Time Resource Pattern (TRP, 7 bit) plays an important role. It determines which subframes are used for transmission of PSSCH. A subframe indicator bitmap of variable length is defined, where the length of this bitmap depends on the duplex mode, FDD or TDD, and in case of TDD which UL-DL configuration is used. In case of FDD the bitmap is 8 bits long. Up to 128 different TRP define now how these 8 bits are used. The resource block (RB) allocation for PSSCH follows the same principles as defined for LTE Rel-8 while interpreting the ‘RB assignment and hopping allocation’ provided by SCI Format 0. The information is transmitted four times.

For Mode 2, the device would autonomously select resources from the transmission pool provided in SIB Type 18.

If a device is out-of-coverage, the device can only autonomously select resources from a pre-configured resource pool.

2.2.6 Synchronization aspects

Synchronization to align transmitter and receiver timing is always crucial for interference free communication throughout the network. Typically, the network assists with a certain set of signals to acquire synchronization in time and frequency. For LTE as specified in 3GPP Release 8 (Rel-8) two synchronization signals were defined: Primary and Secondary Synchronization Signal (PSS/SSS). Both signals occupy certain subcarriers in the frequency domain and OFDM symbols in the time domain. They both have a repetition period of 5 ms, meaning they are transmitted twice per 10 ms LTE radio frame (see [1]). A more detailed introduction to synchronization signals and related principles for cell search and selection for LTE is given in [24].

However, for LTE D2D ProSe it will depend on the scenario and coverage situation how synchronization between two devices is achieved. In general there is a hierarchical principle. First of all, the device needs to determine if it is ‘in-coverage’. A device is considered to be ‘in-coverage’ based on signal quality measurement using the Reference Signal Received Power (RSRP) measurement performed on the downlink signal. In case the measured RSRP values are above a specific threshold, then the device considers itself in coverage and uses LTE Rel-8 downlink signals (PSS, SSS) for synchronization. This threshold is defined as part of broadcasted system information. Both System Information Blocks (SIB; see next section) carry the relevant information. First, they include an information element that dictates (set to ‘true’) if the device shall become a synchronization source or not. If that element is set to ‘false’, the device acts according to the described RSRP threshold coming with the SIBs. If the received signal quality measurement falls under this threshold the device would start transmission of Sidelink Synchronization Signals (SLSS) and the Physical Sidelink Broadcast Channel (PSBCH). These signals have a periodicity of 40 ms. Assuming the device cannot detect an eNB, meaning it is out of coverage, the device starts looking for SLSS from other devices and perform signal quality measurements (S-RSRP) on those synchronization signals [9]. If the measured value is below a pre-configured threshold value, that is stored in the device, the terminal would start transmitting SLSS and PSBCH according to [6] and [12].

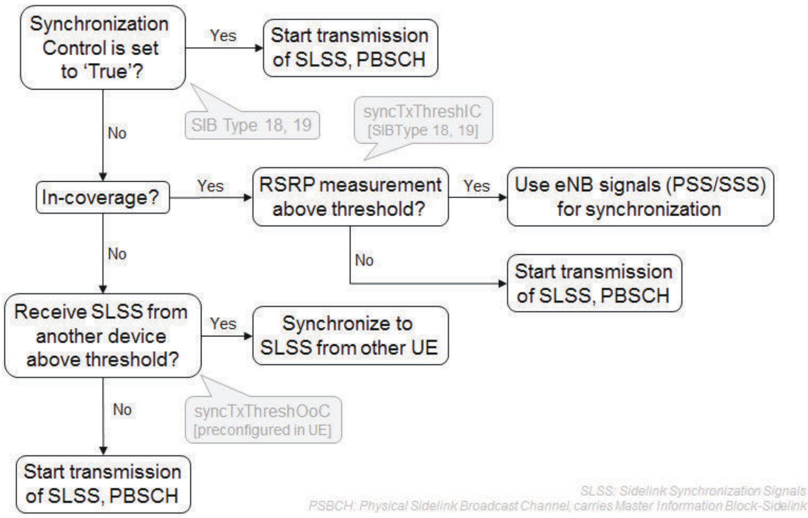


Fig. 2-15: Synchronization Aspects (UE perspective)

Sidelink Synchronization Signals are comprised of two individual signals: the Primary Sidelink Synchronization Signal (PSSS) and the Secondary Sidelink Synchronization Signal (SSSS). PSSS and SSSS are both transmitted in adjacent time slots in the same subframe. The combination of both signals defines a “Sidelink ID” (SID), similar to the “Physical Cell ID” in the Downlink. SID’s are split into two sets. SID’s in the range of {0, 1, ...,167) are reserved for ‘in-coverage’, where {168, 169, …,335} are used when the device is ‘out-of-coverage’. The subframes to be used as radio resources to transmit SLSS and PBSCH are configured by higher layers and no PSDCH, PSCCH, or PSSCH transmissions are allowed in these subframes. The resource mapping is slightly different for normal and extended cyclic prefix where Fig. 2-16 shows the mapping for normal cyclic prefix. In the frequency domain the six inner resource blocks are reserved for SLSS and PSBCH transmission.

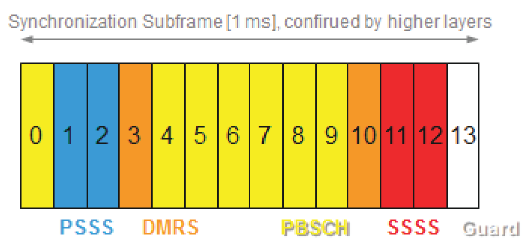


Fig. 2-16: Mapping of Sidelink Synchronization Signals (SLSS) and PSBCH [normal Cyclic Prefix]

2.2.7 New System Information Block Types for LTE D2D ProSe

With Release 12 two new System Information Block (SIB) Types are introduced. SIB Type 18 contains relevant information for ProSe Direct Communication whereas SIB Type 19 provides information for ProSe Direct Discovery.

2.2.7.1 System Information Block (SIB) Type 18

SIB Type 18 provides the resource information for synchronization signal and SBCCH transmission. The possible content provided by SIB Type 18 is shown in Fig. 2-17.

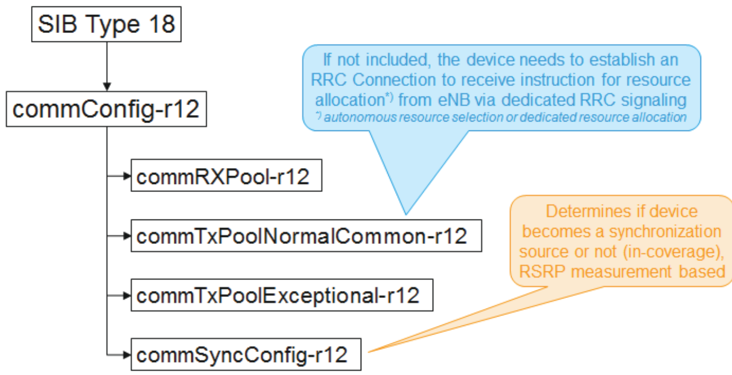


Fig. 2-17: System Information Block (SIB) Type 18

SIB Type 18 provides information for both, the transmission of Sidelink control information and data (PSCCH, PSSCH). First a so called Sidelink Control, short SC, period is defined, that could last up to 320 ms. A UE performs Direct Communication in subframes associated to the Sidelink Control period.

Identical to the information provided with SIB Type 19 also resources in time and frequency are provided that shall be used for communication transmission; see next section for more details.

2.2.7.2 System Information Block (SIB) Type 19

SIB Type 19 provides the information about the radio resource pool where a device is allowed to announce (transmit) or monitor (receive) discovery messages. The resource pool is defined by a discovery period that could be up to 1024 radio frames or 10.24 seconds long. It also defines a bitmap that indicates which subframes could be used for discovery and how often this bitmap is repeated within the discovery period. The number of repetitions depends on the duplex mode, FDD or TDD, and in case of TDD on the used UL-DL configuration. The specification foresees seven different bitmaps[4], where a bit set to ‘0’ indicates not to be used for discovery and ‘1’ means useable for discovery.

[4] 4, 8, 12, 16, 30, 40 or 42 bit long

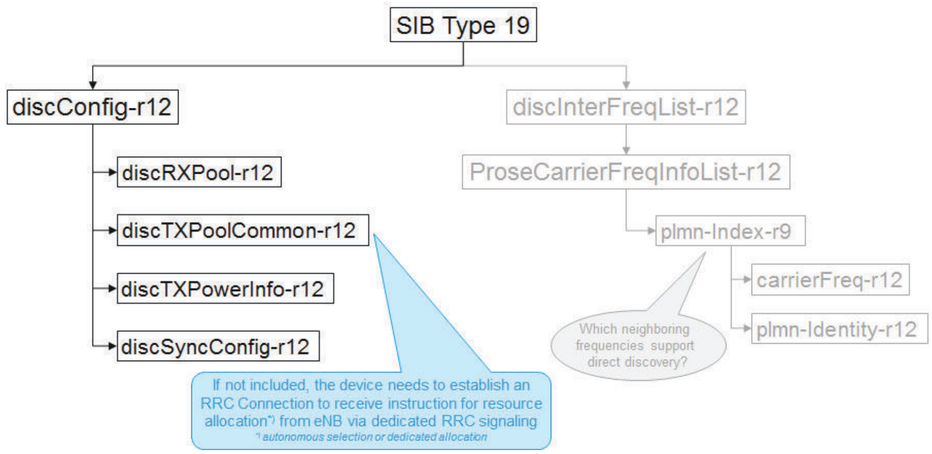


Fig. 2-18: System Information Block (SIB) Type 19 – content

Additionally a resource configuration for the frequency domain is provided. The explicit number of resource blocks is broadcasted, including a start and end number. That allows the network to organize the uplink bandwidth in clusters. Those clusters could be used for direct discovery. Fig. 2-19 illustrates this option in an example.

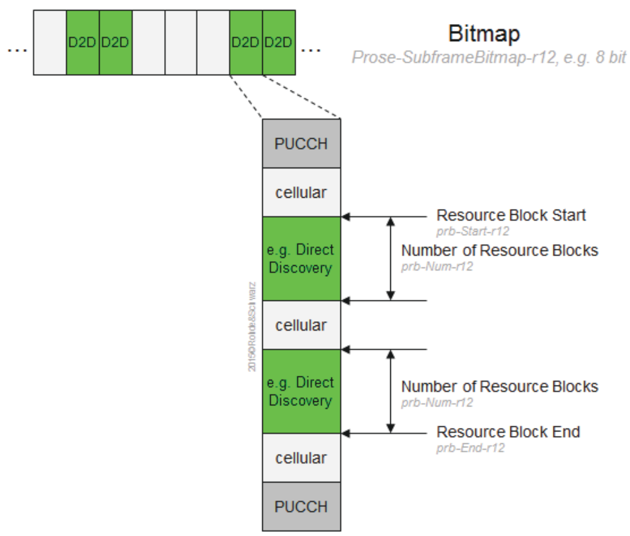


Fig. 2-19: Resource Block Allocation for LTE D2D ProSe (Example: Direct Discovery)

The discovery message size is 232 bits which is equal to the Transport Block Size (TBS). The modulation scheme is QPSK and the message is mapped to 2 contiguous RB per time slot [6], [8]. The message might be repeated several times with the number or repetitions being configurable between 0, 1, 2 and 3.

Assuming the device is in idle mode and SIB Type 19 does not include the *discTxPoolCommon* information element [Fig. 2-18], the device is required to establish a connection to the network. With the help of an *RRCConnectionReconfiguration* message, the network will provide all relevant parameters to the announcing terminal to transmit its discovery message.

2.3 WLAN/3GPP Radio Interworking

Most of today's mobile phones have the WLAN technology integrated. So, it is a natural next step to integrate WLAN into the data transfer in order to use additional spectrum from the ISM bands.

WLAN integration to LTE was defined from Release 8 on. Access to the Evolved Packet Core (EPC) was defined via the non-3GPP access, either directly to the PDN-GW as a trusted access, or via the ePDG as a non-trusted access, see [21] for details.

When a UE is connected with LTE and discovers WLAN access points (APs), there are two decisions:

1. Which of the detected APs shall be used: A necessary requirement for this decision is the knowledge, which of these APs is connected to the operator's EPC and are therefore capable for the offload. But also the operator's preference is an essential point, when the UE detects several APs belonging to different WLAN networks.
2. Which traffic shall be offloaded: Of course, the QoS capability of WLAN must be taken into account here.

2.3.1 Core Network Solution

Up to Release 11, these decisions were completely based on the core network level using user preference and the Access Network Discovery and Selection Function (ANDSF) rules. The ANDSF server is an entity in the EPC and communicates with the UE over the (logical) S14 interface, which is realized above the IP level:

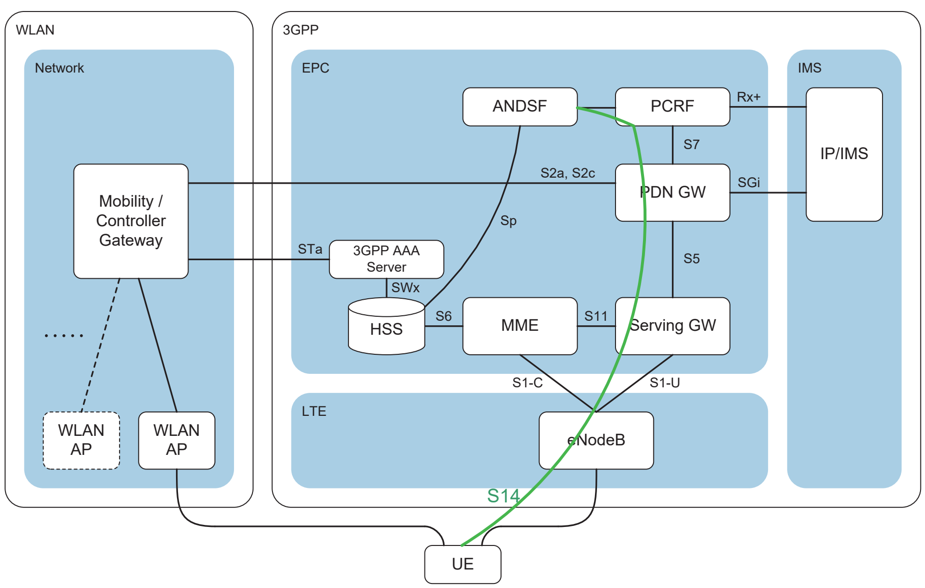


Fig. 2-20: EPC with the WLAN offload, realized as trusted access in this example. The ANDSF is connected to the UE via the PCRF and the PDN-GW in the user plane

The ANDSF information is communicated to the UE using the OMA device management.

This way, the UE is configured with parameters required by a particular network operator. With increasing offload requirements, the ANDSF was extended in the following releases. In Release 12, a new work item for “WLAN Network Selection for 3GPP Terminals” was started by SA2 and CT1. Its output is a list of preferred WLAN APs fulfilling defined selection criteria.

2.3.2 RAN Solution

Due to its architecture, the offload steering using ANDSF is working on a slow time scale. In addition, it is not supported by every UE and not every network operator wants to implement it. Therefore, 3GPP decided to complement the ANDSF rules by RAN assistance information, and to define their own rules (RAN rules) for the case that either the network has no ANDSF rolled out or that the UE does not support it.

In order to have a predictable behavior for the UEs, the following hierarchical decision sequence is applied:

1. User preference, e.g. it is always possible for a user to switch off the WLAN functionality in the UE.
2. ANDSF rules, when both, the network and the UE support it. These rules are extended with RAN assistance in this work item.
3. RAN rules, which are used when neither item 1 nor item 2 is applied.

This sequence is used for both, the access network selection and the traffic steering. It is based on RAN assistance parameters obtained from the eNB and measurement results from the UE’s lower layers.

A subset of RAN assistance parameters and subsequent measurement results are sent to upper layers for a potential use with ANDSF policies. In addition, the RAN assistance parameters are stored in the layer-2 protocol stack for RAN defined network selection and traffic steering rules, which are described in section 2.3.2.2.

When these RAN rules are fulfilled, the UE indicates this to the upper layers, including the information of the WLAN identifiers in case of LTE to WLAN traffic steering. This way, the LTE protocol stack does not need the information about possible ANDSF usage. Consequently, the upper layers finally decide on network selection and traffic steering, as it is already done in the legacy way. Note that if several WLANs fulfill the RAN rules, it is up to UE implementation which of those are selected.

2.3.2.1 RAN Assistance Parameters

RAN assistance parameters consist of two parts:

- The offload configuration
- A list of WLAN identifiers

The offload configuration includes the parameters for traffic steering and network selection. It contains the $T_{steeringWLAN}$ timer, which indicates how long the rules shall be fulfilled before a change is triggered, and an offload preference indicator (OPI), which is used only in ANDSF. Thresholds for the following values are included:

- Reference Signal Received Power RSRP ($Thresh_{ServingOffloadWLAN, P}$)

- Reference Signal Received Quality RSRQ ($Thresh_{ServingOffloadWLAN, Q}$)
- WLAN channel utilization ($Thresh_{ChUtilWLAN}$).
- Available backhaul bandwidth for DL ($Thresh_{BackhRateDLWLAN}$).
- Available backhaul bandwidth for UL ($Thresh_{BackhRateULWLAN}$).
- Signal strength (RSSI) threshold for WLAN ($Thresh_{BeaconRSSIWLAN}$).

Each of these thresholds is provided with two values, low and high, in order to create a pertinent hysteresis.

The list of WLAN identifiers contains a list of WLAN IDs, which is either the Service Set Identifier (SSID), the Basic Service Set Identifier (BSSID), or the Homogeneous Extended Service Set Identifier (HESSID).

The RAN assistance parameters may be provided via broadcast and via dedicated signaling. For broadcast, a new SIB (SIB17) is defined. In this SIB, the offload configuration and WLAN ID list for up to 6 PLMNs is contained. In dedicated signaling the *RRCConnectionReconfiguration* message is used, in which only the offload configuration for the actual PLMN is contained. The list of WLAN identifiers is always taken from SIB17.

Parameters obtained in dedicated signaling overwrite the SIB information. They are used in the RRC_CONNECTED state and for some time after the transition to the RRC_IDLE state. The duration of this time is controlled by a timer, T350, which has a range between 5 and 180 minutes. When T350 expires, or when the UE selects a new cell, the dedicated configuration is deleted and the configuration provided by SIB17 is used. On each of those parameter changes, the current parameters are provided to the upper layers.

When the UE is in the RRC_IDLE state, these parameters are only valid when the UE is camped on a suitable cell.

2.3.2.2 RAN Access Network Selection and Traffic Steering Rules

The RAN rules are based on the following metrics:

- RSRPmeas: Qrxlevmeas in RRC_IDLE and RSRP in RRC_CONNECTED [12]
- RSRQmeas: Qqualmeas in RRC_IDLE and RSRQ in RRC_CONNECTED [12]
- ChannelUtilizationWLAN: WLAN channel utilization [22]
- BackhaulRateDlWLAN: WLAN DL bandwidth [23]
- BackhaulRateUlWLAN: WLAN UL bandwidth [23]
- BeaconRSSI: WLAN Beacon RSSI [9]

These metrics are compared with the thresholds given in section 2.3.2.1. An indication is provided to the upper layers, if they are fulfilled for the time $T_{steeringWLAN}$. In case of carrier aggregation, the E-UTRAN conditions are only evaluated in the PCell.

In traffic steering from LTE to WLAN, only those APs are considered which are included in the list of WLAN identifiers in the RAN assistance parameters, and for which all metrics are available. The conditions are:

- In the LTE serving cell, one of the two conditions:
  - RSRPmeas < $Thresh_{ServingOffloadWLAN, LowP}$
  - RSRQmeas < $Thresh_{ServingOffloadWLAN, LowQ}$
- In the target WLAN, all of the following conditions:
  - ChannelUtilizationWLAN < $Thresh_{ChUtilWLAN, Low}$
  - BackhaulRateDlWLAN > $Thresh_{BackhRateDLWLAN, High}$
  - BackhaulRateUlWLAN > $Thresh_{BackhRateULWLAN, High}$
  - BeaconRSSI > $Thresh_{BeaconRSSIWLAN, High}$

For traffic steering from WLAN to LTE, the following two conditions must be fulfilled:

- In the source WLAN, one of the following conditions must be fulfilled:
  - ChannelUtilizationWLAN > $Thresh_{ChUtilWLAN, High}$
  - BackhaulRateDlWLAN < $Thresh_{BackhRateDLWLAN, Low}$
  - BackhaulRateUlWLAN < $Thresh_{BackhRateULWLAN, Low}$
  - BeaconRSSI < $Thresh_{BeaconRSSIWLAN,Low}$
- In the target LTE cell, both following conditions must be fulfilled:
  - RSRPmeas > $Thresh_{ServingOffloadWLAN, HighP}$
  - Qqualmeas > $Thresh_{ServingOffloadWLAN, HighQ}$

2.4 HetNet mobility enhancements

One way to enhance the capacity of a cellular network is the introduction of heterogeneous networks (HetNets). Additional pico cells are placed in the coverage region of a macro cell (Fig. 2-21).

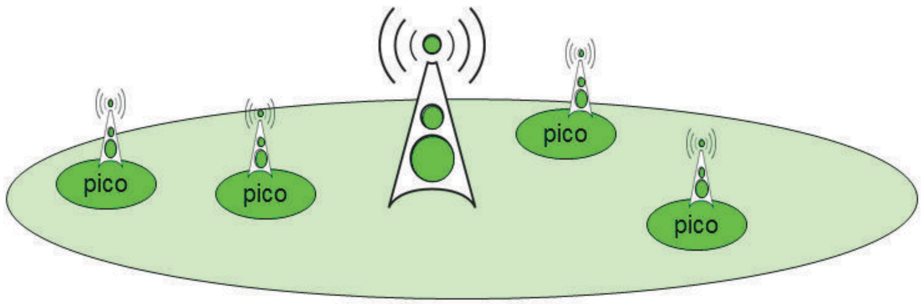


Fig. 2-21: Heterogeneous Network -- PCs are placed in the coverage region of a macro cell

The pico cells are usually on a higher frequency and transmit with less power than the macro cells, so they have only a small range. Consequently, the full cell capacity is available to a comparable small amount of UEs. In addition, several pico cells may be placed in the range of one macro cell without overlapping coverage, so the interference does not play a significant role.

However, this cell densification also creates additional problems. The one which is solved with this technology component is the handover (HO) performance. In HetNets, most HO failures occur in the HO from the pico to the macro cell. This is due to the fact that the pico UEs leave quite fast the coverage range of their cells and the HO command from the eNB is not received anymore.

Three features have been specified in order to improve the HO behavior for HetNets. The first two of those features helps to reduce the HO failures, where one is network based with UE assistance and the other is UE based. However, despite these improvements, HO failures with following radio link failures (RLF) may occur anyway, so the third solution improves the recovery from remaining RLFs.

2.4.1 Improve overall HO performance based on mobility information

The knowledge of the UE's mobility may help the eNB with the pertinent HO decision, especially for small cells. For example, when a UE is fast moving, it is often better not to handover to a pico cell, because the UE would leave the pico cell shortly after the HO completion. Then the UE is mainly doing HO signaling and not data transmission or reception, causing unnecessary HOs with potential HO failures. Mobility information from the UE to the eNB is provided on the RRC_IDLE to the RRC_CONNECTED transition. There are two ways for the UE to indicate its mobility state:

- UE itself estimates its mobility state with a granularity of *normal*, *medium*, and *high*.
- UE stores and delivers a history of previously visited cells.

The mobility history reporting encompasses the last 16 visited cells, no matter in which RRC state these cells have been visited. For each cell in this list, the global cell ID and the time of stay are stored. The eNB can use this information to estimate the UE mobility on its own, this way complementing the UE mobility estimation. In the *RRCConnectionSetupComplete* message, the UE sends its own mobility state estimation and indicates the availability of the mobility history information. The eNB can then retrieve it using the *UEInformationRequest* / *UEInformationResponse* procedure. This way the comparatively large history report is only transmitted when the eNB really needs it.

2.4.2 UE based solutions for mobility robustness

In this approach, mobility robustness improvement is obtained by having a target cell-specific time to trigger (TTT). The network can modify the mobility event by using a higher TTT value for measurements of pico cells. Such higher values for pico cells slow down the trigger of measurement reporting. Consequently, the probability of a fast moving UE to trigger a measurement report for HO to a pico cell is lower, again preventing the fast moving UEs from unnecessary pico cell connections. For each EUTRA measurement object a list of PCI ranges can be provided. In addition, an alternative TTT can be provided in the report configuration. If both are provided, the UE shall use the alternative TTT for those cells given in the measurement object.

2.4.3 Improvements to recovery from RLF

This feature provides a possible early termination of the T310 timer. The RLF and corresponding procedures are then triggered earlier as well. This way, service interruption time may be decreased, because the UE may start earlier with the connection re-establishment instead of remaining in a cell with bad signal quality. On the other hand, generally shortening the T310 creates additional RLFs, because a handover procedure, if initialized, might be terminated too early. The reason is that even if the T310 is started, the UE might still receive the handover command which may come after a shortened T310 expiry. So the idea is that the T310 is shortened only for UEs in a HO procedure and in a way that the HO command would still be received.

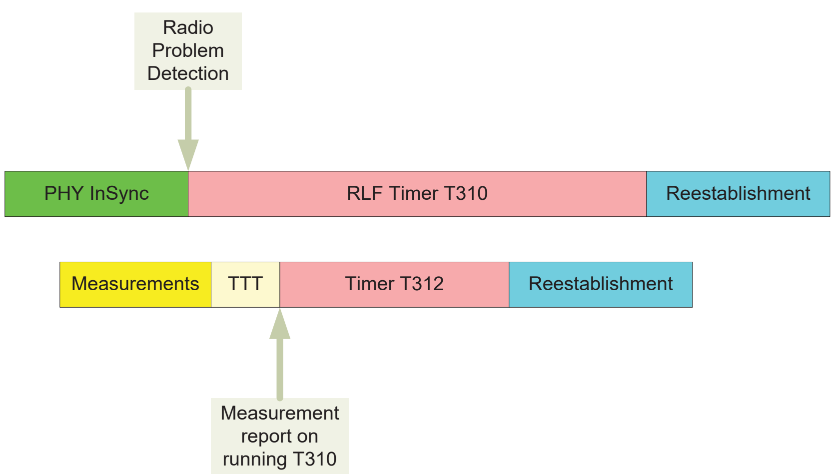


Fig. 2-22: Early T310 termination. The new timer T312 is only started, when the measurement report is triggered while T310 is running

To do this, a new timer T312 is introduced (Fig. 2-22). Usage of this timer is separately configured for each measurement ID, so that it can be restricted to only a subset of HOs, like the pico to macro HO.

If there are physical layer problems, a timer T310 is started. When a measurement report is triggered while T310 is running, T312, if configured, is started as well. With the expiry of the T312 timer, an RLF and the corresponding re-establishment is triggered, which may be earlier than the T310 expiry. Note that this timer never causes an additional delay, because the re-establishment is also started in the legacy way after T310 expiry, if T312 is still running.

2.5 Smart Congestion Mitigation (SCM)

In scenarios like big sports events, many UEs want to access the network simultaneously. Consequently, operators have to apply congestion control like access class barring (ACB), because the available resources are finite and may not be sufficient for all UEs and all services.

Up to Rel-11, there are no exceptions for excluding single services from ACB. However, mobile originated services like voice or SMS are often regarded as more important for optimal user experience, compared e.g. to data transmission. So, the idea is to allow the UE to skip ACB for the following UE originated services:

- MMTEL voice
- MMTEL video
- SMS

Therefore, the barring is still active, if required, but mainly restricted to data services.

In order to control the desired behavior, the eNB may signal a flag for each of these three features in SIB2. For example, if ACB is active and the *ac-BarringSkipForMMTELVoice* flag is set, and none of the other ones, the UE does not consider this cell as barred if it wants to start a voice call, and can so start an RRC Connection Establishment. It considers this cell as barred, if it wants to start any other service.

Although SCM is specified in Rel-12, an implementation on a previous release is possible, since there are no inter-operability problems with any other features.

2.6 RAN enhancements for Machine-Type and other mobile data applications

One of the characteristics of machine type communication (MTC) is the broad spectrum of capabilities the devices have to support. For example a surveillance camera has to deliver a huge amount of UL data while being almost stationary, whereas devices for fleet tracking have a small amount of data while performing a lot of handovers. Another class of devices has neither of these capabilities. They are (almost) stationary and require only a small amount of data which is even not delay sensitive. Examples of these devices are those for meter reading like electricity, gas, or water consumption. However, the number of these MTC devices may become quite big, even up to several orders of magnitude compared to the traditional devices. Using existing LTE technology may then lead to a network overload, because despite of their small amount of user data, the amount of signaling is about the same.

Especially for those devices, several work items have been treated in 3GPP. Examples are UEs configured with low access priorities, provisioning of extended wait timers, or extended access barring. In Release-12 this was extended with the two features of UE *Power Consumption Optimization* and *Signaling Overhead Reduction*.

2.6.1 UE Power Consumption Optimization

MTC devices like meter reading or wireless sensors are often installed at places without power supply. Consequently they run completely on battery and it may be very expensive to change the battery, because these devices may only be accessed by trained staff. Hence, in some cases the battery lifetime can even determine the lifetime of the whole device.

Especially for those devices which send non-frequently and only small data packets, it is very beneficial to reduce its power consumption between the data packets. This is reached by introducing a new mode, the Power Saving Mode (PSM). In this mode the UE can be regarded from the outside as being switched off. PSM is controlled by the NAS. The UE initiates the usage of PSM using Attach/TAU request message including a timer value for T3324, and optionally an extended version of the periodic TAU timer T3412. The network decides whether it accepts it by replying with the Attach/TAU Accept including the accepted timer value for T3324, and T3412 if requested. The procedure is shown in Fig. 2-23. When the UE goes to the IDLE state, it is still reachable for the duration of T3324. Then it automatically transits to the PSM, where it cannot be reached anymore by paging, because it has switched off its RF. The only way to leave the PSM is by UE originated signaling. In the example of Fig. 2-23 this is caused by the expiration of the TAU timer T3412, after which the UE has to do the TAU again. Of course, also any other UE originated signaling, e.g. by the application layer in order to send previously requested data on regular time intervals would deactivate the PSM.

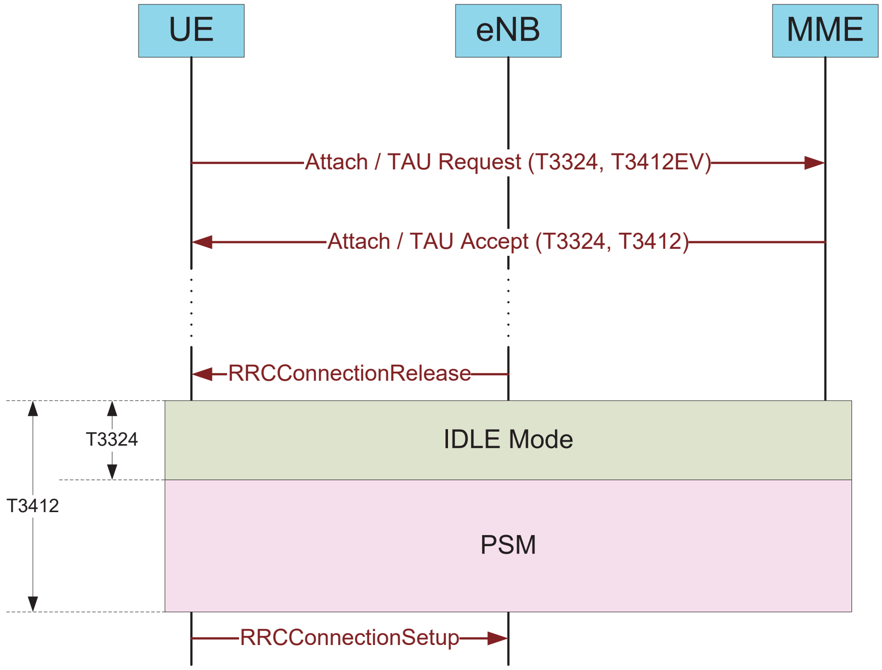


Fig. 2-23: PSM procedures

During PSM the UE remains registered with the network. Thus, PDN connections do not have to be re-attached or re-established. Also, the AS configuration is kept, and all timers continue to run. However, if one of the timers expires, it is up to UE implementation whether the corresponding actions are executed immediately or directly after leaving PSM.

2.6.2 Signaling Overhead Reduction

In devices with small and infrequent amount of data, the signaling overhead to the core network and to the RRC may be quite large. The idea here is to provide assistance information about the UE's traffic type and pattern in order to provide an optimal RRC connection handling, DRX and UL control channel configuration.

An extension of the S1 and X2 application protocol was defined for this purpose. An additional information element, the *Expected UE Behaviour* IE, is added in the INITIAL CONTEXT SETUP REQUEST message. The eNB may use it in order to determine the RRC connection time. This IE may also be included in the HANDOVER REQUEST message from the MME or the source eNB to the target eNB. Its content consists in the expected time between inter-eNB handover, the expected activity time, the expected idle time, and the source of UE activity behaviour information, i.e. whether the expected activity and idle period information is obtained via subscription information or via statistics.

2.7 LTE TDD-FDD joint operation including Carrier Aggregation

When local regulators auction spectrum, typically FDD and TDD spectrum licenses are bundled. Hence, most service providers worldwide hold licenses for paired spectrum (FDD) and unpaired spectrum (TDD). With the ability to aggregate spectrum using carrier aggregation and due to constantly increasing mobile data consumption by their subscribers, network operators requested the ability to also aggregate FDD and TDD spectrum, which 3GPP added to its Release 12.

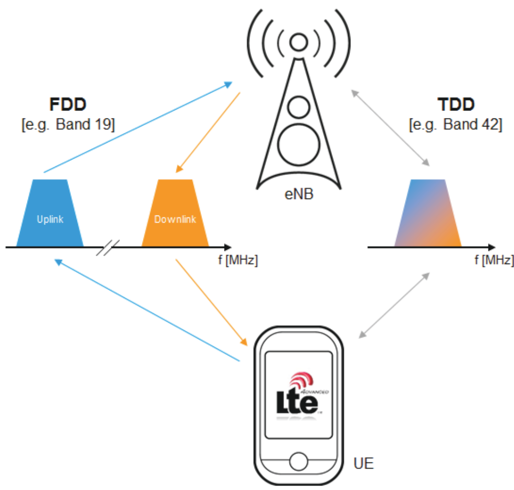


Fig. 2-24: LTE FDD and TD-LTE Carrier Aggregation

2.8 Enhanced Interference Mitigation & Traffic Adaption (eIMTA)

eIMTA is an improvement to the LTE TDD mode. It allows a dynamic reconfiguration of UL/DL time slots within the LTE frame structure. Table 2-11 recalls the seven possible frame configurations defined in LTE TDD as of 3GPP Release 8. The TDD frame configuration in each cell is signaled in SIB1.

Table 2-11: LTE TDD frame configuration

UL/DL Configuration	Subframe number									
	0	1	2	3	4	5	6	7	8	9
0	D	S	U	U	U	D	S	U	U	U
1	D	S	U	U	D	D	S	U	U	D
2	D	S	U	D	D	D	S	U	D	D
3	D	S	U	U	U	D	D	D	D	D
4	D	S	U	U	D	D	D	D	D	D
5	D	S	U	D	D	D	D	D	D	D
6	D	S	U	U	U	D	S	U	U	D

This remains to be the case; however, from 3GPP Release 12 onwards eIMTA allows to reconfigure UL-DL in a more flexible way. DL subframes in the reference configuration provided in SIB1 remain unchanged whereas a subset of UL and special subframes may be reconfigured to DL subframes. DL subframes cannot be changed since legacy UEs would try to monitor CRS in these subframes. It is however possible to change UL subframe to DL subframe. The eNB can use scheduling restrictions and configure PUCCH/SRS/SR resources to other UL subframes in order to „blank“ such UL subframes for legacy TDD UEs. The network sends a L1 signaling to the UE on PCell PDCCH to indicate which uplink-downlink configuration is used for one or more serving cell(s). This uplink-downlink configuration provided by the L1 signaling applies for a RRC-configured number of radio frames. Note that the TDD eIMTA configuration does not affect UE RRM/RLM measurements. Subframe-set dependent overload indication and uplink-downlink configuration, intended to be used by a cell, may be exchanged between eNBs over the X2 interface to facilitate the TDD eIMTA operation. The benefits of this feature is a significant user throughput gain for low to medium load scenarios. However, user throughput gains require sufficient isolation due to deployment or frequency separation. A UE functional eIMTA PDSCH demodulation test was added to [13] in order to verify eIMTA.

2.8.1 Deployment scenarios

As result out of the related study item phase, the following scenarios are used as a basis to develop the technology component.

- Scenario 1: Multiple femto cells deployed on the same carrier frequency

- Scenario 2: Multiple femto cells deployed on the same carrier frequency and multiple macro cells deployed on an adjacent carrier frequency where all macro cells have the same UL-DL configuration and femto cells can adjust UL-DL configuration
- Scenario 3: Multiple outdoor pico cells deployed on the same carrier frequency
- Scenario 4: Multiple outdoor pico cells deployed on the same carrier frequency and multiple macro cells deployed on an adjacent carrier frequency where all macro cells have the same UL-DL configuration and outdoor pico cells can adjust UL-DL configuration

Out of the above scenarios, scenario 3 and 4 were set as first priority.

2.8.2 Reconfiguration procedure and higher layer configuration

As mentioned above Layer 1 signaling facilitates the reconfiguration. More precisely DCI Format 1C provides UL/DL configuration indication numbers (1, 2, ….I), whereas each number consist of 3 bits (sufficient to signal UL/DL configurations 0 to 6, compare Table 2-11). The higher layer parameter *eimta-ReConfigIndex* (see below) determines which of the frame configuration numbers is applied for a specific number of frames (see *eimta-CommandPeriodicity* parameter below). RRC signaling defines the eIMTA configuration using the main information field *EIMTA-MainConfig* including the following parameters [12]:

- A dedicated *eIMTA-RNTI* used for CRC scrambling of the PDCCH
- *eimta-CommandPeriodicity:* Configures the periodicity to monitor PDCCH with eIMTA-RNTI (see [8], section13.1). Value sf10, sf20, sf40 and sf80 correspond to 10, 20, 40 and 80 ms subframes, respectively.
- *eimta-CommandSubframeSet:* Configures the subframe(s) to monitor PDCCH with eIMTA-RNTI within the periodicity configured by *eimta-CommandPeriodicity*. The 10 bits correspond to all subframes in the last radio frame within each periodicity. The left most bit is for subframe 0 and so on. Each bit can be of value 0 or 1. The value of 1 means that the corresponding subframe is configured for monitoring PDCCH with eIMTA-RNTI, and the value of 0 means otherwise. In case of TDD as PCell, only the downlink subframes indicated by the DL/UL subframe configuration in SIB1 can be configured for monitoring PDCCH with eIMTA-RNTI. In case of FDD as PCell, any of the ten subframes can be configured for monitoring PDCCH with eIMTA-RNTI.
- *eimta-ReConfigIndex:* Index of I, see [7] section 5.3.3.1.4. E-UTRAN configures the same value for all serving cells residing on same frequency band.
- *eimta-HarqReferenceConfig:* Indicates DL/UL subframe configuration used as the DL HARQ reference configuration for this serving cell. Value sa2 corresponds to Configuration2, sa4 to Configuration4 and sa5 to Configuration5 as shown in Table 2-11. E-UTRAN configures the same value for all serving cells residing on same frequency band.
- *mbsfn-SubframeConfigList:* Configure the MBSFN subframes for the UE on this serving cell. An uplink subframe indicated by the DL/UL subframe configuration in SIB1 can be configured as MBSFN subframe.

2.8.3 HARQ, CSI feedback and power control

For Uplink scheduling and HARQ timing, the UE follows the reference uplink-downlink configuration based on the one provided in SIB1. For Downlink HARQ timing, the UE follows the reference uplink-downlink configuration provided through dedicated RRC signaling (see *eimta-HarqReferenceConfig* above). The same value is configured on all serving cells residing on the same frequency band. Note that the Layer1 signaled UL/DL configuration might differ from this DL HARQ reference configuration. [8] Table 10.1.3.1-1A provides possible combinations of UL/DL configurations signaled in SIB1 (*subframeAssignment*) and DL HARQ reference configurations. Note that HARQ-ACK bundling is not supported for HARQ-ACK feedback for TDD eIMTA.

The UE uses the SIB1 uplink-downlink configuration and the 10bit bitmap for (E)PDCCH monitoring and the Layer1 signaled in DCI Format 1C for CSI measurements. For DL CSI measurements of each serving cell, two subframe sets may be configured via RRC signaling (see *eimta-CommandSubframeSet* above) to allow separate CSI measurements / reporting. Aperiodic CSI Feedback reporting is supported for all configured measurement subframe sets. In contrast, periodic CSI Feedback reporting is only possible in UL subframes based on DL HARQ reference UL/DL configuration.

Equally for PUSCH/SRS UL power control of each serving cell, two subframe sets with separate open loop power control parameters (P0 and alpha) may be configured via RRC signaling. With respect to power control command step sizes and power headroom reduction (PHR) mechanisms no changes compared with 3GPP Release 11 apply.

2.8.4 UE capabilities

A number of UE capabilities relevant to eIMTA have been added to [10]. These are listed below:

- *csi-SubframeSet*: Indicates whether the UE supports Rel-12 DL CSI subframe set configuration, DL CSI subframe set dependent CSI measurement/feedback, configuration of additional up to 2 CSI-IM resources for a CSI process with no more than 4 CSI-IM resources for all CSI processes of one frequency if the UE supports tm10, configuration of two ZP-CSI-RS for tm1-tm9, PDSCH RE mapping with two ZP-CSI-RS configurations, and EPDCCH RE mapping with two ZP-CSI-RS configurations if the UE supports EPDCCH. This field is only applicable for UEs supporting TDD.
- *phy-TDD-ReConfig-FDDPCell:* This field defines whether the UE supports TDD UL/DL reconfiguration for TDD serving cell(s) via monitoring PDCCH with eIMTA-RNTI on a FDD PCell, and HARQ feedback according to UL and DL HARQ reference configurations.
- *phy-TDD-ReConfig-TDDPCell:* This field defines whether the UE supports TDD UL/DL reconfiguration for TDD serving cell(s) via monitoring PDCCH with eIMTA-RNTI on a TDD PCell, and HARQ feedback according to UL and DL HARQ reference configurations.

- *pusch-SRS-PowerControl-SubframeSet:* This field defines whether the UE supports subframe set dependent UL power control for PUSCH and SRS. This field is only applicable for UEs supporting TDD.

2.8.5 eIMTA in combination with other technology components

It is possible to use eIMTA in combination with enhanced Multicast Broadcast Multimedia Services (eMBMS). A UE can be configured by higher layers via dedicated signaling to assume MBSFN subframes in at least some SIB1-UL subframes when the SIB1-UL subframes are determined by the UE to DL subframes (see *mbsfn-SubframeConfigList* in section 2.8.2 and section 6.3.2 in [12]).

eIMTA can be combined with carrier aggregation (CA) for both cases, i.e. FDD-TDD and TDD-TDD CA. For a UE configured with CA and eIMTA on at least one serving cell, the Rel-10/11 TDD-TDD CA UE behaviors on HARQ-ACK transmission and soft buffer handling and the Release 12 FDD-TDD CA UE behaviors on HARQ-ACK transmission and soft buffer handling apply, except that the eIMTA DL HARQ reference configuration replaces the UL-DL configuration indicated by SIB1 (in case of PCell) and the UL-DL configuration indicated by *tdd-Config-r10* (in case of SCell). For a UE configured with FDD as PCell and eIMTA on a SCell, a 10-bit bitmap is used to configure the set of subframes in the nth radio frame to monitor the L1 reconfiguration DCI, where n represents the periodicity (in unit of radio frames) of monitoring the L1 reconfiguration DCI.

eIMTA and TTI bundling is not configured together as specified in [11], i.e. these technology components cannot be used in combination.

2.9 Further downlink MIMO enhancements

The basis for the Work Item “Further Downlink MIMO Enhancement for LTE-Advanced” is the corresponding study conducted by 3GPP within Release 11 timeframe. The Study Item results are captured in a technical report (see [18]). The main conclusion is that enhancements for DL MIMO are necessary to gain higher system throughput with various antenna configurations. This includes cross-polarized antennas, closely or widely spaced and non-collocated setups with power imbalance. To achieve the better throughput Release 12 introduces the following as further DL MIMO enhancements:

- an enhanced 4Tx codebook
- a new aperiodic PUSCH feedback mode 3-2

The enhanced 4 Tx codebook uses the codebook structure W = W1*W2 already introduced in Rel-10 for four antenna feedback for DMRS based transmission modes. Whether the new 4Tx codebook is applied is configured by setting the Information Element *alternativeCodeBookEnabledFor4TX-r12* to TRUE in the RRC layer. To differentiate from the Rel-8 codebook, the Release 12 codebook is also called “dual codebook”. The Release 12 enhanced codebook is supported for all aperiodic reporting modes that are valid for transmission modes (TM) 8, 9, 10 when PMI/RI is configured and periodic feedback modes 2-1 and 1-1. It is not applicable to TMs 4 and 6. The new codebooks for four antenna ports are given in tables 7.2.4-0A - D of [8] and summarized in this document for quick reference:

Table 2-12: Codebook for 1-layer CSI reporting using antenna ports 0 to 3 or 15 to 18

i_1	i_2							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
0 – 15	$W^{(1)}_{i_1,0}$	$W^{(1)}_{i_1,8}$	$W^{(1)}_{i_1,16}$	$W^{(1)}_{i_1,24}$	$W^{(1)}_{i_1+8,2}$	$W^{(1)}_{i_1+8,10}$	$W^{(1)}_{i_1+8,18}$	$W^{(1)}_{i_1+8,26}$
i_1	i_2							
	8	**9**	**10**	**11**	**12**	**13**	**14**	**15**
0 - 15	$W^{(1)}_{i_1+16,4}$	$W^{(1)}_{i_1+16,12}$	$W^{(1)}_{i_1+16,20}$	$W^{(1)}_{i_1+16,28}$	$W^{(1)}_{i_1+24,6}$	$W^{(1)}_{i_1+24,14}$	$W^{(1)}_{i_1+24,22}$	$W^{(1)}_{i_1+24,30}$
where $W^{(1)}_{m,n} = \frac{1}{2}\begin{bmatrix} v'_m \\ \varphi'_n v'_m \end{bmatrix}$								

Table 2-13: Codebook for 2-layer CSI reporting using antenna ports 0 to 3 or 15 to 18

i_1	i_2			
	0	**1**	**2**	**3**
0 – 15	$W^{(2)}_{i_1,i_1,0}$	$W^{(2)}_{i_1,i_1,1}$	$W^{(2)}_{i_1+8,i_1+8,0}$	$W^{(2)}_{i_1+8,i_1+8,1}$
i_1	i_2			
	4	**5**	**6**	**7**

0 – 15	$W^{(2)}_{i_1+16,i_1+16,0}$	$W^{(2)}_{i_1+16,i_1+16,1}$	$W^{(2)}_{i_1+24,i_1+24,0}$	$W^{(2)}_{i_1+24,i_1+24,1}$
i_1	i_2			
	8	9	10	11
0 – 15	$W^{(2)}_{i_1,i_1+8,0}$	$W^{(2)}_{i_1,i_1+8,1}$	$W^{(2)}_{i_1+8,i_1+16,0}$	$W^{(2)}_{i_1+8,i_1+16,1}$
i_1	i_2			
	12	13	14	15
0 – 15	$W^{(2)}_{i_1,i_1+24,0}$	$W^{(2)}_{i_1,i_1+24,1}$	$W^{(2)}_{i_1+8,i_1+24,0}$	$W^{(2)}_{i_1+8,i_1+24,1}$
where $W^{(2)}_{m,m',n} = \frac{1}{\sqrt{8}}\begin{bmatrix} v'_m & v'_{m'} \\ \varphi_n v'_m & -\varphi_n v'_{m'} \end{bmatrix}$				

Table 2-14: Codebook for 3-layer CSI reporting using antenna ports 15 to 18

i_1	i_2							
	0	1	2	3	4	5	6	7
0	$W_0^{\{124\}}/\sqrt{3}$	$W_1^{\{123\}}/\sqrt{3}$	$W_2^{\{123\}}/\sqrt{3}$	$W_3^{\{123\}}/\sqrt{3}$	$W_4^{\{124\}}/\sqrt{3}$	$W_5^{\{124\}}/\sqrt{3}$	$W_6^{\{134\}}/\sqrt{3}$	$W_7^{\{134\}}/\sqrt{3}$
i_1	i_2							
	8	9	10	11	12	13	14	15
0	$W_8^{\{124\}}/\sqrt{3}$	$W_9^{\{134\}}/\sqrt{3}$	$W_{10}^{\{123\}}/\sqrt{3}$	$W_{11}^{\{134\}}/\sqrt{3}$	$W_{12}^{\{123\}}/\sqrt{3}$	$W_{13}^{\{123\}}/\sqrt{3}$	$W_{14}^{\{123\}}/\sqrt{3}$	$W_{15}^{\{123\}}/\sqrt{3}$

Table 2-15: Codebook for 4-layer CSI reporting using antenna ports 15 to 18

i_1	i_2							
	0	1	2	3	4	5	6	7
0	$W_0^{\{1234\}}/2$	$W_1^{\{1234\}}/2$	$W_2^{\{3214\}}/2$	$W_3^{\{3214\}}/2$	$W_4^{\{1234\}}/2$	$W_5^{\{1234\}}/2$	$W_6^{\{1324\}}/2$	$W_7^{\{1324\}}/2$
i_1	i_2							
	8	9	10	11	12	13	14	15
0	$W_8^{\{1234\}}/2$	$W_9^{\{1234\}}/2$	$W_{10}^{\{1324\}}/2$	$W_{11}^{\{1324\}}/2$	$W_{12}^{\{1234\}}/2$	$W_{13}^{\{1324\}}/2$	$W_{14}^{\{3214\}}/2$	$W_{15}^{\{1234\}}/2$

With

$$\varphi_n = e^{j\pi n/2}$$

$$\varphi'_n = e^{j2\pi n/32}$$

$$v'_m = \begin{bmatrix} 1 & e^{j2\pi m/32} \end{bmatrix}^{\mathrm{T}}$$

The new aperiodic PUSCH feedback mode 3-2 enables the reporting of PMI (Precoding Matric Indicator) for each subband in combination with the CQI (Channel Quality Indicator) for each subband. Hence, the modulation and precoding matrix information are both available on subband basis which was not possible in previous releases. Table 7.2.1-1 in [8] gives a good overview of all PUSCH reporting modes including the new Mode 3-2 (cf. to Table 2-16). Feedback mode 3-2 can only be configured for DMRS-based TMs 8, 9 and 10 when PMI/RI reporting is configured and in TMs 4 and 6 when the Rel-8 codebook is used.

Table 2-16: CQI and PMI Feedback Types for PUSCH CSI reporting Modes

		PMI Feedback Type		
		No PMI	Single PMI	Multiple PMI
PUSCH CQI Feedback Type	Wideband (wideband CQI)			Mode 1-2
	UE Selected (subband CQI)	Mode 2-0		Mode 2-2
	Higher Layer-configured (subband CQI)	Mode 3-0	Mode 3-1	Mode 3-2

2.10 Coverage Enhancements

Prior studies [16] identified UL medium data rate PUSCH and VoIP to be the coverage bottleneck for LTE. The Release 12 work item “LTE Coverage Enhancements” copes with these issues. The gist is the introduction of an enhanced TTI bundling, which improves the coverage by extending the cell range for low data rates. Further coverage enhancements are covered by the Release 11 work item EPDCCH (enhanced DL control channels).

The UE can signal its support of the enhanced TTI bundling in the *UE-EUTRA-Capability* in the information element (IE) *PhyLayerParameters-v12xy* using two IEs. First, the IE *e-HARQ-Pattern-FDD-r12* informs the eNB that the UE is capable to operate with the enhanced HARQ pattern for TTI bundling for FDD. Second, the IE *noResourceRestrictionForTTIBundling-r12* indicates whether the UE can handle more than 3 PRBs for FDD and TDD.

Eventually, the eNB lets the UE know that enhanced TTI bundling is activated by higher layer signaling within the *MAC-MainConfig*. A new parameter *e-HARQ-Pattern-r12* is introduced ([8] and [12]). This IE is only configured and enabled if *ttiBundling* is set to TRUE. Two different UL TTI bundling operations can be configured: With setting *e-HARQ-Pattern-r12* to TRUE, the Rel-12 HARQ pattern is enabled for the enhanced TTI bundling. When setting *e-HARQ-Pattern-r12* to FALSE or not configuring the IE, the legacy Rel-8 bundling pattern is activated. The IE *e-HARQ-Pattern-r12* applies to the primary cell only. In case the UE supports more than 3 PRBs the eNB is free to resolve the resource allocation restriction for the PRB size. For UEs not indicating the support of *noResourceRestrictionForTTIBundling-r12*, the legacy 3 PRB restriction applies. TTI bundling cannot be combined with a configured UL in a SCell.

Moreover, when using enhanced TTI bundling the HARQ RTT is reduced from 16 ms to 12 ms for both UL VoIP and for medium data rate PUSCH for FDD. In this case the number of UL HARQ processes is 3. As for TTI bundling the enhanced TTI bundling is activated by higher layers and the bundling operation uses four consecutive TTIs as well as QPSK modulation.

The only change for TDD is that more than 3 PRBs can be supported for PUSCH with enhanced TTI bundling in Release 12 (provided that *noResourceRestrictionForTTIBundling-r12* is supported). Just like for legacy TTI bundling the enhanced operation is applicable for UL-DL configurations #0, #1 and #6 with 2 or 3 HARQ processes. Simultaneous TTI bundling and SPS is not allowed for TDD as well as the combination of TTI bundling with eIMTA.

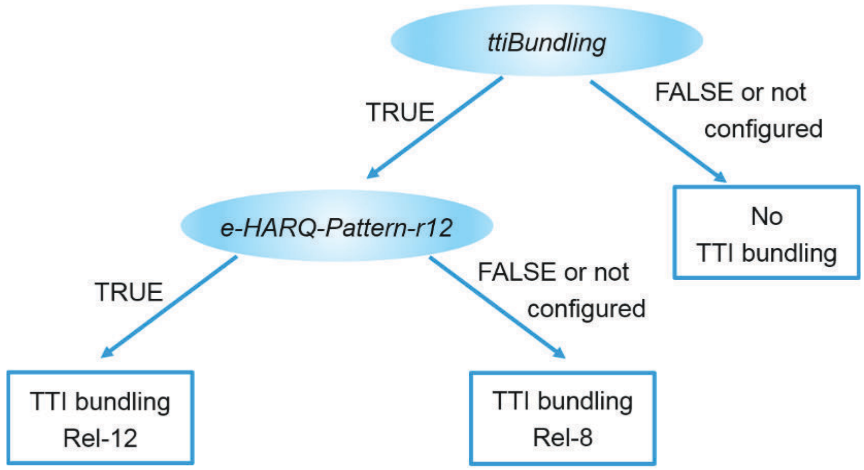


Fig. 2-25: Decision tree for TTI bundling

LTE Coverage Enhancements comprise an enhanced TTI bundling for UL medium data rate PUSCH and VoIP. The main differences compared to TTI bundling are:

- An enhanced HARQ pattern is used for FDD if *e-HARQ-Pattern-r12* is set to TRUE.
- The HARQ RTT is reduced from 16 ms to 12 ms.
- More than 3 PRBs per subframe can be allocated.

Thus, from Release 12 onwards the network can choose from different TTI bundling operation modes according to the UE capability, its coverage situation and the requested application.

2.11 Support for BeiDou Navigation Satellite System

In this work item support for BDS to LTE specifications was included by defining a new GNSS ID and introducing necessary assistance data information. These comprise the Clock Model, Orbit Model, Almanac Model, UTC model, Ionospheric Model and differential corrections for BDS based on the existing GNSS framework.

These extensions allow to natively supporting BDS using LTE signaling.

2.12 Inter-eNB CoMP for LTE

In 3GPP Release 11, CoMP was introduced in order to improve coverage of high data rates, especially on the cell-edge, and to increase system throughput. This feature was restricted to transmission points connected with an ideal backhaul, which implies that the corresponding network interfaces between eNBs were not needed.

In 3GPP Release 12, the associated X2 interface signaling support was specified in order to use CoMP also with eNBs connected with a non-ideal backhaul. Multiple eNBs are coordinated by inter eNB signaling of hypothetical resource allocation information, and with measurement results taken by UEs under their control.

These hypothesis are indicated to neighboring eNBs using the LOAD INFORMATION message (see Fig. 2-26), already defined for inter-cell interference coordination:

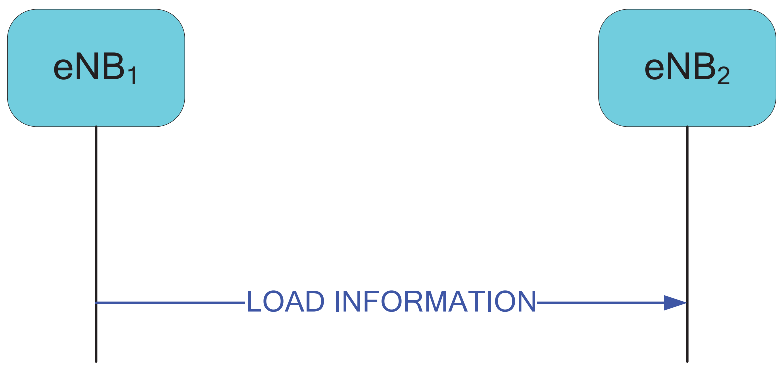


Fig. 2-26: Load information exchange between eNBs

The LOAD INFORMATION message is extended by the *CoMP Information* IE, containing a list of up to 256 *CoMP Hypothesis Sets* and their associated *Benefit Metric*. This information may be used by the receiving eNB for RRM.

The *CoMP Hypothesis Set* is a list of up to 32 Cell IDs, each associated with a *CoMP Hypothesis*. The latter is a bit string, where each entry represents a PRB in a subframe. Here, the value “1” denotes an interference protected resource, whereas “0” has no constraints. This pattern is continuously repeated. Each of these giving cells belong to either the receiving eNB, the sending eNB or their neighbor.

The *Benefit Metric* is an integer, which indicate the trade-off between the cost and the benefit, provided that the associated CoMP hypothesis is applied. Lower values denote higher costs, upper values denote higher benefits.

In addition to these CoMP hypothesis, also RSRP measurements may be used for inter-eNB CoMP decisions, e.g. the CoMP hypotheses may be verified this way. These measurements are indicated over the X2-interface to neighboring eNB by extending the RESURCE STATUS message:

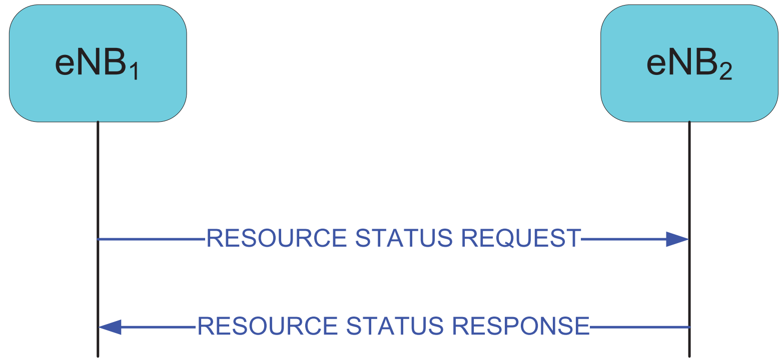


Fig. 2-27: Resource Status communication between eNBs

On request from the eNB_1, eNB_2 instructs UEs under its control to perform the associated measurements. It then reports an RSRP measurement report list in a periodic way with a configurable reporting period (see Fig. 2-27). The report consists of measurements of up to 128 UEs, each carrying RSRP measurements for up to 9 cells. These measurements are defined in the RRC specifications [12].

3 Conclusion

This white paper describes significant enhancements to LTE-Advanced provided within 3GPP Release 12. As with existing cellular technologies evolved over years in 3GPP, also LTE-Advanced is complemented with new functionality in Release 12. The important building blocks comprise further enhancements to support small cell deployments such as Dual Layer Connectivity and 256QAM modulation, further optimization for support of MTC type of devices, tighter interworking of LTE-Advanced and WLAN and most significant the addition of device to device proximity service and device to device communication. It is noted that device to device communication is only applicable to the public safety use case. Still proximity services on their own are judged a significant feature addition to the LTE technology. Dual layer connectivity enables an efficient method to add small cell resources as an alternative to or even in combination with carrier aggregation. Note that the latter is widely deployed in LTE commercial networks. The MTC optimizations enable LTE to address new application scenarios and are expected to be further worked on during upcoming 3GPP releases.

4 LTE / LTE-Advanced frequency bands

Operating bands of LTE/LTE-A up to 3GPP Release 11 are shown in Table 4-1 using paired spectrum and in Table 4-2 using unpaired spectrum.

Table 4-1

Operating FDD bands for LTE / LTE-Advanced							
Operating Band	**Uplink (UL) operating band BS receive/UE transmit**			**Downlink (DL) operating band BS transmit /UE receive**			**Duplex Mode**
	F_{UL_low} [MHz]	-	F_{UL_high}	F_{DL_low}	-	F_{DL_high}	
1	1920	-	1980	2110	-	2170	FDD
2	1850	-	1910	1930	-	1990	
3	1710	-	1785	1805	-	1880	
4	1710	-	1755	2110	-	2155	
5	824	-	849	869	-	894	
6	830	-	840	865	-	875	
7	2500	-	2570	2620	-	2690	
8	880	-	915	925	-	960	
9	1749.9	-	1784.9	1844.9	-	1879.9	
10	1710	-	1770	2110	-	2170	
11	1427.9	-	1447.9	1475.9	-	1495.9	
12	699	-	716	729	-	746	
13	777	-	787	746	-	756	
14	788	-	798	758	-	768	
15	Reserved			Reserved			
16	Reserved			Reserved			
17	704	-	716	734	-	746	
18	815	-	830	860	-	875	
19	830	-	845	875	-	890	
20	832	-	862	791	-	821	
21	1447.9	-	1462.9	1495.9	-	1510.9	
22	3410	-	3500	3510	-	3600	
23	2000	-	2020	2180	-	2200	
24	1626.5	-	1660.5	1525	-	1559	
25	1850	-	1915	1930	-	1995	
26	814	-	849	859	-	894	
27	807	-	824	852	-	869	
28	703	-	748	758	-	803	
29	N/A			717	-	728	

Operating FDD bands for LTE / LTE-Advanced							
Operating Band	Uplink (UL) operating band BS receive/UE transmit			Downlink (DL) operating band BS transmit /UE receive			Duplex Mode
	F_{UL_low} [MHz]	-	F_{UL_high}	F_{DL_low}	-	F_{DL_high}	
30	2305	-	2315	2350	-	2360	FDD
31	452.5	-	457.5	462.5	-	467.5	
32	N/A			1452	-	1496	

Table 4-2

Operating TDD bands for LTE / LTE-Advanced							
Operating Band	Uplink (UL) operating band BS receive/UE transmit			Downlink (DL) operating band BS transmit /UE receive			Duplex Mode
	F_{UL_low} [MHz]	-	F_{UL_high}	F_{DL_low}	-	F_{DL_high}	
33	1900	-	1920	1900	-	1920	TDD
34	2010	-	2025	2010	-	2025	
35	1850	-	1910	1850	-	1910	
36	1930	-	1990	1930	-	1990	
37	1910	-	1930	1910	-	1930	
38	2570	-	2620	2570	-	2620	
39	1880	-	1920	1880	-	1920	
40	2300	-	2400	2300	-	2400	
41	2496	-	2690	2496	-	2690	
42	3400	-	3600	3400	-	3600	
43	3600	-	3800	3600	-	3800	
44	703	-	803	703	-	803	

5 Literature

[1] Rohde & Schwarz: Application Note 1MA111 “UMTS Long Term Evolution (LTE) Technology Introduction”

[2] Rohde & Schwarz: White Paper 1MA191 “LTE Release 9 Technology Introduction”

[3] Rohde & Schwarz: White Paper 1MA169 “LTE-Advanced Technology Introduction”

[4] Rohde & Schwarz: White Paper 1MA232 “LTE-Advanced (3GPP Rel.11) Technology Introduction”

[5] 3GPP TS 36.300 V 12.6.0, June 2015; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2, Release 11

[6] 3GPP TS 36.211 V 12.6.0, June 2015; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation, Release 11

[7] 3GPP TS 36.212 V 12.5.0, June 2015; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Multiplexing and channel coding, Release 11

[8] 3GPP TS 36.213 V 12.6.0, June 2015; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures, Release 11

[9] 3GPP TS 36.214 V 12.2.0, March 2015; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer; Measurements, Release 11

[10] 3GPP TS 36.306 V 12.5.0, June 2015; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio access capabilities, Release 11

[11] 3GPP TS 36.321 V 12.6.0, June 2015; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) protocol specification, Release 11

[12] 3GPP TS 36.331 V 12.6.0, June 2015; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification, Release 11

[13] 3GPP TS 36.101 V 12.8.0, July 2015; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception, Release 11

[14] 3GPP TS 36.104 V 12.8.0, July 2015; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception, Release 11

[15] 3GPP TS 36.133 V 12.8.0, July 2015; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Requirements for support of radio resource management, Release 11

[16] 3GPP TR 36.824 V 12.0.0, June 2012; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); LTE coverage enhancements, Release 11

[17] 3GPP TR 36.842 V 11.0.0, June 2012; Technical Specification Group Radio Access Network; Study on Small Cell enhancements for E-UTRA and E-UTRAN; Higher layer aspects, Release 12

[18] 3GPP TR 36.871 V 11.0.0, December 2011; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Downlink Multiple Input Multiple Output (MIMO) enhancement for LTE-Advanced, Release 11

[19] 3GPP TR 36.872 V 12.1.0, December 2013; Technical Specification Group Radio Access Network; Small Cell enhancements for E-UTRA and E-UTRAN – Physical layer aspects, Release 12

[20] 3GPP TR 36.932 V 12.1.0, March 2013; Technical Specification Group Radio Access Network; Scenarios and requirements for small cell enhancements for E-UTRA and E-UTRAN, Release 12

[21] Rohde & Schwarz: White Paper 1MA214 "WLAN Traffic Offload in LTE"

[22] IEEE 802.11, Part 11: "Wireleass LAN Medium Access Control (MAC) and Physical Layer (PHY) specification, IEEE Std."

[23] Wi-Fi Alliance Technical Committee, Hotspot 2.0 Technical Task Group: "Hotspot 2.0 (Release 2) Technical Specification"

[24] Rohde & Schwarz: Application Note 1MA150 "Cell search and cell selection in UMTS Long Term Evolution (LTE)"

[25] 3GPP TS 23.303 V 12.5.0, June 2015; Technical Specification Group and System Aspects, Proximity-based services (ProSe); Stage 2; Release 12

[26] 3GPP TS 24.334 V12.3.0, June 2015; Technical Specification Group Core Network and Terminals, Proximity-services (ProSe) User Equipment (UE) to ProSe function protocols; Stage 3; Release 12

[27] 3GPP TS 23.003 V12.7.0, June 2015; Technical Specification Group Core Network and Terminals, Numbering, addressing and identification; Release 12

[28] 3GPP TS 24.333 V12.3.0, June 2015; Technical Specification Group Core Network and Terminals, Proximity-services (ProSe) Management Objects (MO); Release 12

[29] 3GPP TS 24.301 V12.9.0, June 2015; Technical Specification Group Core Network and Terminals, Non-Access Stratum (NAS) protocol for Evolved Packet System (EPS), Stage 3; Release 12

[30] 3GPP TS 33.303 V12.4.0, June 2015; Technical Specification Group Services and System Aspects, Proximity-based Services (ProSe), Security Aspects; Release 12

6 Additional Information

Please send your comments and suggestions regarding this application note to

TM-Applications@rohde-schwarz.com

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Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1-888-TEST-RSA (1-888-837-8772)
customer.support@rsa.rohde-schwarz.com

Latin America
+1-410-910-7988
customersupport.la@rohde-schwarz.com

Asia/Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86-800-810-8228 /+86-400-650-5896
customersupport.china@rohde-schwarz.com

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