ITU Centres of Excellence for Europe

Next Generation Mobile and Wireless Networks

Module 2:
LTE mobile networks: technology, regulation and business aspects

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2.1. 3GPP standardization towards LTE

As it was mention in the previous module (Section 1.2) the LTE (Long-Term Evolution) is defined by 3GPP as a highly flexible radio interface which also constitutes a major step towards IMT-Advanced. In fact, already the first release of LTE includes many of the features originally considered for future 4G systems. The first release of LTE (2004), referred to as release-8 provides peak rates of 300 Mbit/s, a radio-network delay of less than 5 ms, a significant increase in spectrum efficiency and a new flat radio-network architecture designed to simplify operation and to reduce cost. Moreover, LTE supports both FDD and TDD and targets also a smooth evolution from earlier 3GPP system such as TD-SCDMA and WCDMA/HSPA as well as 3GPP2 systems such as cdma2000.

If we go back in 3GPP standardisation history towards LTE, to ensure that this system remains competitive in the future, in **November 2004** 3GPP began a project to define the long-term evolution of UMTS cellular technology. The specifications related to this effort are formally known as the evolved UMTS terrestrial radio access (E-UTRA) and evolved UMTS terrestrial radio access network (E-UTRAN), but are more commonly referred to by the project name LTE. The first version of LTE is documented in Release 8 of the 3GPP specifications. A parallel 3GPP project called System Architecture Evolution (**SAE**) is defining a new all-IP, packet-only core network (**CN**) known as the evolved packet core (EPC). The combination of the EPC and the evolved RAN (E-UTRA plus E-UTRAN) is the evolved packet system (**EPS**). Depending on the context, any of the terms LTE, E-UTRA, E-UTRAN, SAE, EPC and EPS may get used to describe some or all of the system. Although EPS is the only correct term for the overall system, the name of the system will often be written as LTE/SAE or simply LTE.

As it was mentioned before, 3GPP's high-level requirements for LTE include reduced cost per bit, better service provisioning, flexible use of new and existing frequency bands, simplified network architecture with open interfaces, and an allowance for reasonable power consumption by terminals.

A timeline for LTE development is shown in Figure 2.1 and moreover, the 3GPP evolution is shown in Figure 2.2. This includes the work of 3GPP in drafting the specifications as well as the conformance test activities of the Global Certification Forum (GCF) and the trials being carried out by the LTE/SAE Trial Initiative (LSTI). The LSTI is an industry forum and complementary group who are working in parallel with 3GPP and GCF with the intent of accelerating the acceptance and deployment of LTE as the logical choice of the industry for next generation mobile networks. The work of LSTI is split into four phases.

The first phase is proof of concept of the basic principles of LTE and SAE, using early prototypes not necessarily compliant with the specifications. The second phase is interoperability development testing (IODT), which is a more detailed phase of testing using standards-compliant equipment but not necessarily commercial platforms. The third stage is interoperability testing (IOT), which is similar in scope to IODT but uses platforms that are intended for commercial deployment. The final phase is friendly customer trials, which will run until mid-2010 when GCF is expected to certify the first UE against the 3GPP conformance tests. Dates beyond mid-2009 are estimates, and actual dates will depend on industry conditions and progress.

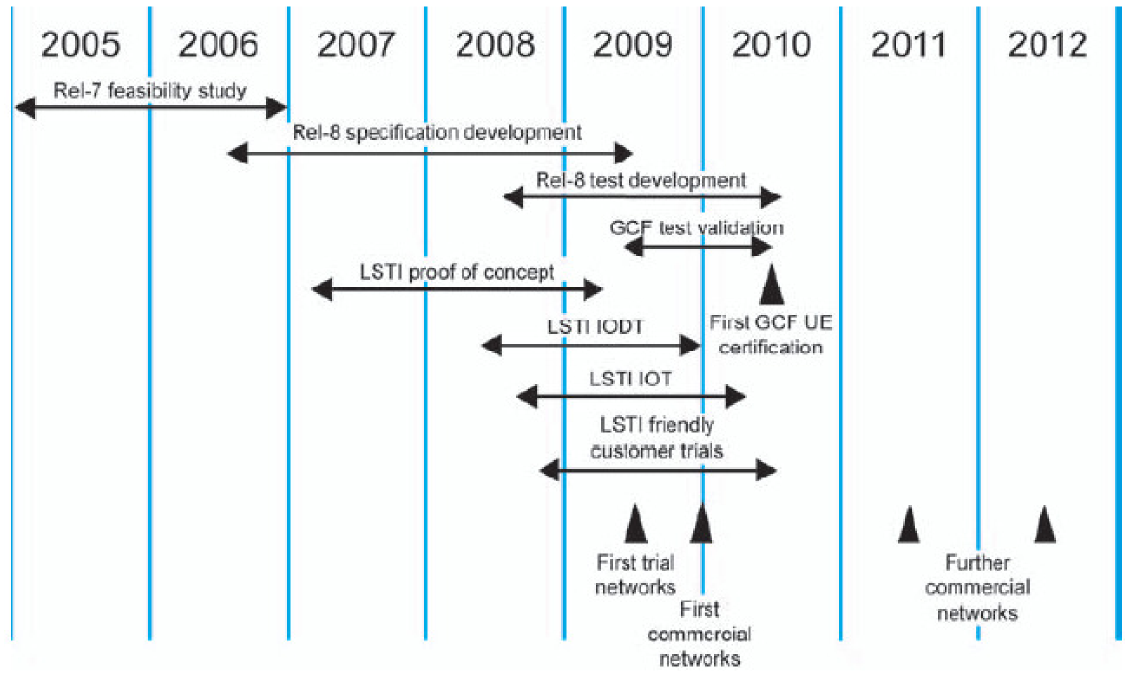


Figure 2.1. LTE development timeline.

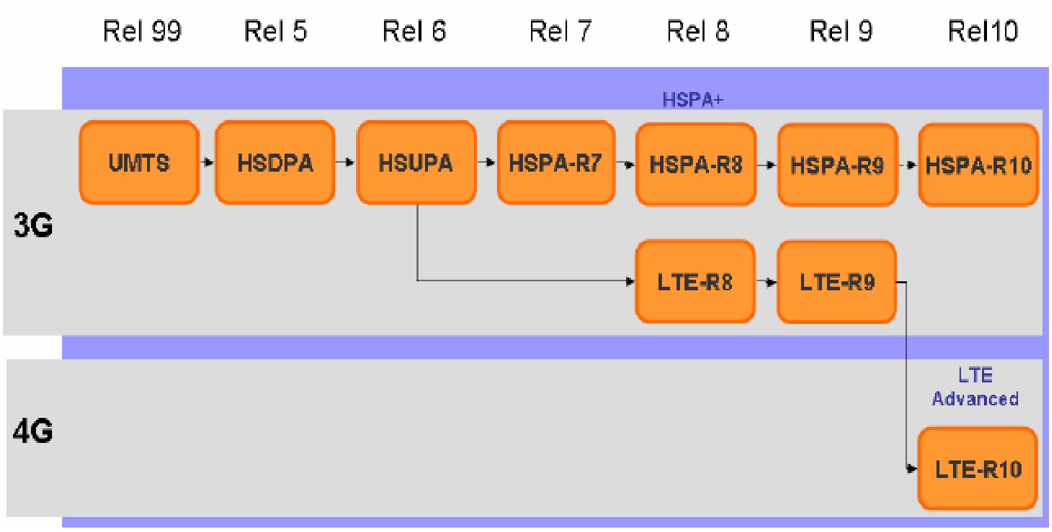


Figure 2.2. 3GPP evolution towards LTE and LTE-Advanced.

Table 2.1 Evolution of the 3GPP standards towards LTE

Release	Functional freeze	Main feature of release
Release 99	March 2000	Basic 3.84 Mcps W-CDMA (FDD & TDD)
Release 4	March 2001	1.28 Mcps TDD (aka TD-SCDMA)
Release 5	June 2002	HSUPA
Release 6	March 2005	HSUPA (E-DCH)
Release 7	December 2007	HSPA+ (64QAM downlink, MIMO, 16QAM uplink) LTE and SAE feasibility study
Release 8	December 2008	LTE work item – OFOMA/SC-FDMA air interface SAE work item – new IP core network Further HSPA improvements
Release 9	December 2009 (3 stages)	SAE Enhancements, WiMAX and LTE/UMTS Interoperability. Dual-Cell HSDPA with MIMO
Release 10	March 2010 – March 2011 (3 stages)	LTE Advanced fulfilling IMT Advanced 4G requirements. Backwards compatible with release 8 (LTE).
Release 11	Planned September 2011 to September 2012 (also in 3 stages)	Advanced IP Interconnection of Services. Service layer interconnection between national operators/carriers as well as third party application providers.

Moreover, in Table 2.1 detail evolution of the 3GPP specifications towards LTE (and beyond) are summarized. There are other standardization activities within 3GPP not shown in Table 2.1 such as those for the GSM Enhanced RAN (GERAN) and the Internet Protocol Multimedia Subsystem (IMS) which are not part of this section.

Each release of the 3GPP specifications represents a defined set of features. A summary of the contents of any release can be found at www.3gpp.org/releases.

The date given for the functional freeze relates to the date when no further new items can be added to the release. Any further changes to the specifications are restricted to essential corrections. After Release 99, 3GPP stopped naming releases after the year and opted for a new scheme that started with Release 4. Release 4 introduced the 1.28 Mcps narrow band version of W-CDMA, also known as time domain synchronous code division multiple access (TD-SCDMA). Following this was Release 5, in which high speed downlink packet access (HDSPA) introduced packet-based data services to UMTS in the same way that the general packet radio service (GPRS) did for GSM in Release 97 (1998). The completion of packet data for UMTS was achieved in Release 6 with the addition of high speed uplink packet access (HSUPA), although the official term for this technology is enhanced dedicated channel (E-DCH). HSDPA and HSUPA are now known collectively as high speed packet access (HSPA). Release 7 contained the first work on LTE/SAE with the completion of the feasibility studies, and further improvements were made to HSPA such as downlink MIMO, 64QAM on the downlink, and 16QAM on the uplink.

In Release **8**, HSPA continues to evolve with the addition of numerous smaller features such as dual cell HSDPA and 64QAM with MIMO. The main work in Release 8, however, is the specification of LTE and SAE. Work beyond Release 8 is also in progress whereby LTE will be enhanced in Release **10** and put forward as LTE-Advanced, a candidate technology for the International Telecommunications Union (ITU) IMT-Advanced program, better known as **4G**.

To emphasize that 3GPP LTE is one of several evolving 3G wireless standards loosely referred to as **3.9G**. The other standards are: 3GPP HSPA+, 3GPP EDGE Evolution and the Mobile WiMAX (IEEE 802.16e), which encompasses the earlier WiBrodeveloped by the Telecommunications Technology Association (TTA) in Korea.

However, all have similar goals in terms of improving spectral efficiency, with the widest bandwidth systems providing the highest single-user data rates. Spectral efficiencies are achieved primarily through the use of less robust, higher-order modulation schemes and multi-antenna technology that ranges from basic transmit and receive diversity to the more advanced MIMO spatial diversity.

Of the 3.9G standards, EDGE evolution and HSPA+ are direct extensions of existing technologies. Mobile WiMAX is based on the existing IEEE 802.16d standard and has had limited implementation in WiBro. Of the standards listed above, only LTE is considered "new." Work on the alternative Ultra Mobile Broadband (UMB) standard being developed by 3GPP2 was discontinued in November 2008 in favor of LTE.

If we look back in the 3GPP LTE specification documents, Release 7 specification included the study phase of LTE. This study resulted in several Technical Reports, of which 25.912 and 25.913 have been noted.

The specifications themselves for the LTE E-UTRA and E-UTRAN are contained in the 36 series of Release 8, divided into the following categories:

- 36.100 series covering radio specifications and evolved Node B (eNB) conformance testing
- 36.200 series covering layer 1 (physical layer) specifications
- 36.300 series covering layer 2 and 3 air interface signaling specifications
- 36.400 series covering network signaling specifications
- 36.500 series covering user equipment conformance testing
- 36.800 and 36.900 series, which are technical reports containing background information

The SAE specifications are found in the 22 series, 23 series, 24 series, and 33 series of Release 8, with work being done in parallel in Release 9. More details about SAE and EPC you can find in Section 2.3.

2.2. LTE radio network and spectrum allocations

Although there are major step changes between LTE and its 3G predecessors, it is nevertheless looked upon as an evolution of the UMTS/3GPP 3G standards. Figure 2.3 illustrates the main differences between LTE and 3G design and network topology. Despite it uses a different form of radio interface, using OFDMA/SC-FDMA instead of CDMA, there are many similarities with the earlier forms of 3G architecture and there is scope for much re-use. Moreover, in the previous module (Section 1.2) we elaborate about the new technologies used in LTE Radio Access Network (RAN) and here will be discuss in more details about the LTE RAN and spectrum allocations.

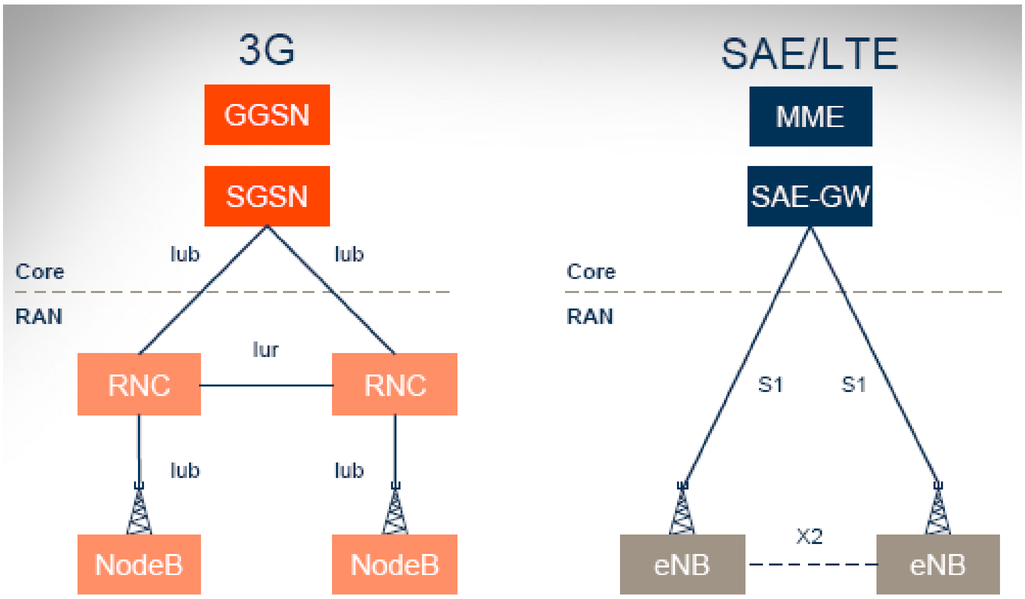


Figure 2.3. Illustration of 3G and LTE/SAE System Architecture.

At a glance, it is worthily to summarizing the key parameters of the 3G LTE specification. In Table 2.2 the 3GPP LTE RAN and spectrum allocation highlight specifications are summarized. Those specifications give an overall view of the performance that 3G LTE is offering. It also provides significant improvements in the use of the available spectrum. Furthermore, all this improvements within the LTE RAN are presented in more details, together with the LTE spectrum allocations.

The LTE radio transmission and reception specifications are documented in 36.101 [6] for the UE and 36.104 [7] for the eNB (base station). As it is well known, the LTE air interface supports both FDD and time division duplex (TDD) modes, each of which has its own frame structure.

Table 2.2. 3GPP LTE highlight specifications

Parameter	Details
Peak downlink speed 64QAM (Mbps)	100 (SISO), 172 (2x2 MIMO), 326 (4x4 MIMO)
Peak uplink speeds (Mbps)	50 (QPSK), 57 (16QAM), 86 (64QAM)
Data type	All packet switched data (voice and data). No circuit switched.
Channel bandwidths (MHz)	1.4, 3, 5, 10, 15, 20
Duplex schemes	FDD and TDD
Mobility	0 - 15 km/h (optimised), 15 - 120 km/h (high performance)
Latency	Idle to active less than 100ms Small packets ~10 ms
Spectral efficiency	Downlink: 3 - 4 times Rel 6 HSDPA Uplink: 2 -3 x Rel 6 HSUPA
Access schemes	OFDMA (Downlink) SC-FDMA (Uplink)
Channel coding	Turbo code
Modulation types supported	QPSK, 16QAM, 64QAM (Uplink and downlink)
Other techniques	Channel sensitive scheduling, link adaptation, power control, ICIC and hybrid ARQ

Additional access modes may be defined, and half-duplex FDD is being considered. Half-duplex FDD allows the sharing of hardware between the uplink and downlink since the uplink and downlink are never used simultaneously. This technique has uses in some frequency bands and also offers a cost saving while halving potential data rates. Moreover, as we mention at the beginning of this section, downlink and uplink transmission in LTE are based on the use of multiple access technologies: specifically, orthogonal frequency division multiple access (OFDMA) for the downlink, and single-carrier frequency division multiple access (SC-FDMA) for the uplink.

The downlink is considered first. OFDMA is a variant of orthogonal frequency division multiplexing (OFDM), a digital multi-carrier modulation scheme that is widely used in wireless systems but relatively new to cellular. Rather than transmit a high-rate stream of data with a single carrier, OFDM makes use of a large number of closely spaced orthogonal subcarriers that are transmitted in parallel. Each subcarrier is modulated with a conventional modulation scheme (such as QPSK, 16QAM, or 64QAM) at a low symbol rate. The combination of hundreds or thousands of subcarriers enables data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

The diagram in Figure 2.4 taken from TR 25.892 illustrates the key features of an OFDM signal in frequency and time. In the frequency domain, multiple adjacent tones or subcarriers are each independently modulated with data. Then in the time domain, guard intervals are inserted between each of the symbols to prevent inter-symbol interference at the receiver caused by multi-path delay spread in the radio channel.

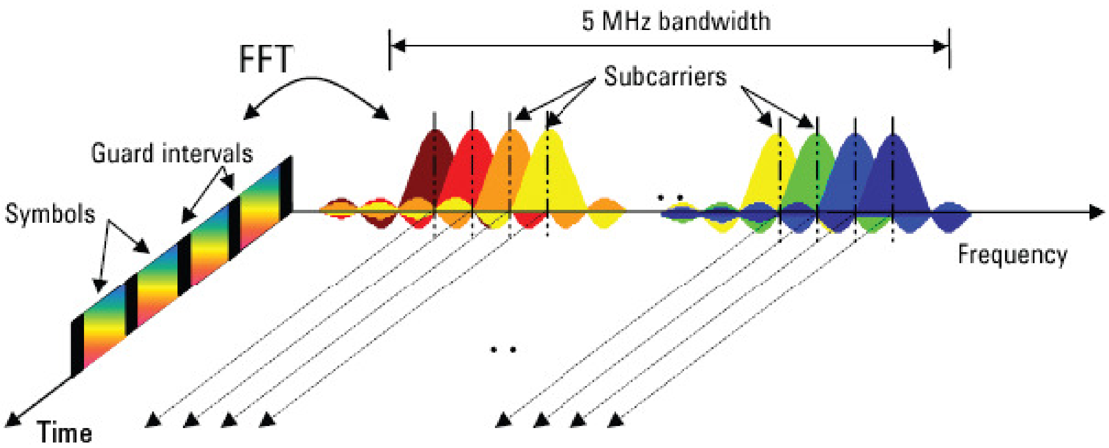


Figure 2.4. OFDM signal represented in frequency and time.

When compared to the CDMA technology upon which UMTS is based, OFDM o ffers a number of distinct advantages:

- ✓ OFDM can easily be scaled up to wide channels that are more resistant to fading.
- ✓ OFDM channel equalizers are much simpler to implement than are CDMA equalizers, as the OFDM signal is represented in the frequency domain rather than the time domain.
- ✓ OFDM can be made completely resistant to multi-path delay spread. This is possible because the long symbols used for OFDM can be separated by a guard interval known as the cyclic prefix (CP). The CP is a copy of the end of a symbol inserted at the beginning. By sampling the received signal at the optimum time, the receiver can remove the time domain interference between adjacent symbols caused by multi-path delay spread in the radio channel.
- ✓ OFDM is better suited to MIMO. The frequency domain representation of the signal enables easy precoding to match the signal to the frequency and phase characteristics of the multi-path radio channel.

However, OFDM does have some disadvantages. The subcarriers are closely spaced making OFDM sensitive to frequency errors and phase noise. For the same reason, OFDM is also sensitive to Doppler shift, which causes interference between the subcarriers. Pure OFDM also creates high peak-to-average signals, and that is why a modification of the technology called SC-FDMA is used in the uplink.

A mathematical description of an SC-FDMA symbol in the time domain is given in [9] sub-clause 5.6. A brief description is as follows: data symbols in the time domain are converted to the frequency domain using a discrete Fourier transform (DFT); then in the frequency domain they are mapped to the desired location in the overall channel bandwidth before being converted back to the time domain using an inverse FFT (IFFT). Finally, the CP is inserted. Because SC-FDMA uses this technique, it is sometimes called discrete Fourier transform spread OFDM or (DFT-SOFDM).

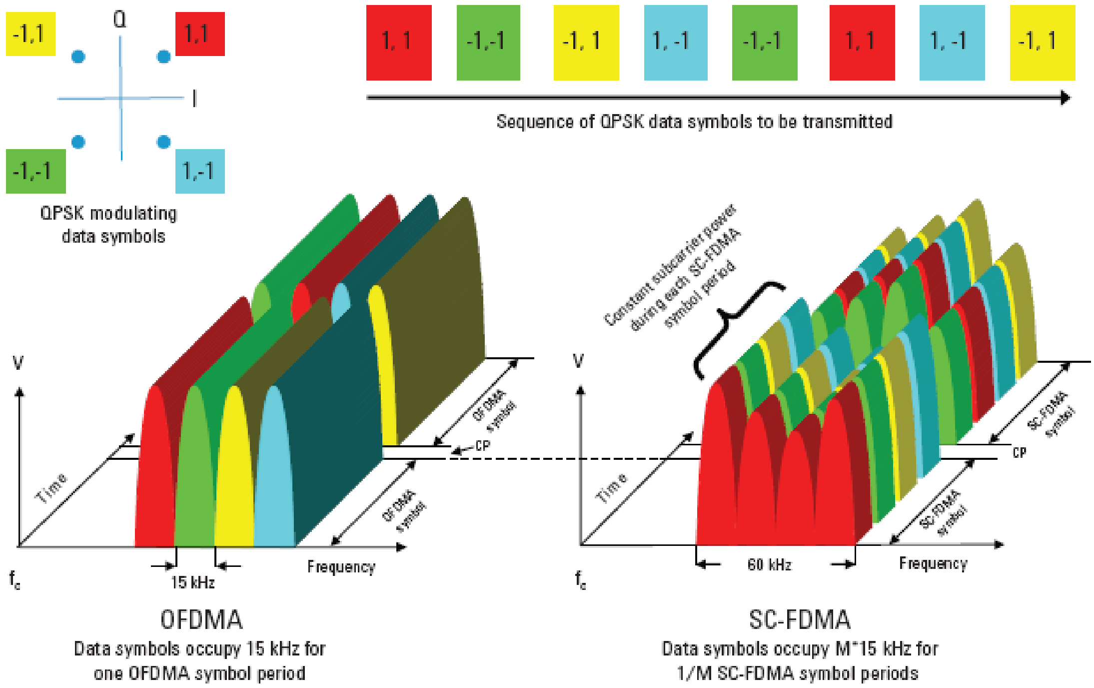


Figure 2.5. Comparison of OFDMA and SC-FDMA transmitting a series of QPSK data symbols.

A graphical comparison of OFDMA and SC-FDMA as shown in Figure 2.5 is helpful in understanding the differences between these two modulation schemes. For clarity this example uses only four (M) subcarriers over two symbol periods with the payload data represented by quadrature phase shift keying (QPSK) modulation. As described earlier, real LTE signals are allocated in units of 12 adjacent subcarriers. On the left side of Figure 2.5, M adjacent 15 kHz subcarriers—already positioned at the desired place in the channel bandwidth—are each modulated for the OFDMA symbol period of 66.7 μs by one QPSK data symbol. In this four subcarrier example, four symbols are taken in parallel. These are QPSK data symbols so only the phase of each subcarrier is modulated and the subcarrier power remains constant between symbols. After one OFDMA symbol period has elapsed, the CP is inserted and the next four symbols are transmitted in parallel.

For visual clarity, the CP is shown as a gap; however, it is actually filled with a copy of the end of the next symbol, which means that the transmission power is continuous but has a phase discontinuity at the symbol boundary. To create the transmitted signal, an IFFT is performed on each subcarrier to create M timedomain signals. These in turn are vector-summed to create the final time-domain waveform used for transmission. SC-FDMA signal generation begins with a special precoding process but then continues in a manner similar to OFDMA.

However, before getting into the details of the generation process it is helpful to describe the end result as shown on the right side of Figure 2.5. The most obvious difference between the two schemes is that OFDMA transmits the four QPSK data symbols in parallel, one per subcarrier, while SC-FDMA transmits the four QPSK data symbols in series at four times the rate, with each data symbol occupying M x 15 kHz bandwidth.

Visually, the OFDMA signal is clearly multi-carrier with one data symbol per subcarrier, but the SC-FDMA signal appears to be more like a single-carrier (hence the "SC" in the SC-FDMA name) with each data symbol being represented by one wide signal. Note that OFDMA and SC-FDMA symbol lengths are the same at 66.7 μs; however, the SC-FDMA symbol contains M "sub-symbols" that represent the modulating data. It is the parallel transmission of multiple symbols that creates the undesirable high PAR of OFDMA. By transmitting the M data symbols in series at M times the rate, the SC-FDMA occupied bandwidth is the same as multi-carrier OFDMA but, crucially, the PAR is the same as that used for the original data symbols. Adding together many narrowband QPSK waveforms in OFDMA will always create higher peaks than would be seen in the wider-bandwidth, single-carrier QPSK waveform of SC-FDMA. As the number of subcarriers M increases, the PAR of OFDMA with random modulating data approaches Gaussian noise statistics but, regardless of the value of M, the SC-FDMA PAR remains the same as that used for the original data symbols.

MIMO, Multiple Input Multiple Output is another of the LTE major technology innovations used to improve the performance of the system. This technology provides LTE with the ability to further improve its data throughput and spectral efficiency above that obtained by the use of OFDM.

Although MIMO adds complexity to the system in terms of processing and the number of antennas required, it enables far high data rates to be achieved along with much improved spectral efficiency. As a result, MIMO has been included as an integral part of LTE.

Seven multiple antenna transmission modes have been defined for LTE to optimize **downlink** performance under varying radio conditions:

1. Single-antenna port; port 0—SIMO
2. Transmit diversity—MISO
3. Open-loop spatial multiplexing—MIMO, no precoding
4. Closed-loop spatial multiplexing—MIMO, precoding
5. Multi-user MIMO—MIMO, separate UE
6. Closed-loop Rank = 1 precoding—MISO, beamsteering
7. Single-antenna port; port 5—MISO, beamsteering

The first mode uses only one transmitter, and since the UE must have at least two receivers, this is a SIMO configuration, better known as, receive diversity. This mode specifies the baseline receiver capability for which performance requirements will be defined. It is typically implemented using maximum ratio combining of the received streams to improve the SNR in poor conditions. Rx diversity provides little gain in good conditions.

The second downlink mode, Tx diversity, is identical in concept to the open-loop Tx diversity introduced in UMTS Release 99. The more complex, closed-loop Tx diversity techniques from UMTS have not been adopted in LTE, which instead uses the more advanced MIMO, which was not part of Release 99. LTE supports either two or four antennas for Tx diversity.

The third downlink mode is open-loop MIMO spatial multiplexing, which is supported for two and four antenna configurations. Assuming a two-channel UE receiver, this scheme allows for 2x2 or 4x2 MIMO. A four-channel UE receiver, which is required for a 4x4 configuration, has been defined but is not likely to be implemented in the near future. The most common configuration will be 2x2 or 4x2 SU-MIMO. The open-loop designation refers to the fact that there is no precoding of the streams, which are instead directly mapped to each antenna. However, the UE-preferred rank and the channel quality indicator (CQI) are used to adapt to the channel, which is a form of closed-loop feedback.

The fourth mode is closed-loop MIMO, which requires precoding of the data streams. Depending on the precoding used, each code word is represented at different powers and phases on the antennas. For the FDD case the transmitter must have knowledge of the channel, which is provided by the UE on the uplink control channel. This knowledge consists of the CQI, the precoding matrix Indicator (PMI), and the rank indication (RI). The PMI feedback uses a codebook approach to provide an index into a predetermined set of precoding matrices. For 2x2 there are three different codewords; for 4x2 there are 16 codewords. Since the channel is continually changing, sub-band CQI and PMI information can be provided for multiple points across the channel bandwidth, at regular time intervals, up to several hundred times a second. The RI is only provided wideband for the whole channel. The UE that can best estimate the channel conditions and then signal the best coding to use will get the best performance out of the channel. Although the use of a codebook for precoding limits the best fit to the channel, it significantly simplifies the channel estimation process by the UE and the amount of uplink signaling needed to convey the desired precoding.

The fifth transmission mode is MU-MIMO. This is a special case of mode 3 in which the codewords are destined for different UE. Closed-loop MU-MIMO does not apply in this case.

The sixth downlink transmission mode is a form of beamsteering, described here as Closed-loop Rank = 1 precoding and is the fall-back mode when mode 4 reports Rank = 1. Conventional phased-array beamsteering, which can be applied independent of the radio standard, introduces phase and amplitude offsets to the whole of the signal feeding each transmitting antenna. The intention is to focus the signal power in a particular direction. The same technique of applying phase and amplitude offsets can be used on the receiving antennas to make the receiver more sensitive to signals coming from a particular direction. In LTE, the amplitude and phase of individual RBs can be adjusted, making beamsteering far more flexible. In addition to the conventional beamsteering methods, with the sixth transmission mode, beamsteering is implemented by taking advantage of the closed-loop precoding similar to that used for MIMO. Since Rank = 1, only one codeword is used for beamsteering, and the purpose of the precoding function is to correlate the signals from each transmitter towards the receiver of an individual user. Beamsteering does not increase data rates but has a similar effect of increasing signal robustness. The effectiveness of beamsteering increases with the number of transmitting antennas, which allows for the creation of a narrower beam. The gains possible with only two antennas are generally not considered worthwhile and so beamsteering generally is considered only for the four-antenna option.

The seventh and final transmission mode is another form of beamsteering. It is similar to mode 6 except that an additional antenna (port 5) is used to form a dedicated beam towards the UE which also carries a UE-specific beamformed reference signal.

One of the challenges in supporting both MIMO and beamsteering is that conflicting constraints are put on the design of the antennas. Beamsteering relies on correlation of the transmitted signals whereas MIMO relies on de-correlation, reportedly performing best with cross-polarized antennas.

On the other hand, three types of multiple antenna techniques are defined for the **uplink** LTE:

1. Receive diversity at the eNB
2. SU-MIMO for single UE
3. MU-MIMO for multiple UE

Received diversity was described before.

SU-MIMO is within the scope of LTE but is not fully defined in 3GPP Release 8. To implement SU-MIMO the UE will require two transmitters. This is a significant challenge in terms of cost, size, and battery consumption, and for these reasons SU-MIMO is not currently a priority for development. Also, the increased data rates in the uplink that might be possible from SU-MIMO are not as important as they are in the downlink due to asymmetrical traffic distribution. Furthermore, if the system is deployed to be uplink-performance-limited, it may be impractical to increase the transmit power from the UE sufficiently to achieve the SNR needed at the eNB receivers.

While MU-MIMO does not increase an individual user’s data rate, it does offer cell capacity gains that are similar to, or better than, those provided by SU-MIMO. In Figure 2.6, the two data streams originate from different UE. The two transmitters are much farther apart than in the single user case, and the lack of physical connection means that there is no opportunity to optimize the coding to the channel Eigen modes by mixing the two data streams. However, the extra spatial separation does increase the chance of the eNB picking up pairs of UE which have uncorrelated paths. This maximizes the potential capacity gain, in contrast to the precoded SU-MIMO case in which the closeness of the antennas could be problematic, especially at frequencies less than 1 GHz. MU-MIMO has an additional important advantage: the UE does not require the expense and power drain of two transmitters, yet the cell still benefits from increased capacity. To get the most gain out of MU-MIMO, the UE must be well aligned in time and power as received at the eNB.

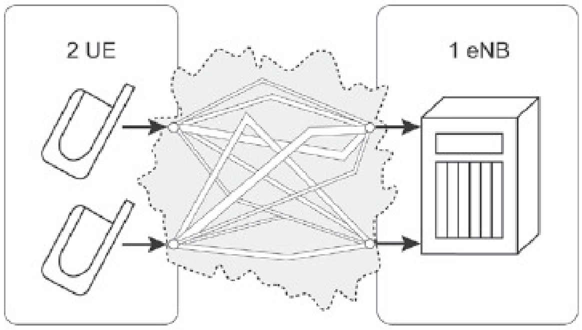


Figure 2.6. Multi-user MIMO in the uplink.

Moreover, Figure 2.7 from 36.201 [10] shows the E-UTRA radio interface protocol architecture around the physical layer (Layer 1). The physical layer provides data transport services to the higher layers. These services are accessed through transport channels via the MAC sub-layer. The physical layer provides transport channels to the Layer 2 MAC sub-layer, and the MAC sub-layer provides logical channels to the Layer 2 radio link control (RLC) sub-layer. Transport channels are characterized by how the information is transferred over the radio interface, whereas logical channels are characterized by the type of information transferred. In the Figure 2.7 diagram, the circles between different layers or sub-layers indicate service access points (SAPs). Layer 1 also interfaces to the Layer 3 radio resource control (RRC) layer.

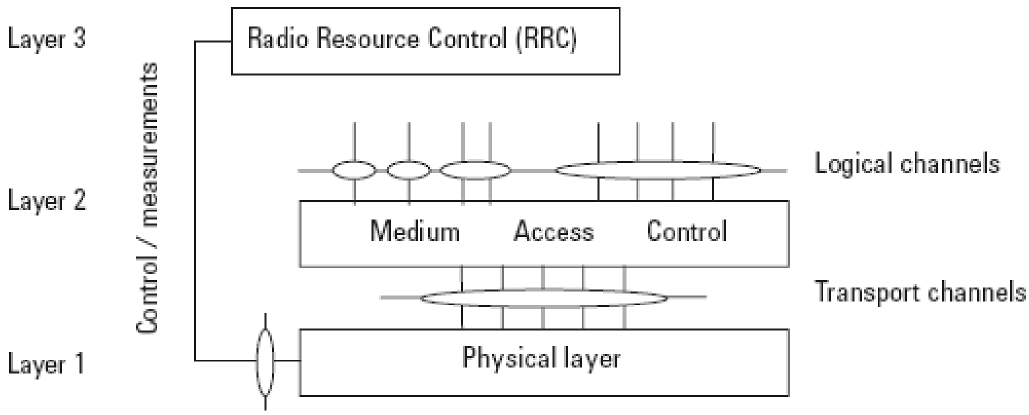


Figure 2.7. LTE radio interface protocol architecture around the physical layer.

In order to enable data transport service to the higher layers, the physical layer performs a series of functions that include the following:

- ✓ Error detection on the transport channels.
- ✓ Forward error correction (FEC) encoding/decoding of the transport channels.
- ✓ Hybrid automatic repeat request (HARQ) soft-combining.
- ✓ Rate matching and mapping of coded transport channels to physical channels.
- ✓ Power weighting of physical channels.
- ✓ Modulation and demodulation of physical channels.

- ✓ Frequency and time synchronization.
- ✓ Radio characteristics measurements and indication to higher layers.
- ✓ MIMO antenna processing.
- ✓ Transmit diversity.
- ✓ Beamsteering.
- ✓ RF processing.

The allowed signal and channel modulation schemes for the downlink and uplink are shown in Table 2.3. Detailed specifications for the physical signals and channels, along with their modulation and mapping, are documented throughout [9] and [10].

Table 2.3. Modulation schemes for the LTE downlink and uplink.

Downlink	
Downlink channels	**Modulation scheme**
PBCH	QPSK
PDCCH	QPSK
PDSCH	QPSK, 16QAM, 64QAM
PMCH	QPSK, 16QAM, 64QAM
PCFICH	QPSK
PHICH	BPSK modulated on I and Q with the spreading factor 2 or 4 Walsh codes
Physical signals	**Modulation scheme**
RS	Complex I+jQ pseudo random sequence (length-31 Gold sequence) derived from cell ID
Primary synchronization	One of three Zadoff-Chu sequences
Secondary synchronization	Two 31-bit BPSK M-sequence
Uplink	
Physical channels	**Modulation scheme**
PUCCH	BPSK, QPSK
PUSCH	QPSK, 16QAM, 64QAM
PRACH	uth root Zadoff-Chu
Physical signals	**Modulation scheme**
Demodulation RS	Zadoff-Chu
Sounding RS	Based on Zadoff-Chu

The LTE air interface also supports the multimedia broadcast and multicast service (MBMS), a relatively new technology for broadcasting content such as digital TV to UE using point-to-multi-point connections. The 3GPP specifications for MBMS first appeared for UMTS in Release 6. LTE will specify a more advanced evolved MBMS (eMBMS) service, which operates over a multicast/broadcast over single-frequency network (MBSFN) using a time-synchronized common waveform that can be transmitted from multiple cells for a given duration. The MBSFN allows over-the-air combining of multi-cell transmissions in the UE, using the cyclic prefix (CP) to cover the difference in the propagation delays. To the UE, the transmissions appear to come from a single large cell. This technique makes LTE highly efficient for MBMS transmission. The eMBMS service will be fully defined in Release 9 of the 3GPP specifications.

Moreover, LTE must support the international wireless market and regional spectrum regulations and spectrum availability. To this end the specifications include variable channel bandwidths selectable from 1.4 to 20 MHz, with subcarrier spacing of 15 kHz. If the new LTE eMBMS is used, a subcarrier spacing of 7.5 kHz is also possible. Subcarrier spacing is constant regardless of the channel bandwidth. 3GPP has defined the LTE air interface to be “bandwidth agnostic,” which allows the air interface to adapt to different channel bandwidths with minimal impact on system operation. The smallest amount of resource that can be allocated in the uplink or downlink is called a resource block (RB). An RB is 180 kHz wide and lasts for one 0.5 ms timeslot. For standard LTE, an RB comprises 12 subcarriers at a 15 kHz spacing, and for eMBMS with the optional 7.5 kHz subcarrier spacing an RB comprises 24 subcarriers for 0.5 ms. The maximum number of RBs supported by each transmission bandwidth is given in Table 2.4.

Table 2.4. Transmission bandwidth configuration (based on [6] Table 5.6-1)

Channel bandwidth (MHz)	1.4	3	5	10	15	20
Transmission bandwidth configuration (MHz)	1.08	2.7	4.5	9	13.5	18
Transmission bandwidth configuration (RB)	6	15	25	50	75	100

The LTE specifications inherit all the frequency bands defined for UMTS, which is a list that continues to grow. There are at the time of this writing 15 FDD operating bands and 8 TDD operating bands. Significant overlap exists between some of the bands, but this does not necessarily simplify designs since there can be band-specific performance requirements based on regional needs. There is no consensus on which band LTE will first be deployed, since the answer is highly dependent on local variables. This lack of consensus is a significant complication for equipment manufacturers and contrasts with the start of GSM and W-CDMA, both of which were specified for only one band. What is now firmly established is that one may no longer assume that any particular band is reserved for any one access technology. In Table 2.5, the E-UTRA operating bands ([6] Table 5.5-1) is given.

FDD spectrum requires pair bands, one of the uplink and one for the downlink, and TDD requires a single band as uplink and downlink are on the same frequency but time separated. As a result, there are different LTE band allocations for TDD and FDD. In some cases these bands may overlap, and it is therefore feasible, although unlikely that both TDD and FDD transmissions could be present on a particular LTE frequency band. The greater likelihood is that a single UE or mobile will need to detect whether a TDD or FDD transmission should be made on a given band. UEs that roam may encounter both types on the same band. They will therefore need to detect what type of transmission is being made on that particular LTE band in its current location.

As we can notice from Table 2.5, the different LTE frequency allocations or LTE frequency bands are allocated numbers. Currently the LTE bands between 1 & 22 are for paired spectrum, i.e. FDD, and LTE bands between 33 & 40 are for unpaired spectrum, i.e. TDD.

The number of bands allocated for use has increased as the pressure increases on spectrum. It has not been possible for all LTE band allocations to be the same across the globe because of the different regulatory positions in different countries. It has not been possible to gain global allocations. As we mentioned before, in some cases bands appear to overlap. This is because of the different levels of availability around the globe. This means that roaming with LTE may have some limitations as not all handsets or UEs will be able to access the same frequencies.

Table 2.5. E-UTRA operating bands.

E-UTRA operating band	Uplink (UL) operating band BS receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex mode
	$F_{UL\_low} - F_{UL\_high}$	$F_{DL\_low} - F_{DL\_high}$	
1	1920 – 1980 MHz	2110 – 2170 MHz	FDD
2	1850 – 1910 MHz	1930 – 1990 MHz	FDD
3	1710 – 1785 MHz	1805 – 1880 MHz	FDD
4	1710 – 1755 MHz	2110 – 2155 MHz	FDD
5	824 – 849 MHz	869 – 894 MHz	FDD
6	830 – 840 MHz	875 – 885 MHz	FDD
7	2500 – 2570 MHz	2620 – 2690 MHz	FDD
8	880 – 915 MHz	925 – 960 MHz	FDD
9	1749.9 – 1784.9 MHz	1844.9 – 1879.9 MHz	FDD
10	1710 – 1770 MHz	2110 – 2170 MHz	FDD
11	1427.9 – 1452.9 MHz	1475.9 – 1500.9 MHz	FDD
12	698 – 716 MHz	728 – 746 MHz	FDD
13	777 – 787 MHz	746 – 756 MHz	FDD
14	788 – 798 MHz	758 – 768 MHz	FDD
...			
17	704 – 716 MHz	734 – 746 MHz	FDD
...			
33	1900 – 1920 MHz	1900 – 1920 MHz	TDD
34	2010 – 2025 MHz	2010 – 2025 MHz	TDD
35	1850 – 1910 MHz	1850 – 1910 MHz	TDD
36	1930 – 1990 MHz	1930 – 1990 MHz	TDD
37	1910 – 1930 MHz	1910 – 1930 MHz	TDD
38	2570 – 2620 MHz	2570 – 2620 MHz	TDD
39	1880 – 1920 MHz	1880 – 1920 MHz	TDD
40	2300 – 2400 MHz	2300 – 2400 MHz	TDD

2.3. System Architecture Evolution (SAE) and Evolved Packet Core (EPC)

Along with 3G LTE - Long Term Evolution that applies more to the radio access technology of the cellular telecommunications system, there is also an evolution of the core network - branded as System Architecture Evolution (**SAE**). 3GPP has proposed a framework to evolve the 3GPP system to a higher data rate, lower latency, packet-optimized packet core system (Evolved Packet Core (**EPC**)) that supports multiple access technologies, including 3GPP Internet Protocol Connectivity Access Network (IP CANs) like GSM EDGE Radio Access Network (GERAN), UTRAN and Evolved UTRAN (E-UTRAN) and non-3GPP IP CANs like WiFi, WiMAX and even wired technologies. This access independent evolution of the packet core system architecture is the first major step towards the realization of an All IP Network (AIPN) and also it is fully compatible with LTE Advanced, the new 4G technology.

The new SAE network is based upon the GSM / WCDMA core networks to enable simplified operations and easy deployment. Despite this, the SAE network brings in some major changes, and allows far more efficient and effect transfer of data. Moreover, there are several common principles used in the development of the LTE SAE network:

- ✓ a common gateway node and anchor point for all technologies.
- ✓ an optimised architecture for the user plane with only two node types.
- ✓ an all IP based system with IP based protocols used on all interfaces.
- ✓ a split in the control / user plane between the MME, mobility management entity and the gateway.
- ✓ a radio access network / core network functional split similar to that used on WCDMA / HSPA.
- ✓ integration of non-3GPP access technologies (e.g. cdma2000, WiMAX, etc) using client as well as network based mobile-IP.

The main element of the LTE SAE network is what is termed the Evolved Packet Core or EPC. This connects to the eNodeBs. Moreover, the Figure 2.8 illustrates the functional decomposition of the Evolved Packet Core for 3GPP and non-3GPP IP CAN. It is also possible that one physical network element in the EPC implements multiple logical nodes. Also, in Figure 2.9 is given a detail illustration of EPC/SAE architecture.

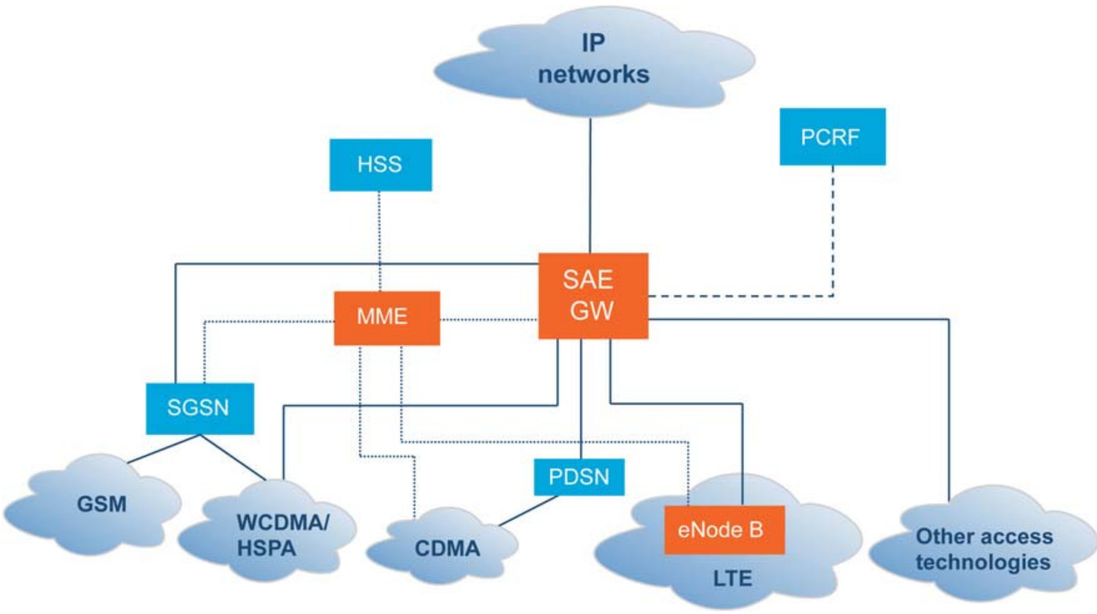


Figure. 2.8. EPC/SAE architecture.

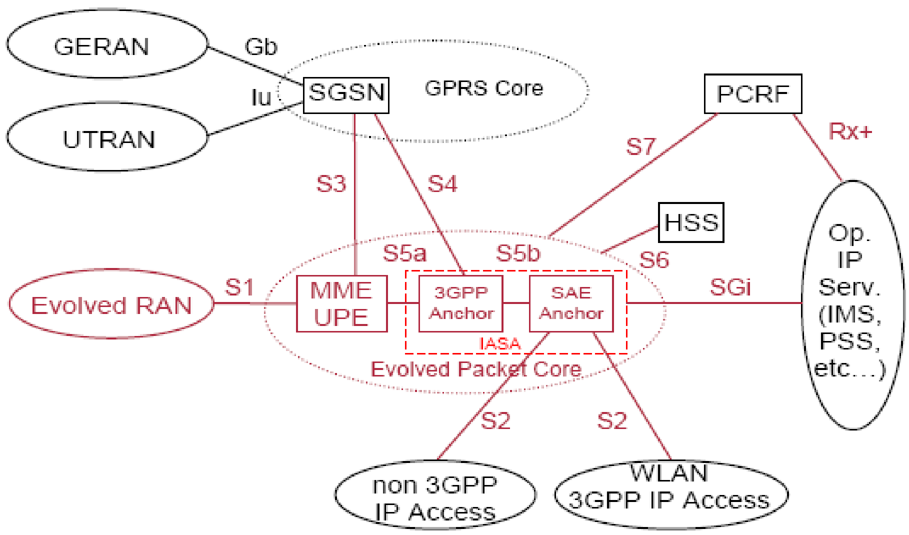


Figure. 2.9. EPC/SAE architecture: baseline.

As seen within the above two figures, the LTE SAE Evolved Packet Core, consists of four main elements as listed below:

- **Mobility Management Entity, MME**: The MME is the main control node for the LTE SAE access network, handling a number of features:
  - Idle mode UE tracking
  - Bearer activation / de-activation
  - Choice of SGW for a UE
  - Intra-LTE handover involving core network node location
  - Interacting with HSS to authenticate user on attachment and implements roaming restrictions

- It acts as a termination for the Non-Access Stratum (NAS)
- Provides temporary identities for UEs
- The SAE MME acts the termination point for ciphering protection for NAS signaling. As part of this it also handles the security key management. Accordingly the MME is the point at which lawful interception of signalling may be made.
- Paging procedure
- The S3 interface terminates in the MME thereby providing the control plane function for mobility between LTE and 2G/3G access networks.

The SAE MME also terminates the S6a interface for the home HSS for roaming UEs. It can therefore be seen that the SAE MME provides a considerable level of overall control functionality.

- **Serving Gateway, SGW**: The Serving Gateway, SGW, is a data plane element within the LTE SAE. Its main purpose is to manage the user plane mobility and it also acts as the main border between the Radio Access Network, RAN and the core network. The SGW also maintains the data paths between the eNodeBs and the PDN Gateways. In this way the SGW forms a interface for the data packet network at the E-UTRAN.

  Also when UEs move across areas served by different eNodeBs, the SGW serves as a mobility anchor ensuring that the data path is maintained.
- **PDN Gateway, PGW**: The LTE SAE PDN gateway provides connectivity for the UE to external packet data networks, fulfilling the function of entry and exit point for UE data. The UE may have connectivity with more than one PGW for accessing multiple PDNs.
- **Policy and Charging Rules Function, PCRF**: This is the generic name for the entity within the LTE SAE EPC which detects the service flow, enforces charging policy. For applications that require dynamic policy or charging control, a network element entitled the Applications Function, AF is used.

In order that requirements for increased data capacity and reduced latency can be met, along with the move to an all-IP network, it is necessary to adopt a new approach to the network structure. For 3G UMTS / WCDMA the UTRAN (UMTS Terrestrial Radio Access Network, comprising the Node B's or basestations and Radio Network Controllers) employed low levels of autonomy. The Node Bs were connected in a star formation to the Radio Network Controllers (RNCs) which carried out the majority of the management of the radio resource. In turn the RNCs connected to the core network and connect in turn to the Core Network.

To provide the required functionality within LTE SAE, the basic system architecture sees the removal of a layer of management. The RNC is removed and the radio resource management is devolved to the base-stations. The new style base-stations are called eNodeBs or eNBs.

The eNBs are connected directly to the core network gateway via a newly defined "S1 interface". In addition to this the new eNBs also connect to adjacent eNBs in a mesh via an "X2 interface". This provides a much greater level of direct interconnectivity. It also enables many calls to be routed very directly as a large number of calls and connections are to other mobiles in the same or adjacent cells. The new structure allows many calls to be routed far more directly and with only minimum interaction with the core network.

In addition to the new Layer 1 and Layer 2 functionality, eNBs handle several other functions. This includes the radio resource control including admission control, load balancing and radio mobility control including handover decisions for the mobile or user equipment (UE). The additional levels of flexibility and functionality given to the new eNBs mean that they are more complex than the UMTS and previous generations of base-station. However the new 3G LTE SAE network structure enables far higher levels of performance. In addition to this their flexibility enables them to be updated to handle new upgrades to the system including the transition from 3G LTE to 4G LTE Advanced.

Moreover, The EPC specifies two types of IP-IP Gateway logical functions for the user plane – the Serving Gateway (S-GW) and the PDN Gateway (P-GW). The S-GW and P-GW are core network functions of the E-UTRAN based access. They may be implemented in one physical node or in separate physical nodes. Early deployments are likely to see a single node implementation of S-GW and P-GW functions with future proof design to decouple these functions such that S-GWs in visited networks can connect to P-GWs of home networks for home PLMN routed IP services.

As shown in Figure 2.10, both the S-GW and P-GW are built on core datacom routing and switching technologies supporting the Layer 2 and Layer 3 suite of an All IP Network. Therefore, it is anticipated that the S-GW and P-GW are logical migration and evolution paths for the traditional IP-IP Gateway product lines. Each IP-IP Gateway vendor will have their own hardware and platform USP that supports line-rate switching and packet forwarding with very low latency of high volume IP traffic. There exists a striking similarity between the S-GW and P-GW functions. Other than the commonality at the core datacom layer, they both act as the Policy Enforcement Points (PEP) for dynamic QoS policies. While the S-GW is dedicated to policy and QoS enforcement at packet level, the P-GW functions as the PEP at the service level. On the charging front, both the S-GW and P-GW have a role to play. While the S-GW is involved in generating charging records at packet level, the P-GW takes up the responsibility for producing charging records at service level. Deep Packet Inspection and Legal Intercept are dedicated functions of the P-GW, but nothing prevents the S-GW from implementing these functions as well. Given that the S-GW is the direct interface point for E-UTRAN eNodeB (S1-U interface), functions such as inter-E-UTRAN mobility anchoring for the user plane (coordinating with the MME) and eNodeB packet reordering are exclusively meant for S-GW implementation. Since the S-GW directly interfaces with the GERAN and UTRAN networks (S4 and S12 interfaces), it also acts as the anchor point for inter-3GPP RAT mobility.

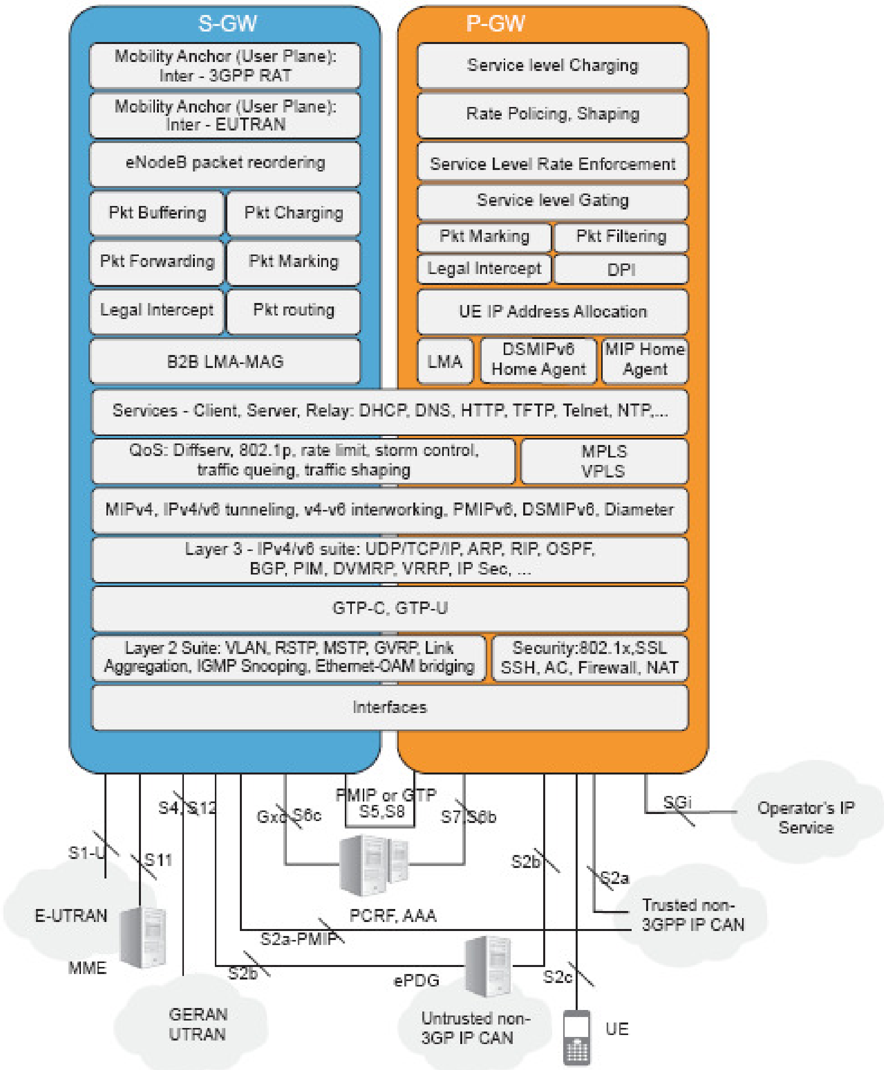


Figure. 2.10. SAE Gateway (S-GW) and PDN Gateway (P-GW) Architecture.

The P-GW on the other hand is primarily responsible for the IP address allocation of the UE in the AIPN and acts as the anchor point for mobility across the non-3GPP IP-CANs (for both trusted and non-trusted). For network based mobility, the P-GW acts as the Gateway Local Mobility Anchor (LMA) terminating Proxy Mobile IPv6 (PMIPv6) for the control signaling and IPv4/IPv6 tunneling for the user plane. This corresponds to the S2a and S2b interfaces for the trusted and non-trusted non-3GPP IP-CAN respectively, where the non-3GPP IP-CANs directly terminate into the P-GW, bypassing the S-GW (as in the case of the non roaming architecture for EPS or home routed architecture or the case of local breakout within the visited PLMN). The trusted or non-trusted non-3GPP IP-CAN typically emulates the MAG function of the network based mobility architecture. For deployment architectures where the S-GW is in the path of the chained home routed solution, the S-GW additionally plays the role of a back-to-back Gateway LMA and MAG function. In such scenarios, the S2a and S2b interfaces from the trusted and non-trusted non-3GPP IP-CAN respectively, are routed to the P-GW via the S-GW.

There are **two deployment models** to address host-based mobility. In the first deployment model, the S2a and S2b interfaces are based on MIPv4 technology. The P-GW acts as a MIPv4 Home Agent and the trusted and non-trusted non-3GPP IP-CAN provide the Foreign Agent function for the Mobile Node (the UE). The user plane is based on the tunneling of end-to-end IPv4 over transport IPv4. The second deployment model assumes that the UE is capable of acting as a DSMIPv6 client and the P-GW is the DSMIPv6 Home Agent. All other nodes in the network are IP Access router systems. This deployment model applies to both 3GPP and non-3GPP IP-CANs (the S2c interface between the UE and the P-GW). The formal interface between the S-GW and the P-GW is called S5 (where S-GW and P-GW are within the same PLMN) and S8 (where S-GW belongs to visited PLMN and the P-GW to the home PLMN). The S5 and S8 interfaces are otherwise functionally similar. There are two protocol options for these interfaces. The first option is to support GTP tunnels between S-GW and P-GW, GTP-C for control signaling and IP tunneling over GTP-U for the user plane. This typically applies to 3GPP access deployments, where the S-GW acts as a GTP-U relay between the 3GPP access network and the P-GW. If the UE over the 3GPP access network supports DSMIPv6, then it is possible to run the S2c interface over GTP over the P-GW and S-GW connection.

The second deployment model allows PMIPv6 to run as the control signaling protocol on the S5 and S8 interfaces. For 3GPP access, this implies that the S-GW terminates the GTP-U tunnels and tunnels user IP over transport IP towards P-GW. Initial deployments will possibly start with non-roaming architectures, with the S-GW and P-GW interface being initially S5 focused. Additionally, equipment vendors will be looking into collapsed S-GW and P-GW functions within a single physical node. Hence, vendors are likely to start implementing the S5 interface as proprietary lightweight implementations. However, the interface design must be future proof to make a way for the more formal S5 interface and to evolve to the S8 interface for decoupled S-GW and P-GW solutions, as operators start insisting on roaming architectures and home PLMN routed IP services.

Both the S-GW and P-GW will have Diameter interfaces towards network hosted Policy and Charging Rules Functions (PCRFs) and Service-based Policy Decision Functions (SPDFs)/Radio Access Control Functions (RACFs). The Diameter based Gxc and S7 interfaces control the Policy and Charging Enforcement Function (PCEF) within the S-GW and P-GW functions. It is also likely that the operator network may not have a centralized Policy Decision Point – in this case the S-GW and P-GW must be in a position to accept dynamic policy and QoS decisions from distributed PDPs in the network after implementing a local PDP within the Gateway for resolving policy conflicts. The Gateways must also realize the Diameter interfaces (S6b and S6c) towards external AAA functions for non-3GPP accesses.

As a conclusion we can clearly say that the new System Architecture Evolution for LTE provides a new approach for the core network, enabling far higher levels of data to be transported to enable it to support the much higher data rates that will be possible with LTE. In addition to this, other features that enable the CAPEX and OPEX to be reduced when compared to existing systems, thereby enabling higher levels of efficiency to be achieved.

2.4. Common IMS

The IP Multimedia Subsystem (**IMS**) standard defines a generic architecture for offering Voice over IP (VoIP), integration of multimedia services and providing FMC in NGN (and also in NGMWN) networks. It is an international, recognized standard, first specified by the Third Generation Partnership Project (3GPP/3GPP2, for Release 5 onwards in 2002) and now being embraced by other standards bodies including ETSI/TISPAN. Since Rel-7, 3GPP's definition of IMS has been open to access by non-cellular technologies; it has generated cooperation with groups specifying IMS for wireline applications. Moreover, in Rel-8 (LTE), 3GPP's Organizational Partners (OPs) have decided that 3GPP should be the focus for all IMS specification under their responsibility. The common IMS work is an agreement between the 3GPP OPs to migrate work on the IMS and some associated aspects to 3GPP for all access technologies. This will simplify the deployment of Fixed Mobile Convergence (FMC) solutions, minimize the risk of divergent standardization and make the standardization process more efficient.

LTE technology (Rel-8) is the **first technology** directly impacted by **Common IMS**. 3GPP is working with groups in the Ops to manage the transfer of work. SDOs outside the 3GPP OPs are, of course, not bound by the Common IMS agreement. 3GPP will continue to work with bodies like ITU-T, 3GPP2 and Cablelabs on the use of IMS specifications in their areas. The IMS standard supports multiple access types –including GSM/EDGE, WCDMA, CDMA2000, Wireline broadband access, WiMAX, LTE, LTE-Advanced and WLAN.

In other words said, IMS is an open-system architecture that supports a range of IP-based services over the PS domain, employing both wireless and fixed access technologies. The NGN IMS architecture is illustrated in Figure 2.11. IMS for NGMN (and also for IMT-Advanced) is basis for the paradigm: "My communications services-anywhere, anytime, any-terminal."

For users, IMS-based services enable person-to-person and person-to-content communications in a variety of modes – including voice, text, pictures and video, or any combination of these – in a highly personalized and controlled way. The user can connect to an IMS network in various ways, most of which use the standard Internet Protocol (IP). IMS terminals (such as mobile phones, personal digital assistants (PDAs) and computers) can register directly on an IMS network, even when they are roaming in another network or country (the visited network). The only requirement is that they can use IP and run Session Initiation Protocol (SIP) user agents. Fixed access (e.g., Digital Subscriber Line (DSL), cable modems, Ethernet), mobile access (e.g. W-CDMA, CDMA2000, GSM, GPRS, EDGE, LTE) and wireless access (e.g. WLAN, WiMAX) are all supported. Other phone systems like plain old telephone service (POTS—the old analogue telephones), H.323 and non IMS-compatible VoIP systems, are supported through gateways.

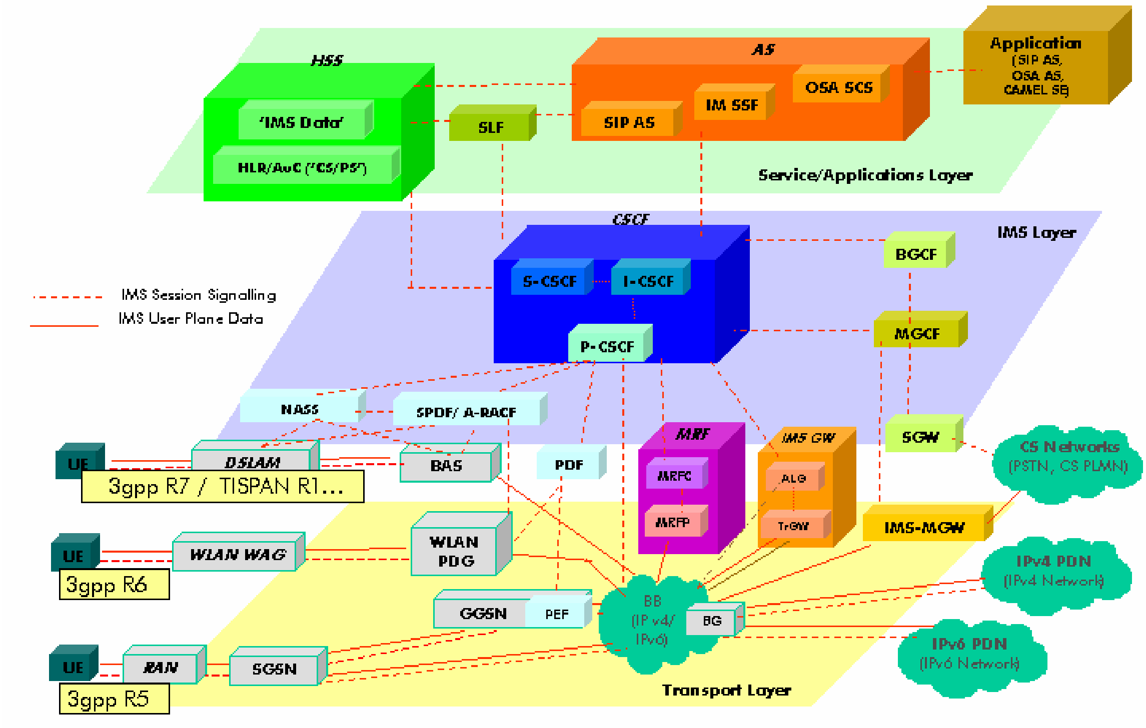


Figure 2.11 – Overview of the NGN IMS architecture.

For operators, IMS takes the concept of layered architecture one step further by defining a horizontal architecture, where service enablers and common functions can be reused for multiple applications. The horizontal architecture in IMS also specifies interoperability and roaming, and provides bearer control, charging and security. What is more, it is well integrated with existing voice and data networks, while adopting many of the key benefits of the IT domain.

This makes Common IMS a key enabler for fixed-mobile convergence (FMC). For these reasons, IMS will become preferred solution for fixed and mobile operators' multimedia business. IMS enables services to be delivered in a standardized, well-structured way that truly makes the most of layered architecture. At the same time, it provides a future-proof architecture that simplifies and speeds up the service creation and provisioning process, while enabling legacy interworking.

The horizontal architecture of IMS enables operators to move away from vertical 'stovepipe' implementations of new services – eliminating the costly and complex traditional network structure of overlapping functionality for charging, presence, group and list management, routing and provisioning.

For fixed and mobile operators there are benefits of introducing the IMS architecture today. On longer term, IMS enables a secure migration path to an all-IP architecture that will meet end-user demands for new enriched services.

According to said above, IMS provides a very good fit with the user and operator requirements outlined and will therefore be the natural technology solution. It provides an open, standardized way of using horizontal, layered network architecture. Moreover, let we see how IMS supports multimedia communications in practice, and then look at the capabilities required to deliver these capabilities. Many of the functions and enablers described in this section already exist, and are not unique to IMS: the point is that IMS provides a more user-focused, integrated way of using them.

Enriched communication and improved interaction between voice and data are important aspects to person-to-person communication. The following scenario illustrates how Common IMS enables these capabilities to help in everyday life.

> ***Scenario 1:*** While in a taxi from the airport, Anna calls her work colleague Tomas on his mobile number to discuss some issues with an important construction project. Anna activates the phone's video mode so that she can show Tomas exactly what she is talking about. Tomas views the images on his mobile while they discuss how best to move forward. The two decide that they need a little help from their colleagues back in the office. Anna selects the project work group from her buddy list, sees who is available, and initiates a push to talk group session. John and Jeff answer that they have also been thinking about the problem, and have a few ideas that they would like Anna to look at. When she gets to the hotel, Anna starts her laptop computer, opens her personal buddy list and invites Tomas, John and Jeff to join a videoconference. John opens up a presentation and shares it with his colleagues. At the start of the videoconference, Tomas is still walking back to the office and participates on his mobile phone, but swaps to his PC when he arrives at his desk a few minutes later.

This scenario shows us how simple rich communications can be when supported by IMS. It is not only technology that will dictate the evolution to these capabilities: end-user and enterprise needs will drive multimedia service demand for both mobile and fixed operators.

Let we see now, what role does IMS play in Anna's interaction with her colleagues. The interaction starts with a traditional phone call. During the conversation there is a need to show and share, and the call is enriched with video. This is a service that is based on existing behaviour and easily enriched to fulfil users' needs as they change. Anna is on the move and currently within another operator's network. This does not affect communications – she still has access to the same services, regardless of where she is. Anna can still use her buddy list and invite the predefined work group to a push to talk session. This requires the service interoperability supported by IMS. Presence and group list management are a natural part of the communication and support different services: the same buddy list is presented, regardless of service.

The services are not specific to access type or terminal. The videoconference has participants using both fixed and mobile devices. NGN IMS enables this convergence by supporting services independent of access. With pictures, images, video-telephony and combinational multimedia services, users will be able to vary their communication modes by using any combination of communications media. To make this happen, IMS is a must, in the core of NGN.

Let now go back to the IMS architecture basic overview that is shown in Figure 2.12 (simplified version of the Figure 2.10). The service/application layer comprises application and content servers to execute value-added services for the user. Generic service enablers as defined in the IMS standard (such as presence and group list management) are implemented as services in a SIP Application Server (AS). SIP Application servers (AS) host and execute services, and interface with the S-CSCF using Session Initiation Protocol (SIP). An example of an application server that is being developed in 3GPP is the Voice call continuity Function (VCC Server). Depending on the actual service, the AS can operate in SIP proxy mode, SIP UA (user agent) mode or SIP B2BUA mode. An AS can be located in the home network or in an external third-party network. If located in the home network, it can query the HSS with the Diameter Sh or Si interfaces (for a SIP-AS).

Figure 2.12 – Basic overview of the IMS architecture.

The control layer comprises network control servers for managing call or session set-up, modification and release. The most important of these is the CSCF (Call Session Control Function), also known as a SIP server. There are three types of CSCF servers: Proxy-CSCF (P-CSCF), Serving-CSCF (S-CSCF) and Interrogating-CSCF (I-CSCF).

- **P-CSCF** is a SIP proxy that is the first point of contact for the IMS terminal. It can be located either in the visited network (in full IMS networks) or in the home network (when the visited network isn't IMS compliant yet). Some networks may use a Session Border Controller for this function. The P-CSCF is at its core a specialized SBC for the User-Network Interface which not only protects the network, but also the IMS terminal. The use of additional SBC between the IMS terminal and the P-CSCF as such pointless and also not feasible due to the signalling being encrypted on this leg. The terminal discovers its P-CSCF with either DHCP, or it may be configured (e.g. during initial provisioning or via a 3GPP IMS Management Object (MO)) or in the ISIM or assigned in the PDP Context (in General Packet Radio Service (GPRS)).

- It is assigned to an IMS terminal before registration, and does not change for the duration of the registration
- it sits on the path of all signalling, and can inspect every signal; the IMS terminal must ignore any other unencrypted signalling
- it provides subscriber authentication and may establish an IPsec or TLS security association with the IMS terminal. This prevents spoofing attacks and replay attacks and protects the privacy of the subscriber.
- it inspects the signaling and ensures that the IMS terminals do not misbehave (e.g. change normal signaling routes, do not obey home network's routing policy)
- it can also compress and decompress SIP messages using SigComp, which reduces the round-trip over slow radio links it may include a Policy Decision Function (PDF), which authorizes media plane resources e.g. quality of service (QoS) over the media plane. It's used for policy control, bandwidth management, etc. The PDF can also be a separate function.
- it also generates charging records

➢ **S-CSCF** is the central node of the signalling plane. It is a SIP server, but performs session control too. It is always located in the home network. It uses Diameter Cx and Dx interfaces to the HSS to download user profiles and upload user-to-S-CSCF associations (the user profile is only cached locally for processing reasons only and is not changed). All necessary subscriber profile information is loaded from the HSS.

- it handles SIP registrations, which allows it to bind the user location (e.g. the IP address of the terminal) and the SIP address
- it sits on the path of all signaling messages of the locally registered users, and can inspect every message
- it decides to which application server(s) the SIP message will be forwarded, in order to provide their services
- it provides routing services, typically using Electronic Numbering (ENUM) lookups
- it enforces the policy of the network operator
- there can be multiple S-CSCFs in the network for load distribution and high availability reasons. It's the HSS that assigns the S-CSCF to a user, when it's queried by the I-CSCF. There are multiple options for this purpose, including a mandatory/optional capabilities to be matched between subscribers and S-CSCFs.

- **I-CSCF** is another SIP function located at the edge of an administrative domain. Its IP address is published in the Domain Name System (DNS) of the domain (using NAPTR and SRV type of DNS records), so that remote servers can find it, and use it as a forwarding point (e.g. registering) for SIP packets to this domain.
  - it queries the HSS to retrieve the address of the S-CSCF and assign it to a user performing SIP registration
  - it also forwards SIP request or response to the S-CSCF
  - Up to Release 6 it can also be used to hide the internal network from the outside world (encrypting parts of the SIP message), in which case it's called a Topology Hiding Inter-network Gateway (THIG). From Release 7 onwards this "entry point" function is removed from the I-CSCF and is now part of the Interconnection Border Control Function (IBCF). The IBCF is used as gateway to external networks, and provides NAT and Firewall functions (pinholing). The IBCF is practically a Session Border Controller specialized for the NNI.

In the IMS control layer also are contained a full suite of support functions, such as provisioning, charging and operation & management (O&M). Also, the Home Subscriber Server (HSS), or User Profile Server Function (UPSF), is in this layer, and it is a master user database that supports the IMS network entities that actually handle calls. It contains the subscription-related information (subscriber profiles), performs authentication and authorization of the user, and can provide information about the subscriber's location and IP information. It is similar to the GSM Home Location Register (HLR) and Authentication Centre (AuC). A Subscriber Location Function (SLF) is needed to map user addresses when multiple HSSs are used.

Moreover, the interworking with other operators' networks and/or other types of networks is handled by border gateways. The connectivity layer comprises routers and switches, both for the backbone and the access network.

In the pre-IMS world, services are specified and supported by a single logical node, or set of nodes, performing specialized features for the service. Each service appears as an island, with its own service-specific node(s). The only possible way to interface between services – for example, for service composition – is through protocols. In the absence of any common service framework, each service may have to be designed and implemented from scratch. On the other hand, with the introduction of the IMS architecture, many functions can be reused for fast service creation and delivery. IMS services are hosted by Application Servers, which means they are implicitly placed in the IMS application layer, and that various aspects of service control are defined. For example, IMS defines how service requests are routed, which protocols are supported, how charging is performed and how service composition is enabled. A single Application Server may host multiple services – for example, telephony and messaging. Collocation of multiple services has significant advantages, especially with regard to the loading of IMS core network nodes. Collocating services in one Application Server reduces the workload of the CSCF in the control IMS layer.

Here must be emphasize that IMS takes the concept of layered architecture one step further by defining a horizontal architecture where service enablers and common functions can be reused for multiple applications. The horizontal architecture in IMS also specifies interoperability and roaming, and provides bearer control, charging and security. The horizontal architecture of IMS enables operators to move away from traditional vertical “spaghetti” implementations of new services.

This traditional network structure – with its service-unique functionality for charging, presence, group and list management, routing and provisioning – is very costly and complex to build and maintain. Separate implementations of each layer must be built for every service in a pre-IMS network, and the structure is replicated across the network, from the terminal via the core network to the other user’s terminal.

IMS provides for a number of common functions that are generic in their structure and implementation, and can be reused by virtually all services in the network. Examples of these common functions are group/list management, presence, provisioning, operation and management, directory, charging and deployment. In addition to speeding up and simplifying the service creation and delivery process, the reuse of common infrastructure, enablers and competence provided by IMS minimizes OPEX and CAPEX for operators – especially in areas such as service provisioning, O&M, customer care and billing.

Another advantage is that the operations competence required across services is more generic – and can be overlaid with service-specific knowledge – rather than demanding specialist operational competence for each service.

Moreover, IMS facilitates the creation and delivery of multimedia services based on common enablers in a “write once - use many” way. These key elements in the IMS architecture are so-called service enablers. They represent generic and reusable building blocks for service creation. The service enablers developed for successful applications can become “global enablers” that are automatically included in new applications and services. There may be a large number of service enablers, but possibly the two most important are **presence** and **group list management**.

The presence service enabler allows a set of users to be informed about the availability and means of communication of the other users in the group. It enables a paradigm shift in person-to-person and other communications – for example, by enabling users to “see” each other before connecting (active address book) or to receive alerts when other users become available. In IMS, presence is sensitive to different media types, users (requestors), and user preferences. IMS presence function is also aware of what terminals the user can be reached on across the various wireline and wireless networks. Different rules can be set by the user to define who can view what information.

Furthermore, the group list management service enabler allows users to create and manage network-based group definitions for use by any service deployed in the network. There are generic mechanisms for notification of changes in group definitions. Application examples for group management include:

- ✓ personal buddy lists;
- ✓ “block” lists;
- ✓ public/private groups (for example, the easy definition of VPN-oriented service packages);
- ✓ access control lists;
- ✓ public or private chat groups;
- ✓ and any application where a list of public identities is required.

IMS enables a much more user-focused approach to deliver personal services than traditional networks. In the pre-IMS world, users access personal services from one or more service-specific, user-independent access point(s). The routing to the server is also service-specific and often proprietary. The service architecture is also service-centric and scalability is a fundamental, service-specific issue. With IMS, users access personal services via a dynamically associated, user-centric, service-independent and standardized access point, the CSCF. The CSCF is dynamically allocated to the user at log-on or when a request addressed to the user is received. Routing to the server is service-independent and standardized. The service architecture is user-centric and is highly scalable.

Moreover, the IMS greatly simplifies the sign-on and authentication process, for both operators and users. In the pre-NGN IMS world, each service often has its own way of authenticating users, which may be standardized or proprietary. It may not authenticate the user at all, relying instead on lower-level authentication. The operator may need to introduce a special Single Sign On (SSO) service in order to avoid re-authentication for multiple services. Once authenticated through an IMS service, the user is able to access all the other IMS services that he is authorized to use. Authentication is handled by the CSCF as the user signs on. When it receives a service request, the SIP Application Server (AS) can verify that the user has been authenticated.

One of the key interfaces towards the end-user is the contact list. This not only lists the user’s contacts, it also shows their availability and for which service on what terminal. When an end-user logs on to his mobile phone or PC software client, the system is automatically updated on the user’s new presence state.

Also, IMS enables the reuse of inter-operator relations. Rather than develop different interconnect relations and agreements for each service, IMS enables a single inter-operator relationship to be established and built upon for each service. Today, when one user wishes to access another user’s service – for example, to check status or location – routing to the other user’s service is service-specific, and the requesting user’s operator service has to be involved. What’s more, there has to be service-specific network-to-network interface, routing, service access point and security in place – and therefore a specific interoperator service agreement as well. Once IMS is in place, access to other users’ services is an IMS network issue, common to all IMS personal services, as shown in Figure 2.13. The requesting user’s operator service does not need to be involved in routing the request. The inter-operator network-to-network interface is established in IMS, and the general IMS inter-operator service agreement, routing, service network access point and security are all reused.

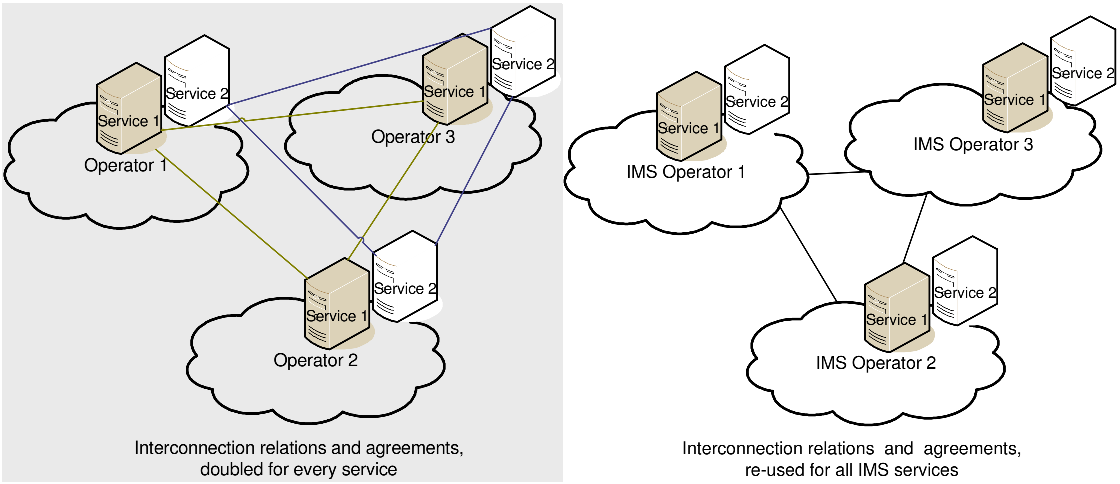


Figure 2.13 –Service interoperability in a pre-IMS network (left)
vs IMS enabled operators (right).

On the other hand, let we see about one another aspect of IMS-Regulatory issues. Those issues are important in all types of networks. However, the IP revolution has seen the emergence of many networks where these issues have been neglected. Providing cheap, or free, Internet calls has been more attractive than providing mechanisms for lawful intercept and other regulatory functions. There are strong forces in the VoIP community that argue that IP telephony should not be regulated in the same way as the classic telephony network has been. A number of regulatory functions have been standardized in the IMS architecture for NGN. Lawful intercept is one. The ability to determine the geographic location of the user will be implemented in the next release of the IMS standard. This function will be applicable for both wireline and wireless networks. However, the operators who see their future in offering IP multimedia services should begin implementing IMS without delay. The reason is that IMS provides a standardized, well-structured way of delivering services, legacy interworking and fixed–mobile convergence. At the same time, it provides a future-proof architecture that simplifies and speeds up the service creation and provisioning process. The IMS standard is being adopted by an ever growing section of the telecom community. It is today the only standard for SIP-based communication. NGN operators can implement IMS solutions today, in order to derive its benefits as soon as possible. The NGN IMS architecture not only delivers revenue-generating services straight away, but can also leverage existing user behavior. Moreover, using IMS in future NGNs, operators can adopt a strategy of first exploring the opportunities of IP multimedia, and then taking appropriate steps to mass-market IP multimedia services, according to market and business motivations. The hard lessons of the Internet bubble have brought us back to sound business logic, based on increased revenues and cost control. The introduction of new services and capabilities must not disturb the current profitable mix of telephony services. They should rather use it as a base for a superior user experience making it even more compelling.

On the other hand, the all-IP vision enables one core network for multiple accesses and so reduces cost of ownership. By introducing the concept of horizontalization in IMS, the operators get an excellent opportunity to capitalize even further on the layered architecture that is being introduced in both wireline and wireless networks. Utilizing the horizontal architecture, with its reusable common functions, the operator can in a service oriented and revenue focused way start the journey towards all-IP. However, from a network infrastructure perspective, IMS can be very cost efficient – not only as a result of the benefits of horizontalization, but also in terms of operation and maintenance.

From above said, we can conclude that IMS in LTE (and future IMT-Advanced) architecture provides sound, business-focused evolution options for delivering attractive, easy-to-use, reliable and profitable multimedia services. It also enables operators achieve fixed–mobile convergence. Strategies are in place for operators to begin rolling out IMS-based services that take advantage of fast, flexible service creation and provisioning capabilities, while also providing for legacy interworking and combinational services that make the most of existing investments. Operators can then build onwards toward the all-IP vision of offering rich, multi-access multimedia services across next generation mobile networks and 4G.

2.5. Mobility and location management

As we see in the section 2.3, in LTE/SAE things work a bit different from all other 3G networks and that's the main reason why the mechanisms had to change as well. The biggest difference in SAE is that once a mobile device is switched on it always has at least a default bearer. In other words, it always has an IP address when it is switched on. And again it's not possible for a mobile device to be attached to the network and not have an IP address. Hence, session managements makes no sense in LTE/SAE. As can be seen within LTE/SAE architecture (Figure 2.8), a flatter network architecture exists which leads to improved data latency, and also improved support of interactive and real-time communications which are inherently delay sensitive; whilst simultaneously providing both voice and data services over a single all-IP core network. Moreover, for the mobility and location management functions LTE/SAE has developed specific entity call Mobility Management Entity (**MME**).

The Mobility Management Entity (MME) performs similar role of the SGSN in existing GPRS networks. Its functions consist of mobility management, including security parameters and UE identities. It governs all of the control plane (C-Plane) functions related to session and subscriber management. It can also be thought of as a control plane element, which allows user plane traffic to be throughput over a direct tunnel. Within LTE the NAS (Non-Access Stratum) procedures, in particular the connection management procedures, are very similar to UMTS. One major difference as compared with the current Core Network 3G architecture is that the EPC is able to concatenate several procedures, which result in a faster establishment of the bearers and the connection.

Finally, it should be noted that it is possible to implement both the MME and the Serving-GW on either one physical node or on separate nodes, which can result in significant cost savings for the Operator.

A breakdown of the MME's functions is listed below:

- ✓ MME selection for handovers & MME change/re-selection.
- ✓ SGSN selection for handovers to 2G or 3G access networks & authentication.
- ✓ Tracking area list management (UE in both idle and active mode).
- ✓ SGW and PDN GW selection & Roaming (towards home HSS) Inter CN node signalling between 3G access networks (mobility).
- ✓ UE-Reachability in ECM-Idle state (Enhanced Connection Mobility) including execution and control of paging retransmission.
- ✓ Non Access Stratum (NAS) signalling & NAS signalling security.
- ✓ Warning message transfer function (including selection of appropriate eNB) & UE reachability procedures.
- ✓ Lawful interception of signalling traffic & bearer management, and dedicated bearer establishment.

To emphasize that, in EPC MME, there are also Session Management (ESM) Functions, which are including support for:

- ✓ Maintenance of the UE's bearer context states.
- ✓ IP address allocation procedure (via NAS signaling, via dynamic host confi guration protocol (DHCP)).
- ✓ Procedures for network initiated default and dedicated bearer context activation, modifi cation and deactivation.
- ✓ Procedures for UE initiated PDN connect and disconnect; bearer resource allocation and de-allocation.

The MME is the signaling focal point for intra-EUTRAN mobility and handovers (as shown in Figure 2.14). As the LTE and EPS architecture allows an E-UTRAN (essentially eNodeB) to connect to multiple MMEs and Serving Gateways (S-GW), multiple handover schemes are possible namely, Inter-eNodeB handover with and without MME relocation in the control plane, combined with or without relocation of Serving Gateway in the user plane. The MME-MME S10 interface facilitates MME relocation. The MME also acts as the signaling anchor for 3GPP inter-RAT (GERAN and UTRAN) mobility, terminating the S3 interface from the UTRAN/GERAN Serving GPRS Support Node (SGSN).

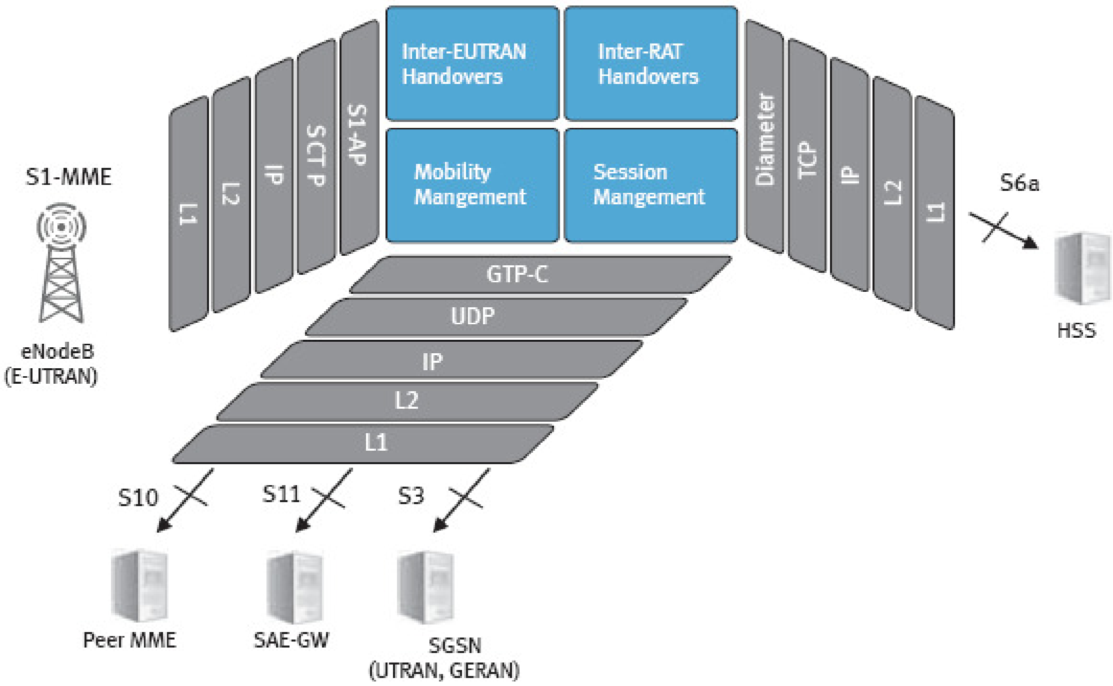


Figure 2.14. Mobility Management Entity (MME) Architecture.

On the other hand, the location management is a critical function for any cellular network, including LTE. When being active, the mobile location is known at the cell level, as the network needs to quickly react to terminal cell change, allocate new resources in the new cell and release old, unused resources in the previously serving cell. In this case, the terminal mobility is driven by handover procedures, described further in this section. For all mobiles not being active (or being in IDLE mode), location management is still an important item, as the network needs to know the current terminal location at any time in case of mobile-terminated session setup or push services. However, IDLE mode procedures do not require the network to know each terminal location with a high degree of accuracy (such as the cell level). For that reason, the concept of Tracking Area (TA) has been introduced in LTE.

Basically, a TA is defined as a set of contiguous cells. The identity of the TA the cell belongs to, or TAI (Tracking Area Identity), is part of the system information broadcast on the BCCH. As in the 3GPP definition, Tracking Areas do not overlap each other. When the network needs to join the terminal, a paging message is sent in all the cells which belong to the Tracking Area.

The dimensioning of TA is a typical network-engineering issue, which results from a trade-off between network signalling load and radio paging load:

- ✓ If TA are too small, terminal moves will result in a large number of TA update procedures and high signalling load. This issue can be worked out by increasing the size of the TA.
- ✓ On the other hand, if the TA are too large, all the cells within the TAwill have to cope with a high traffic load on the Paging channel. Since the Packet Core does not know the idle terminal location with more accuracy than the TA, one single mobile-terminated call will generate a paging message in each cell of the TA in which the terminal is located.

In practice, Tracking Areas are dimensioned according to the estimation of IDLE mode terminal density. In hot-spot, or low-speed, dense urban areas, TA are usually small so as to limit the paging load. In contrast, in rural or low-speed, dense areas, TA size can be increased without compromising the network signalling load. There are actually **three cases** in which the current terminal TA is signalled to the TLE Core Network:

- ➢ At initial registration, the terminal communicates to the Core Network its current Tracking Area.
- ➢ When the terminal changes zones, as a result of subscriber move within the network, the new TA is updated in order to keep the Packet Core network updated.
- ➢ In addition, the current TA is periodically updated (or refreshed), even if it does not change, so that the Packet Core network does not keep alive a context for a terminal which is no longer reachable in the network. This can happen if the terminal fails to de-register or suddenly runs out of coverage.

Moreover, the Figure 2.15 describes an example of a Tracking Area update (TAU). In this case, the terminal changes both MME and Serving GW nodes. A similar procedure also applies when the terminal is moving between EPS and the 2G or 3G network. In such a case, the terminal moves between two different types of zones: a TA on the EPS side, and a RA (Routing Area) on the 2G or 3G side. However, the principles for such a procedure are not that different from the intra-EPS Tracking Area Update described hereafter.

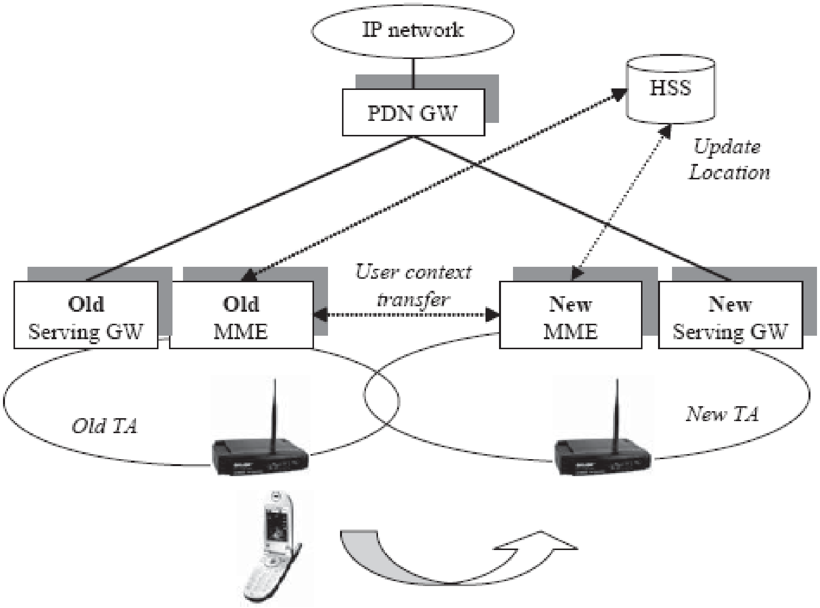


Figure 2.15. An example of a Tracking Area Update.

In short, the following operations need to be performed during a TAU:

- ✓ Bearer path update – when a bearer is available, as a consequence of the Always-On IP connectivity, the bearer path in the EPC (corresponding to the initial default bearer, or any bearer the subscriber would have asked for) needs to be updated. This implies that the PDN Gateway is updated with the reference of the Serving GW in charge of the new TA, and a new bearer needs to be created between the terminal and new Serving GW.
- ✓ User context transfer from old to newMME– this allows the newMMEto get the subscriber context information from the old MME. This context includes information such as user IMSI and subscription data.
- ✓ HSS database update – at the end, the HSS is updated with the terminal's new serving MME identity and IP address.

Furthermore, in Figure 2.16 the messages exchanged between the network entities so as to achieve the operations listed above is shown. Not all Tracking Area Updates generate as much signalling. In the case that the new and old TA are served by the same MME and Serving GW, the overall procedure is much simpler and only limited to the TA update between the terminal and the MME, without involvement of the PDN GW and the HSS.

At some time, following a cell reselection, the terminal detects that it has entered into a TA which does not belong to the list of TA it is registered to. This triggers the initiation of a TA Update Request message sent to the new MME which serves the current eNodeB. This message contains two key parameters: the S-TMSI (which identifies the subscriber) and the old TAI. This will help the new MME to identify the old serving MME. The new MME can then retrieve the user information from the old MME, using the MME Context Request procedure, which contains the S-TMSI and the old TAI. This context contains the user's IMSI, user's subscription information as well as a set of authentication vectors.

The new MME can therefore run the AKA procedure in order to authenticate the terminal and protect all subsequent signalling exchanges over the radio interface. Once the TA update is accepted by the new MME, the bearer path needs to be updated. This operation is under the control of the new MME (using the Create Bearer Request message) and relayed by the new Serving GW to the PDN GW. Following this phase, the HSS is updated with the new terminal location (Update Location procedure) and the old MME is informed by the HSS that the subscriber has been successfully located within another MME. This later triggers the old bearer release between the old Serving GW and the PDN GW.

Eventually, the new MME informs the terminal about the successful outcome of the whole procedure. The TA Update Accept message may contain a new S-TMSI allocated by the new MME, which is acknowledged by the terminal using the TA Update Complete message.

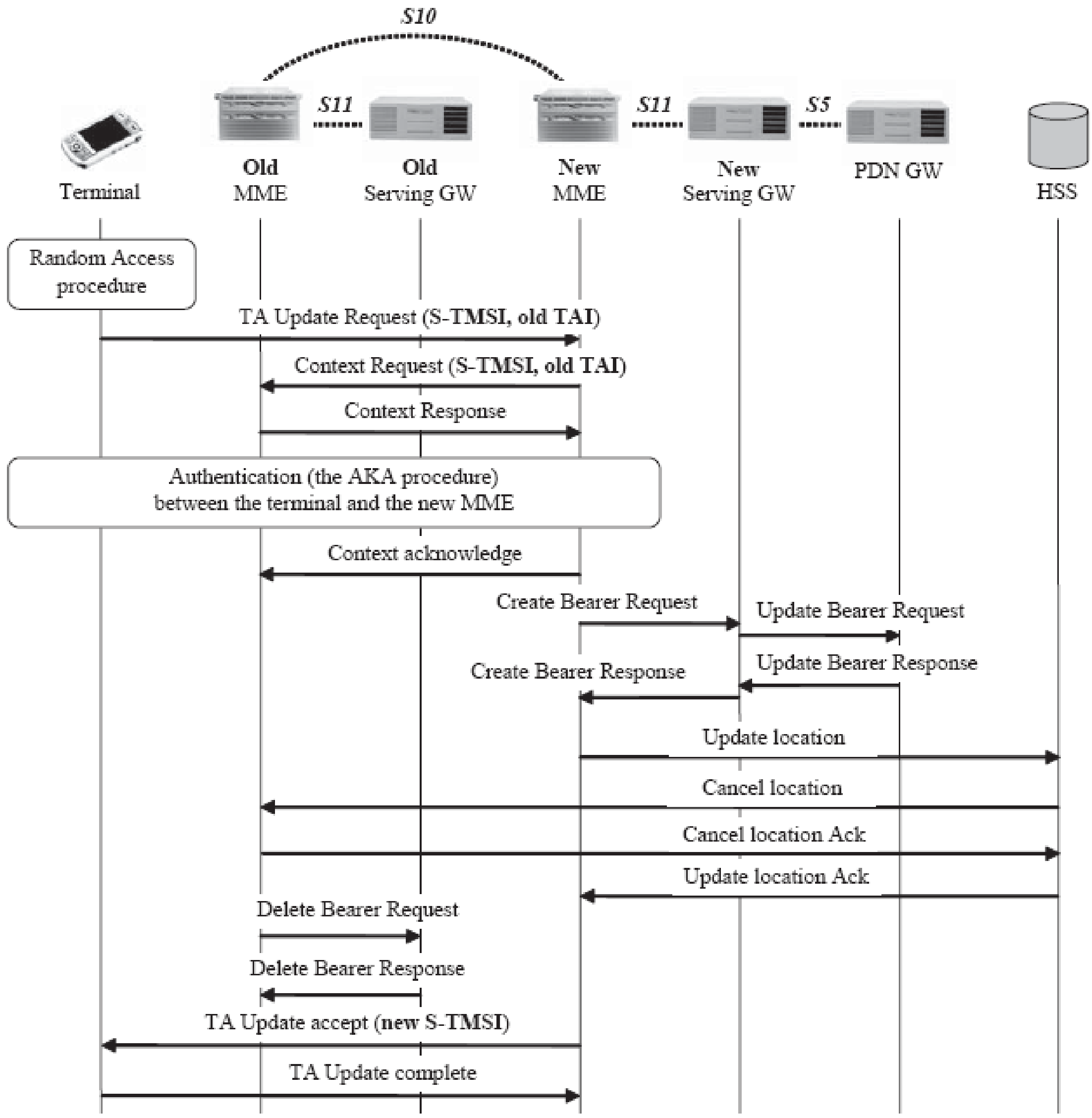


Figure 2.16. Inter-MME Tracking Area Update – message flow.

As opposed to IDLE mode, active terminal mobility (also called handover) is completely under the control of the network. The decision to move as well as the choice for the target cell and technology (when applicable) is made by the current serving eNodeB, based on measurements performed by the eNodeB itself and the terminal. In addition, ACTIVE mode mobility requires some specific features to be supported and implemented by the network so as to limit interaction on user experience and preserve the on-going service.

In this domain, the E-UTRAN handover cases follow (as much as possible) two main principles inherited from 2G/GSM and 3G/UMTS systems:

- ✓ **Make before break**. In all the cases, the resources and context in the target nodes (whatever the target technology is) are reserved before the actual handover (or change of radio equipment which serves the terminal) is performed. This ensures that the interruption time is kept to a minimum, since the time for resource reservation in the target nodes is not predictable – if it does not fail.
- ✓ **Packet data forwarding**. Due to the nature of the E-UTRAN radio interface, the amount of packets stored in radio equipment before scheduled transmission over the radio may not be negligible. For that reason, some mobility cases make use – when applicable – of packetforwarding mechanisms between source and target nodes so as to limit packet loss during the overall handover.

There may be many drivers for terminal mobility in ACTIVE mode. The most common one is related to degrading radio conditions due to, for example, increasing interference or terminal mobility. In such conditions, not doing the handover to a suitable cell in a timely manner will most probably lead to a call drop. However, there may be some other reasons to perform a handover, corresponding to less critical conditions, which may depend on operator policy and network engineering constraints. For example, this may include:

- ✓ Traffic load balancing between network layers using different frequencies or radio access technologies.
- ✓ Handover for service reasons, depending on the service being used or requested by the enduser.
- ✓ Network sharing. When local agreements have been set up between operators, a roaming subscriber may be handed over a cell from its home network when available.

In the following we present a subset of mobility cases considered as being the most representative, from the simplest to the most complex:

- ➢ Intra-E-UTRAN mobility with X2 support – the basic one.
- ➢ Intra-E-UTRAN mobility without X2 support – a refinement of the previous case, when direct communication between the source and target eNodeB is not available.
- ➢ Intra E-UTRAN mobility with EPC node relocation – a more complex case involving more support of Packet Core nodes.
- ➢ Mobility between 2G/3G packet and E-UTRAN – an example of inter-technology packet handover.

- ➢ Voice Call Continuity between 2G/Circuit and E-UTRAN – this case combines a change of service domain and technology so as to ensure legacy 2G/GSM circuit voice continuity.

For illustration purposes, see in the [11], where some message exchange flows are presented. In general, they all are composed of two parts:

- ✓ The preparation phase, which corresponds to the handover decision (made by the source nodes) and the resource reservation (in terms of radio, terrestrial interfaces and possibly memory context and processing capability) in the target nodes.
- ✓ And the execution phase, which is the handover execution itself, including the synchronization to the target radio nodes and resource release in the old serving nodes.

Moreover, in the following, one example of mobility management between 2G/3G Packet and E-UTRAN is given. As a basic feature, EPS networks are able to support seamless mobility to and from 2G and 3G packet systems. Figure 2.17 describes an example of such a mobility case, for a terminal moving from a E-UTRAN access towards a 3G/UTRAN target cell.

For simplicity, the target 3G RNC and BTS nodes are represented as one box, connected to the target SGSN towards the standard UMTS Iu interface. In the case of mobility towards a 2G/GPRS system, the picture would actually be quite similar, as the SGSN node exists in both 2G and 3G packet core architecture. As represented in the figure 2.17, the Serving GW acts as a sort of User plane anchor point. The control plane for NAS signalling (for session setup and control) is moved over the S3 interface from the serving MME to the target SGSN, which is the standard point for terminating this protocol in 2G and 3G packet architecture. Regarding the User plane, a new tunnel is built between the Serving GW and the target SGSN over the S4 interface so as to ensure packet transmission continuity. Since the Serving GW still remains in the data path, the PDN GW is not involved in the mobility procedure. There is, however, one little exception to that. Due to the change in radio access technology, the Serving GW may inform the PDN GW about the handover, mainly for charging purpose. This gives flexibility to the charging system to apply different rate and billing procedures, depending on the access system technology and associated specific QoS representation. Once the handover is completed, the old resources and connections on the radio as well as S1 user and signalling interface (represented using dotted lines) are released.

Finally, Figure 2.18 describes the messages and procedures involved in such an E-UTRAN to 2G or 3G mobility. Handover in the other direction is not further described, as it actually makes use of very similar principles and procedures. When the handover decision is made, the session context (including session-related EPS bearers and associated Quality of Service attributes) is moved from the source MME to the target SGSN using the Forward Relocation procedure, as in the Intra E-UTRAN mobility with EPC nodes relocation' mobility case. This procedure is actually an extension of the existing Forward Relocation procedure which applies in the case of inter-SGSN mobility within 2G or 3G networks.

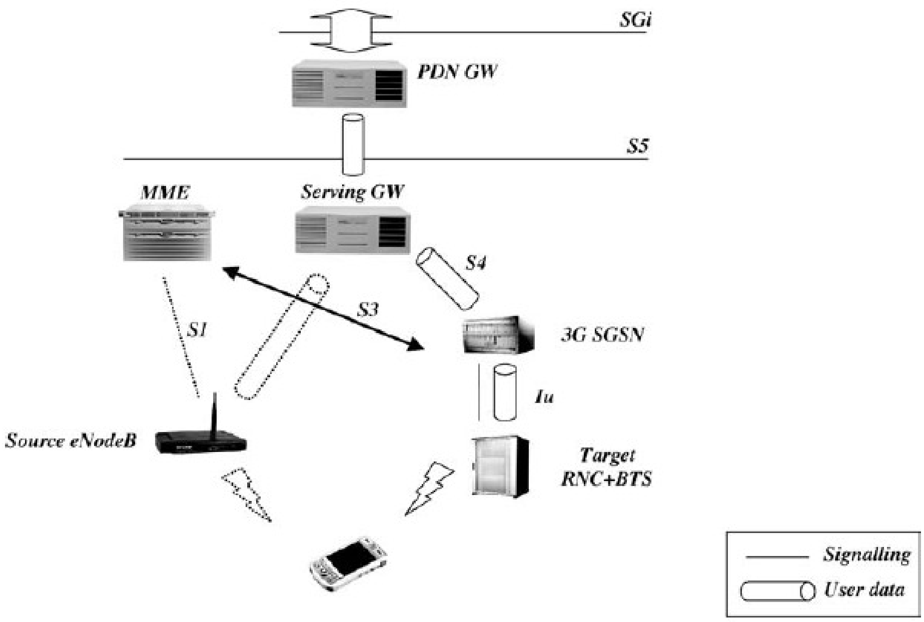


Figure 2.17. Overview of E-UTRAN to 2G/3G mobility.

On this occasion, the MME translates the EPC Quality of Service attributes into their 2G or 3G equivalent, in the form of PDP context attributes. E-UTRAN to 2G/3G mobility may support data forwarding, from the eNodeB to the target SGSN, so as to avoid that all packets still stored at the eNodeB may eventually be sent to the terminal. Data forwarding is always requested by the eNodeB (and reflected by the content of the Handover Required message). The 3GPP standard proposes two types of data forwarding:

- Direct forwarding – in which buffered data are sent directly from the eNodeB to the target SGSN. All necessary information (such as IP address and Tunnel identifier) is part of the Forward Relocation Response message.
- Indirect forwarding – in which buffered data are transmitted to the target SGSN via a Serving GW.

The handover execution phase is then triggered by a Handover Command message. When applicable, this message contains all information for the eNodeB to be able to forward buffered data, either in direct or indirect mode. Once the terminal is synchronized on the target BTS and the handover considered as completed from the Access Network point of view, a Forward Relocation Complete is sent from the SGSN to the MME. This signal is used as an indication that resources in the old serving E-UTRAN and MME nodes are no longer useful and can be released. Simultaneously, the target SGSN updates the bearer path towards the Serving GW using the Update Bearer procedure.

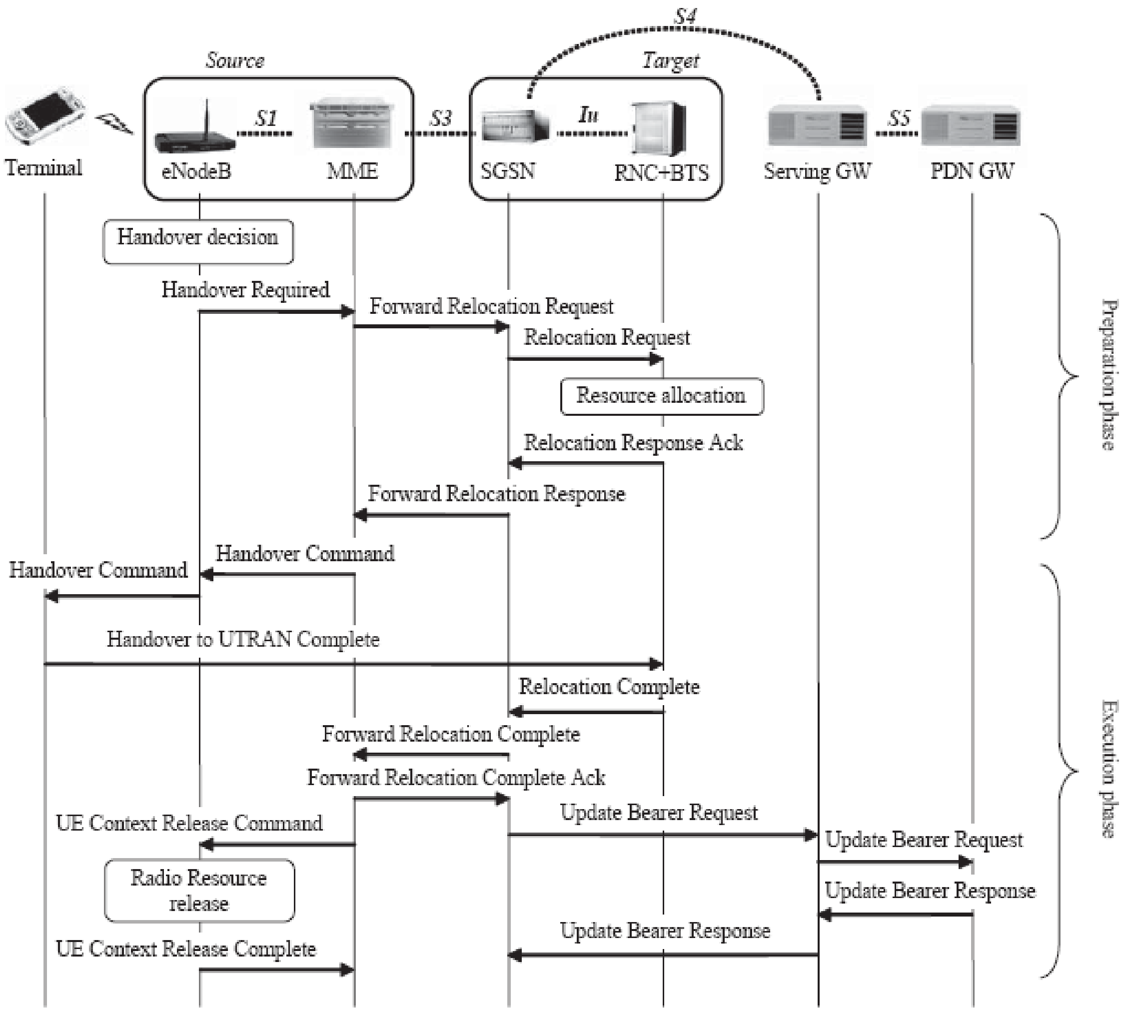


Figure 2.18. E-UTRAN to 2G/3G mobility – message flow.

2.6. VoIP and broadcast multicast services over LTE

In this section we describe the VoIP and broadcast and multicast services over LTE systems, as specified by the 3GPP documents. The VoIP service over LTE or shortly **VoLTE**, was devised as a result of operators seeking a standardised system for transferring voice traffic over LTE. Originally LTE was seen as a completely IP cellular system just for carrying data, and operators would be able to carry voice either by reverting to 2G/3G systems or by using VoIP. Operators, however saw the fact that a voice format was not defined as a major omission for the system. It was seen that the lack of standardisation may provide problems with scenarios including roaming. In addition to this, SMS is a key requirement. It is not often realised, that SMS is used to set-up many mobile broadband connections, and a lack of SMS is seen as a show-stopper by many. As mobile operators receive over 80% of their revenues from voice and SMS traffic, it is necessary to have a viable and standardized scheme to provide these services and protect this revenue.

On the other hand, there is a Multimedia Broadcast and Multicast Service (**MBMS**) over LTE networks. The benefit of MBMS is that multiple subscribers can receive the same data at the same time, sent only once on each link. For the radio interface, the obvious benefit is that in a given cell, the radio resource cost is limited to what is needed for one transmission in a given cell, for the sake of radio interference and capacity. The gain on terrestrial interfaces is not also negligible, as the interfaces between the content source and the radio equipment will also benefit from broadcast techniques.

When looking at the options for ways of carrying voice over LTE, a number of possible solutions were investigated. A number of alliances were set up to promote different ways of providing the service. A number of systems were prosed as outlined below:

- CSFB, Circuit Switched Fall Back: The circuit switched fallback, CSFB option for providing voice over LTE has been standardised under 3GPP specification 23.272. Essentially LTE CSFB uses a variety of processes and network elements to enable the circuit to fall back to the 2G or 3G connection (GSM, UMTS, CDMA2000 1x) before a circuit switched call is initiated. The specification also allows for SMS to be carried as this is essential for very many set-up procedures for cellular telecommunications. To achieve this the handset uses an interface known as SGs which allows messages to be sent over an LTE channel. In addition to this CSFB requires modification to elements within the network, in particular the MSCs as well as support, obviously on new devices. MSC modifications are also required for the SMS over SGs facilities. For CSFB, this is required from the initial launch of CSFB in view of the criticality of SMS for many procedures.

- SV-LTE - simultaneous voice LTE: SV-LTE allows to run packet switched LTE services simultaneously with a circuit switched voice service. SV-LTE facility provides the facilities of CSFB at the same time as running a packet switched data service. This is an option that many operators will opt for. However it has the disadvantage that it requires two radios to run at the same time within the handset. This has a serious impact on battery life.
- VoLGA, Voice over LTE via GAN: The VoLGA standard was based on the existing 3GPP Generic Access Network (GAN) standard, and the aim was to enable LTE users to receive a consistent set of voice, SMS (and other circuit-switched) services as they transition between GSM, UMTS and LTE access networks. For mobile operators, the aim of VoLGA was to provide a low-cost and low-risk approach for bringing their primary revenue generating services (voice and SMS) onto the new LTE network deployments.
- One Voice / later called Voice over LTE, VoLTE: The Voice over LTE, VoLTE schem for providing voice over an LTE system utilises IMS enabling it to become part of a rich media solution.
- The 3GPP Multi-Media Telephony (MMTel) solution gives operators the possibility to evolve their telephony service by incorporating the multimedia feature-richness needed to compete with OTTs. Additionally, MMTel can leverage the world's biggest mobile user community – Mobile Subscriber Integrated Services Digital Network number (MSISDN) – as well as classical telecommunication values, such as:
    - High-quality, guaranteed end-to-end QoS
    - Regulatory services support (such as emergency calls)
    - Global reach.

Furthermore, the basic scenario (see Figure 2.19) in the VoLTE profile assumes full LTE coverage or LTE coverage complemented by another VoIP capable packet Switched technology, such as HSPA or 1xEVDO, including the following functionalities:

- ✓ QoS handling to guarantee a high quality MMTel service. Voice media is therefore mapped to Guaranteed Bit Rate (GBR) bearers, and SIP signaling is protected by mapping in to non-GBR dedicated bearers.
- ✓ Mobility based on internal EPC/LTE procedures, which are transparent to the IMS/Application layers. If complementary Packet Switched technologies are used for coverage, IRAT PS Hand Over is also included.
- ✓ Advanced radio features like LTE DRX mode for terminal battery saving and Robust Header Compression (RoCH) techniques to improve voice efficiency.
- ✓ Self management of Supplementary Services via Web Portal or terminal browser (standard http based interfaces from 3GPP).
- ✓ GSM-alike subset of MMTel Supplementary services supporting smooth evolution towards the full multimedia capabilities.

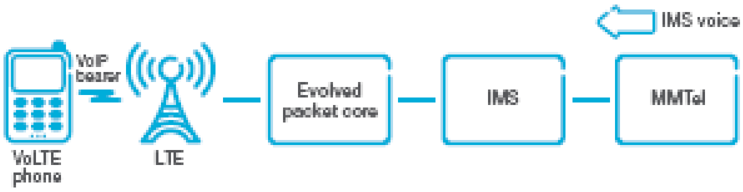


Figure 2.19. Scenario for VoIP over LTE.

Complementary scenarios are also defined in the voice over LTE profile to cope with the cases where LTE coverage needs to be complemented with existing WCDMA/GSM CS coverage. For these scenarios, the previously mentioned 3GPP CS co-existence mechanisms are included: IMS and SRVCC.

Furthermore two advanced handover for VoIP users: SRVCC (Single Radio Voice Call Continuity) and IRAT PS are presented. The SRVCC is specified in 3GPP TS 23.216. SRVCC allows IMS session continuity when the terminal is Single Radio, thus only one RAT can be active at a time. So when moving out from IMS Voice capable LTE coverage, SRVCC allows MMTel voice continuity via handover to 2G/3G CS. It builds upon ICS, so it relies on the SCC AS to anchor the call and perform the call transfer between LTE and WCDMA/GSM CS access domains. It also needs a new interface between the EPC and the CS Core, the Sv interface, so the MME can request the MSC-S to reserve the necessary WCDMA/GSM CS resources before handover execution. The Single Radio Voice Call Continuity is shown in Figure 2.20.

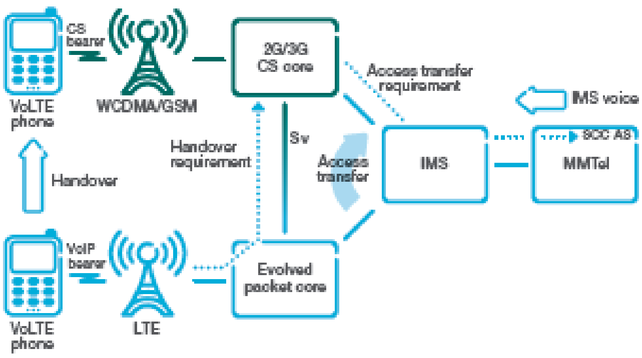


Figure 2.20. Illustration for Single Radio Voice Call Continuity.

IRAT PS Handover is specified in 3GPP TS 23.401 (see Figure 2.21). IRAT PS Handover allows service continuity for all PS sessions between different 3GPP/3GPP2 PS accesses (e.g. LTE and HSPA) in a way that is transparent for the application. Radio resources are reserved in the target network prior to handover, so interruption time is minimized. The user’s IP address is maintained at the GGSN/PDN GW, and IP sessions are transferred to the target network depending on required bearer availability.

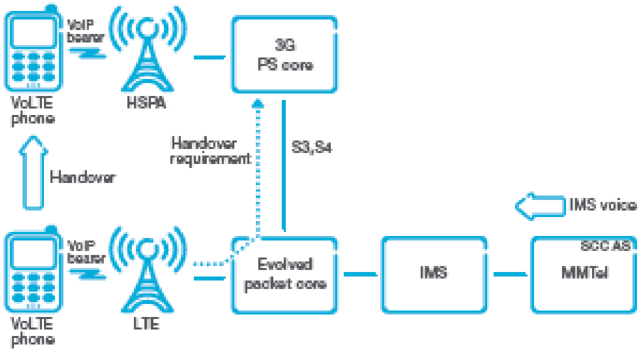


Figure 2.21. Illustration for IRAT PS.

Moreover, the mobile broadband is exploding and LTE deployment is gaining momentum with mass-market reach expected by 2012. Operators will benefit from evaluating their voice over LTE strategy to take advantage of their strengths before LTE coverage is fully deployed, and link the resulting LTE strategy to communication services evolution and FMC plans.

Generally, in order to provide the VoLTE service, three interfaces are being defined:

- User Network interface, UNI: This interface is located between the user's equipment and the operators network.
- Roaming Network Network Interface, R-NNI: The R-NNI is an interface located between the Home and Visited Network. This is used for a user that is not attached to their Home network, i.e. roaming.
- Interconnect Network Network Interface, I-NNI: The I-NNI is the interface located between the networks of the two parties making a call.

However, the work on the definition of VoLTE, Voice over LTE is ongoing. It will include a variety of elements including some of the following:

- ✓ It will be necessary to ensure the continuity of Voice calls when a user moves from an LTE coverage area to another where a fallback to another technology is required. This form of handover will be achieved using Single Radio Voice Call Continuity, or SR-VCC).
- ✓ It will be important to provide the optimal routing of bearers for voice calls when customers are roaming.
- ✓ Another area of importance will be to establish commercial frameworks for roaming and interconnect for services implemented using VoLTE definitions. This will enable roaming agreements to be set up.
- ✓ Provision of capabilities associated with the model of roaming hubbing.
- ✓ For any services, including LTE, it is necessary to undertake a thorough security and fraud threat audit to prevent hacking and un-authorised entry into any area within the network.

In many ways the implementation of VoLTE at a high level is straightforward. The handset or phone needs to have software loaded to provide the VoLTE functionality. This can be in the form of an App. The network then requires to be IMS compatible. While this may appear straightforward, there are many issues for this to be made operational, especially via the vagaries of the radio access network where time delays and propagation anomalies add considerably to the complexity.

Furthermore, we will discuss about providing MBMS over LTE. The 3GPP MBMS service is actually composed of two distinct services: broadcast and multicast. There are many common areas between broadcast and multicast. However, although supported in the same way over the radio interface, the two services shall be distinguished, as there is a key difference between them:

- Broadcast service may be received by any subscriber located in the area in which the service is offered.
- Conversely, multicast services can only be received by users having subscribed to the service and having joined the multicast group associated with the service.

In the MBMS scope, broadcast and multicast services are unidirectional point-to-multipoint transmissions of multimedia data. These two services may be used to broadcast, for example, text, audio, picture, video from a single source (which is called the BM-SC for Broadcast Multicast Service Centre) to:

- Any user located in the service area (in the case of a broadcast service).
- Only members of a multicast group (in the case of a multicast service).

Broadcast only requires the service to be enabled by the user on its terminal. For this reason, the operator cannot apply charging rules to the end-user, as the network does not know which subscribers have received the service and for how much time the users have been receiving it. For such a service, only the broadcast service providers can be charged possibly based on the amount of data broadcasted, size of service area or broadcast service duration.

Multicast is subject to service subscription, and requires the end-user to explicitly join the group (MGroup = multicast group) in order to receive the service. Because it is subject to subscription, the multicast service allows the operator to set specific user charging rules for this service. For example, all subscribers watching the same TV channel in the MGroup, the total number of MGroups in the network is equal with TV channels. However, subscribers are distributed at different locations and experience different fading and path-loss due to time-varying wireless channels, it remains challenging to provide satisfactory multicast services to all subscribers.

Upon completion of the above step, the service provider provides the content access information and then the end-user can receive the video. In other words, the multi-channel multicast address is used to forward the content to the end user. In this multicast algorithm showed in Figure 2.22, service provider checks weather multicast stream exists or not, for the VoD contents requested by customer. If the multicast stream exists, server will send an address of multicast group to the user, thus he can join to the multicast stream.

On the other hand, if it’s not highly requested content, it is delivered by unicast transmission without any delay through the dedicated channel. If it’s highly requested content, MBMS of LTE starts multi-channel multicast transmission algorithm. Multicast transmission can use multicast address to forward content to the end user; hence user can receive the VoD.

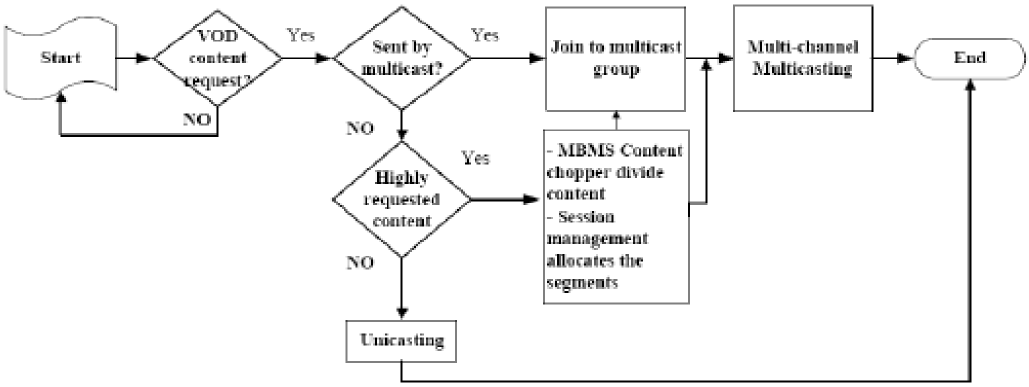


Figure 2.22. Service procedure for IPTV VoD service over LTE.

Furthermore, we look at a multi-channel multicast algorithm which allocates the content (segments) packets into several channels of cellular network, including MBMS as shown in Figure 2.23. The multicast broadcast transmission is performed through the MBMS of LTE by adding only 1 additional functional entity: MBMS controller. Multicast is a bandwidth conserving technology that allows an E-UTRAN to send packets (video segments in this case) to a subset of all SSs as a group transmission.

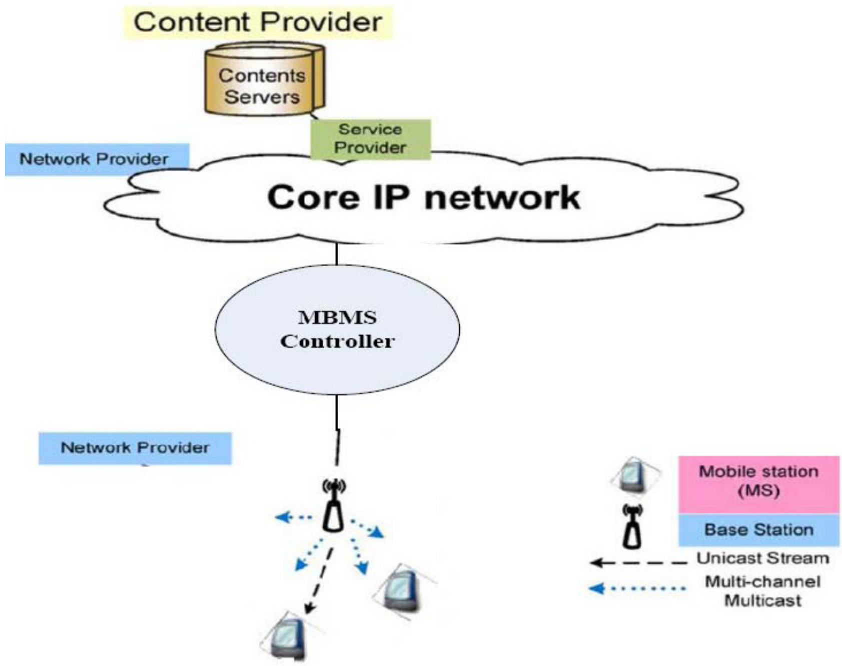


Figure 2.23. MBMS LTE network architecture.

An MBMS session refers to a logical connection, established between an MS and the MBMS controller, by which the MBMS video is delivered to the users. An MS identifies each session by the tuple id of a channel identifier, named as a logical channel ID, and a MBMS data ID. The MBMS creates and maintains session information. It also transmits the packets from the content chopper. The content chopping mechanism is added in order to efficiently deliver the multicast VoD contents. Since 3GPP LTE with MBMS defined criteria only for PHY and MAC layer, we need a model for the end-to-end transmission over LTE as shown in below Figure 2.24.

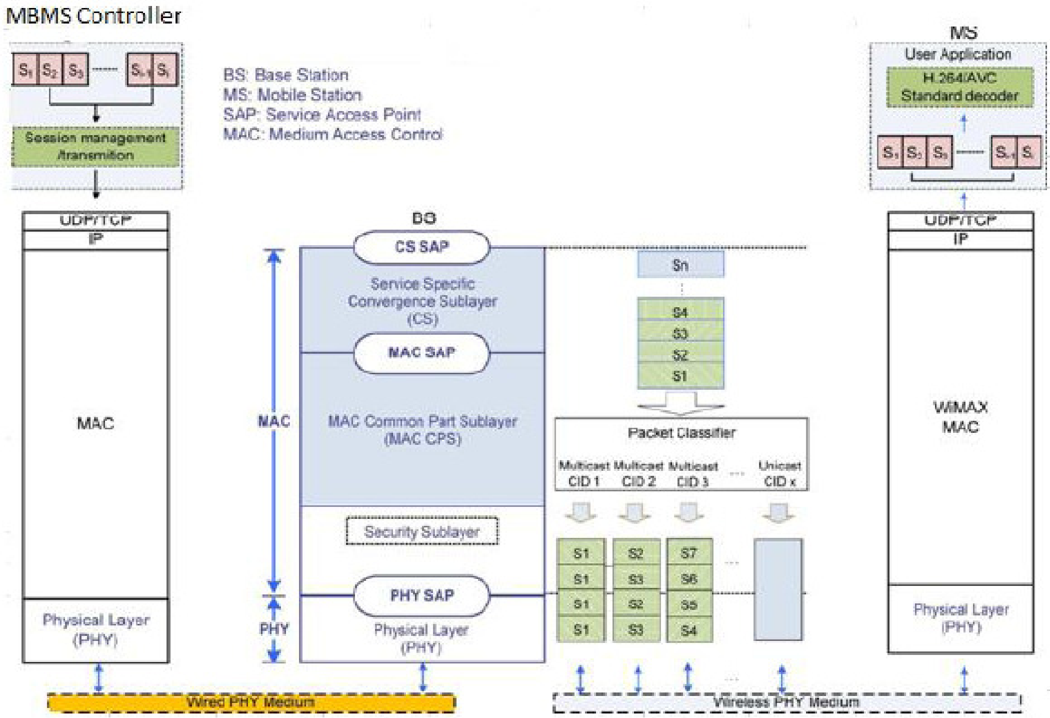


Figure 2.24. End-to-end MBMS solution over LTE

After MBMS content division function finished dividing video into segments, these will be converted to the MBS packets by MBMS session management/transmission function. Then those packets will be transmitted to the BS. LTE - MBMS can support in either constructing PHY/MAC layer with OFDMA to transmit a mix of unicast and multicast service or upper layer with content copper. Then BS starts to map the segmented contents to dedicated channel ID for transmission over LTE PHY/MAC, next LTE PHY layer handles burst scheduling and OFDMA data for each mac/pdu. UE need to have enough storage (greater than 10Gb) to buffer the streaming and downloading whole content, channel switcher, standard decoder. With signaling information of multicasting from MBMS of LTE through the base station like eNodeB, mobile subscriber starts to receive the multicast stream and select channels via logical channel switcher. Next, the channel switcher determines channel id according to the requested content and indicates. LTE PHY/MAC will decode only those MBMS MAC PDUs associated with the selected channel ID. After receiving the first segment from the channel, S1, it also receives other related segments from the rest of the channels simultaneously while MS watches S1. Finally user application decrypts and reconstructs the content packets according to standard H.264/AVC video decoding. After MS receives all the segments, the segments ordering will be performed by FLUTE of MBMS. Because of transmission environment, the segment order might be changed.

2.7. LTE network design and deployment

In this section we will describe in more details the network design and network deployment of LTE technology. As it was mention before, in contrast to the circuit-switched model of previous cellular systems, Long Term Evolution (LTE) has been designed to support only packet-switched services. It aims to provide seamless Internet Protocol (IP) connectivity between user equipment (UE) and the packet data network (PDN), without any disruption to the end users' applications during mobility. While the term "LTE" encompasses the evolution of the UMTS radio access through the Evolved UTRAN (E-UTRAN), it is accompanied by an evolution of the non-radio aspects under the term "SAE", which (as we described before) includes the Evolved Packet Core (EPC) network. Together LTE and SAE comprise the EPS.

EPS uses the concept of EPS bearers to route IP traffic from a gateway in the PDN to the UE. A bearer is an IP packet flow with a defined quality of service (QoS) between the gateway and the UE. The E-UTRAN and EPC together set up and release bearers as required by applications. EPS provides the user with IP connectivity to a PDN for accessing the Internet, as well as for running services such as VoIP. An EPS bearer is typically associated with a QoS. Multiple bearers can be established for a user in order to provide different QoS streams or connectivity to different PDNs. For example, a user might be engaged in a voice (VoIP) call while at the same time performing web browsing or FTP download. A VoIP bearer would provide the necessary QoS for the voice call, while a best-effort bearer would be suitable for the web browsing or FTP session.

The network must also provide sufficient security and privacy for the user and protection for the network against fraudulent use. This is achieved by means of several EPS network elements that have different roles. Figure 2.25 shows the overall network architecture, including the network elements and the standardized interfaces.

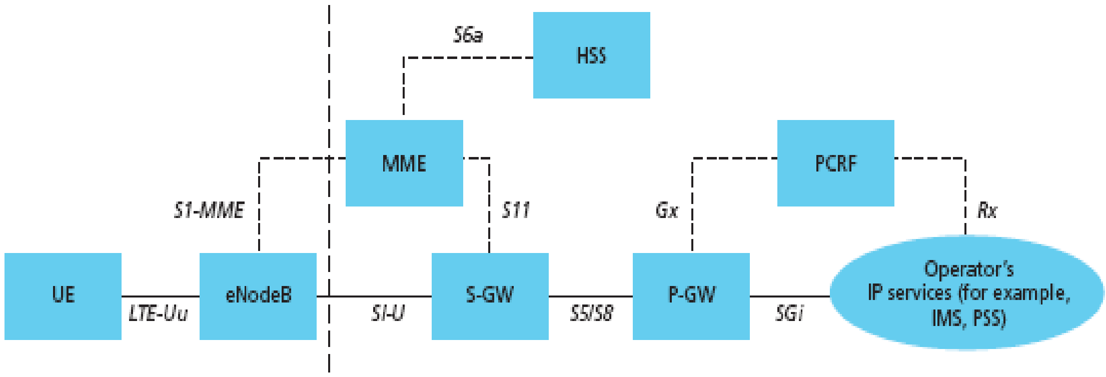


Figure 2.25. Illustration of the EPS network elements.

At a high level, the network is comprised of the CN (EPC) and the access network E-UTRAN. While the CN consists of many logical nodes, the access network is made up of essentially just one node, the evolved NodeB (eNodeB), which connects to the UEs. Each of these network elements is interconnected by means of interfaces that are standardized in order to allow multi-vendor interoperability. This gives network operators the possibility to source different network elements from different vendors. In fact, network operators may choose in their physical implementations to split or merge these logical network elements depending on commercial considerations. The functional split between the EPC and E-UTRAN is shown in Figure 2.26. The EPC and E-UTRAN network elements are described in more detail below.

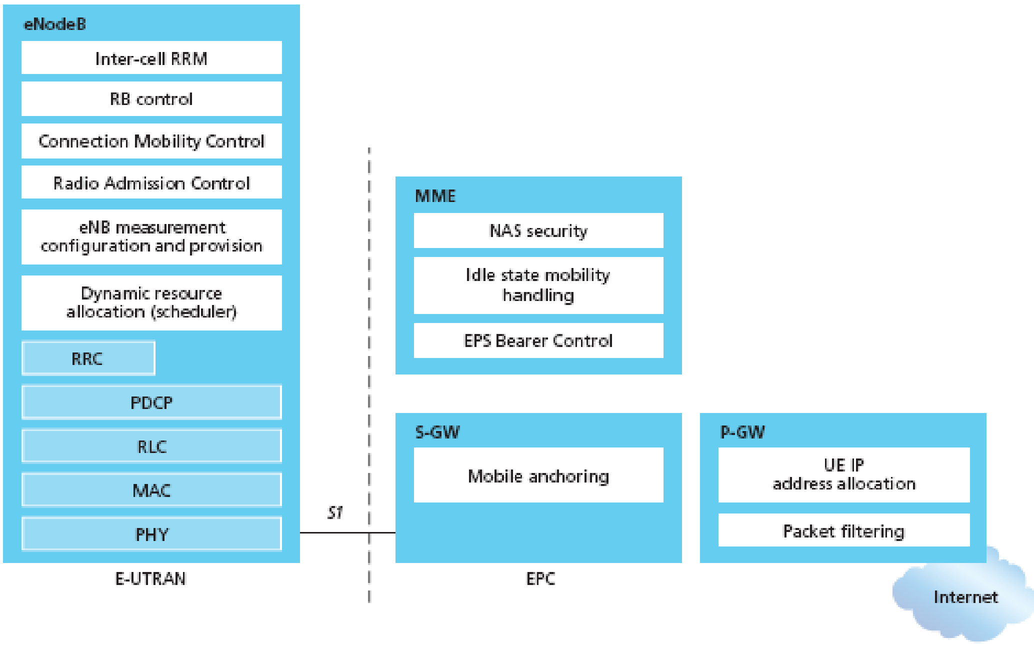


Figure 2.26. Functional split between E-UTRAN and EPC.

- **The core network**

The core network (called EPC in SAE) is responsible for the overall control of the UE and establishment of the bearers. The main logical nodes of the EPC are:

- ✓ PDN Gateway (**P-GW**)
- ✓ Serving Gateway (**S-GW**)
- ✓ Mobility Management Entity (**MME**)

In addition to these nodes, EPC also includes other logical nodes and functions such as the Home Subscriber Server (**HSS**) and the Policy Control and Charging Rules Function (**PCRF**). Since the EPS only provides a bearer path of a certain QoS, control of multimedia applications such as VoIP is provided by the **IMS**, which is considered to be outside the EPS itself.

The logical CN nodes are shown in Figure 2.25 and discussed in more detail below:

- ✓ PCRF – The **Policy Control and Charging Rules Function** is responsible for policy control decision-making, as well as for controlling the flow-based charging functionalities in the Policy Control Enforcement Function (PCEF), which resides in the P-GW. The PCRF provides the QoS authorization (QoS class identifier [QCI] and bit rates) that decides how a certain data flow will be treated in the PCEF and ensures that this is in accordance with the user's subscription profile.
- ✓ HSS – The **Home Subscriber Server** contains users' SAE subscription data such as the EPS-subscribed QoS profile and any access restrictions for roaming. It also holds information about the PDNs to which the user can connect. This could be in the form of an access point name (APN) (which is a label according to DNS naming conventions describing the access point to the PDN) or a PDN address (indicating subscribed IP address(es)). In addition the HSS holds dynamic information such as the identity of the MME to which the user is currently attached or registered. The HSS may also integrate the authentication center (AUC), which generates the vectors for authentication and security keys.
- ✓ P-GW – The **PDN Gateway** is responsible for IP address allocation for the UE, as well as QoS enforcement and flow-based charging according to rules from the PCRF. It is responsible for the filtering of downlink user IP packets into the different QoS-based bearers. This is performed based on Traffic Flow Templates (TFTs). The P-GW performs QoS enforcement for guaranteed bit rate (GBR) bearers. It also serves as the mobility anchor for interworking with non-3GPP technologies such as CDMA2000 and WiMAX networks.
- ✓ S-GW – All user IP packets are transferred through the **Serving Gateway**, which serves as the local mobility anchor for the data bearers when the UE moves between eNodeBs. It also retains the information about the bearers when the UE is in the idle state (known as "EPS Connection Management — IDLE" [ECM-IDLE]) and temporarily buffers downlink data while the MME initiates paging of the UE to reestablish the bearers. In addition, the S-GW performs some administrative functions in the visited network such as collecting information for charging (for example, the volume of data sent to or received from the user) and lawful interception. It also serves as the mobility anchor for interworking with other 3GPP technologies such as general packet radio service (GPRS) and UMTS.
- ✓ MME – The **Mobility Management Entity** (MME) is the control node that processes the signaling between the UE and the CN. The protocols running between the UE and the CN are known as the Non Access Stratum (NAS) protocols.

  The main functions supported by the MME can be classified as:
  - ▪ Functions related to bearer management – This includes the establishment, maintenance and release of the bearers and is handled by the session management layer in the NAS protocol.
  - ▪ Functions related to connection management – This includes the establishment of the connection and security between the network

and UE and is handled by the connection or mobility management layer in the NAS protocol layer.

Non Access Stratum (NAS) control procedures are specified in [15] and are discussed in more detail in the following.

The NAS procedures, especially the connection management procedures, are fundamentally similar to UMTS. The main change from UMTS is that EPS allows concatenation of some procedures to allow faster establishment of the connection and the bearers. The MME creates a UE context when a UE is turned on and attaches to the network. It assigns a unique short temporary identity termed the SAE Temporary Mobile Subscriber Identity (S-TMSI) to the UE that identifies the UE context in the MME. This UE context holds user subscription information downloaded from the HSS. The local storage of subscription data in the MME allows faster execution of procedures such as bearer establishment since it removes the need to consult the HSS every time. In addition, the UE context also holds dynamic information such as the list of bearers that are established and the terminal capabilities.

To reduce the overhead in the E-UTRAN and processing in the UE, all UE-related information in the access network, including the radio bearers, can be released during long periods of data inactivity. This is the ECM-IDLE state. The MME retains the UE context and the information about the established bearers during these idle periods. To allow the network to contact an ECM-IDLE UE, the UE updates the network as to its new location whenever it moves out of its current tracking area (TA); this procedure is called a tracking area update. The MME is responsible for keeping track of the user location while the UE is in ECM-IDLE. When there is a need to deliver downlink data to an ECM-IDLE UE, the MME sends a paging message to all the eNodeBs in its current TA, and the eNodeBs page the UE over the radio interface. On receipt of a paging message, the UE performs a Service Request procedure, which results in moving the UE to the ECM-CONNECTED state. UE-related information is thereby created in the E-UTRAN, and the radio bearers are reestablished. The MME is responsible for the reestablishment of the radio bearers and updating the UE context in the eNodeB. This transition between the UE states is called an idle-to-active transition. To speed up the idle-to-active transition and bearer establishment, EPS supports concatenation of the NAS and Access Stratum (AS) procedures for bearer activation.

Some interrelationship between the NAS and AS protocols is intentionally used to allow procedures to run simultaneously rather than sequentially, as in UMTS. For example, the bearer establishment procedure can be executed by the network without waiting for the completion of the security procedure. Security functions are the responsibility of the MME for both signaling and user data. When a UE attaches with the network, a mutual authentication of the UE and the network is performed between the UE and the MME/HSS. This authentication function also establishes the security keys that are used for encryption of the bearers.

➢ **The access network**

The access network of LTE, **E-UTRAN**, simply consists of a network of eNodeBs, as illustrated in Figure 2.27. For normal user traffic (as opposed to broadcast), there is no centralized controller in E-UTRAN; hence the E-UTRAN architecture is said to be flat. The eNodeBs are normally interconnected with each other by means of an interface known as "X2" and to the EPC by means of the S1 interface — more specifically, to the MME by means of the S1-MME interface and to the S-GW by means of the S1-U interface.

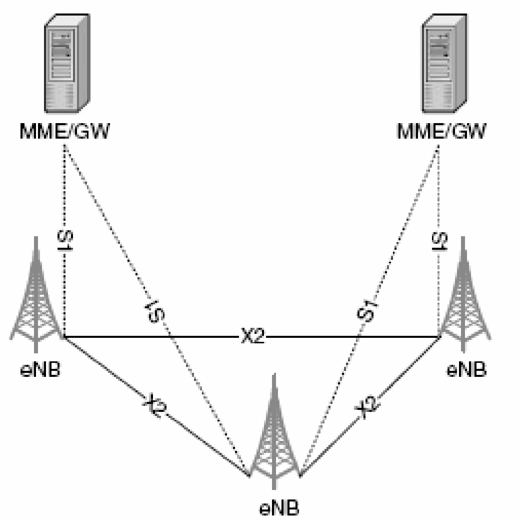


Figure 2.27. Overall E-UTRAN architecture.

The protocols that run between the eNodeBs and the UE are known as the "AS protocols." The E-UTRAN is responsible for all radio-related functions, which can be summarized briefly as:

- ✓ Radio resource management (RRM) – This covers all functions related to the radio bearers, such as radio bearer control, radio admission control, radio mobility control, scheduling and dynamic allocation of resources to UEs in both uplink and downlink.
- ✓ Header Compression – This helps to ensure efficient use of the radio interface by compressing the IP packet headers that could otherwise represent a significant overhead, especially for small packets such as VoIP.
- ✓ Security – All data sent over the radio interface is encrypted.
- ✓ Connectivity to the EPC – This consists of the signaling toward MME and the bearer path toward the S-GW.

On the network side, all of these functions reside in the eNodeBs, each of which can be responsible for managing multiple cells. Unlike some of the previous second- and third-generation technologies, LTE integrates the radio controller function into the eNodeB. This allows tight interaction between the different protocol layers of the radio access network (RAN), thus reducing latency and improving efficiency. Such distributed control eliminates the need for a high-availability, processing-intensive controller, which in turn has the potential to reduce costs and avoid “single points of failure.” Furthermore, as LTE does not support soft handover there is no need for a centralized data-combining function in the network. One consequence of the lack of a centralized controller node is that, as the UE moves, the network must transfer all information related to a UE, that is, the UE context, together with any buffered data, from one eNodeB to another. Mechanisms are therefore needed to avoid data loss during handover. The operation of the X2 interface for this purpose is explained in more detail in [18]. An important feature of the S1 interface linking the access network to the CN is known as “S1-flex.” This is a concept whereby multiple CN nodes (MME/S-GWs) can serve a common geographical area, being connected by a mesh network to the set of eNodeBs in that area.

An eNodeB may thus be served by multiple MME/S-GWs, as is the case for eNodeB #2 in Figure 2.27. The set of MME/S-GW nodes that serves a common area is called an MME/S-GW pool, and the area covered by such a pool of MME/S-GWs is called a pool area. This concept allows UEs in the cell or cells controlled by one eNodeB to be shared between multiple CN nodes, thereby providing a possibility for load sharing and also eliminating single points of failure for the CN nodes. The UE context normally remains with the same MME as long as the UE is located within the pool area.

- **The Roaming architecture**

A network run by one operator in one country is known as a “public land mobile network (PLMN).” Roaming, where users are allowed to connect to PLMNs other than those to which they are directly subscribed is a powerful feature for mobile networks, and LTE/SAE is no exception. A roaming user is connected to the E-UTRAN, MME and S-GW of the visited LTE network. However, LTE/SAE allows the P-GW of either the visited or the home network to be used, as shown in Figure 2.28. Using the home network’s P-GW allows the user to access the home operator’s services even while in a visited network. A P-GW in the visited network allows a “local breakout” to the Internet in the visited network.

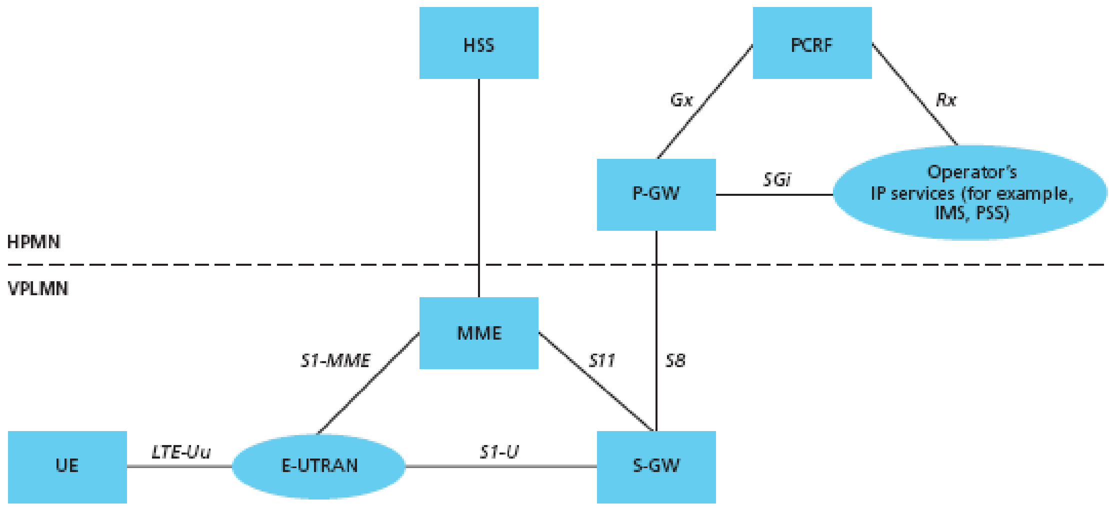


Figure. 2.28. Roaming architecture for 3GPP accesses with P-GW in home network.

- **Interworking with other networks**

The EPS also supports interworking and mobility (handover) with networks using other Radio Access Technologies (RATs), notably Global System for Mobile Communications (GSM), UMTS, CDMA2000 and WiMAX. The architecture for interworking with 2G and 3G GPRS/UMTS networks is shown in Figure 2.29. The S-GW acts as the mobility anchor for interworking with other 3GPP technologies such as GSM and UMTS, while the P-GW serves as an anchor allowing seamless mobility to non-3GPP networks such as CDMA2000 or WiMAX. The P-GW may also support a Proxy Mobile Internet Protocol (PMIP)-based interface. More details of the radio interface procedures for interworking are specified in [21].

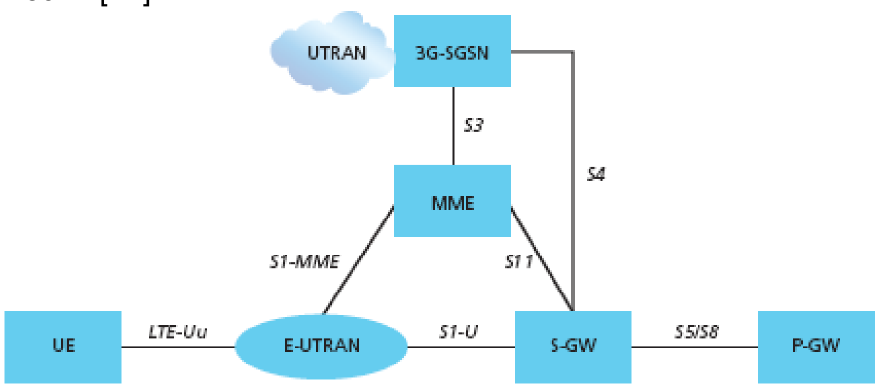


Figure. 2.29. Architecture for LTE - 3G UMTS interworking.

Furthermore, we outline the radio protocol architecture of E-UTRAN (from user and control plane perspective).

- **User plane**

An IP packet for a UE is encapsulated in an EPC-specific protocol and tunneled between the P-GW and the eNodeB for transmission to the UE. Different tunneling protocols are used across different interfaces. A 3GPP-specific tunneling protocol called the GPRS Tunneling Protocol (GTP) is used over the CN interfaces, S1 and S5/S8.1.

The E-UTRAN user plane protocol stack is shown in blue in Figure 2.30, consisting of the Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC) and Medium Access Control (MAC) sublayers that are terminated in the eNodeB on the network side. The respective roles of each of these layers are explained in detail in Chapter 4 of [19].

In the absence of any centralized controller node, data buffering during handover due to user mobility in the E-UTRAN must be performed in the eNodeB itself. Data protection during handover is a responsibility of the PDCP layer. The RLC and MAC layers both start afresh in a new cell after handover.

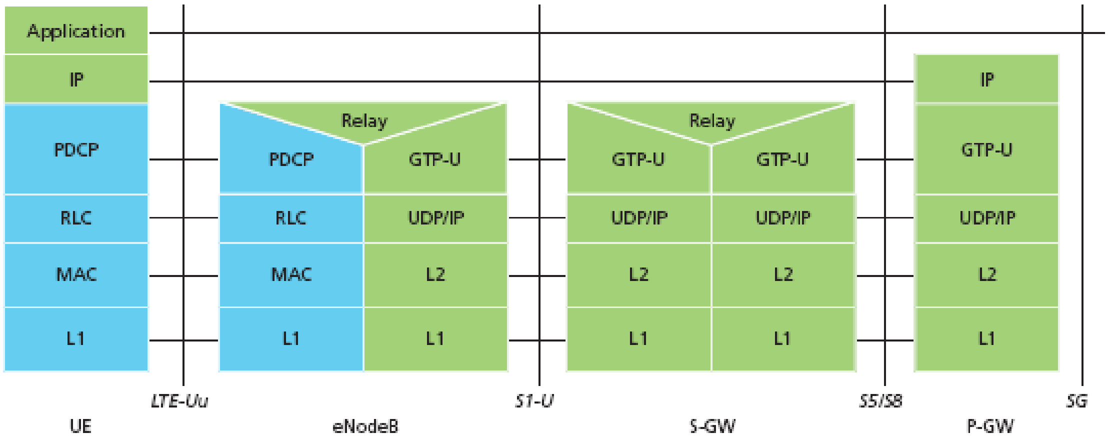


Figure. 2.30. The E-UTRAN user plane protocol stack.

- **Control plane**

The protocol stack for the control plane between the UE and MME is shown in Figure 2.31. The blue region of the stack indicates the AS protocols. The lower layers perform the same functions as for the user plane with the exception that there is no header compression function for the control plane. The Radio Resource Control (RRC) protocol is known as “layer 3” in the AS protocol stack. It is the main controlling function in the AS, being responsible for establishing the radio bearers and configuring all the lower layers using RRC signaling between the eNodeB and the UE.

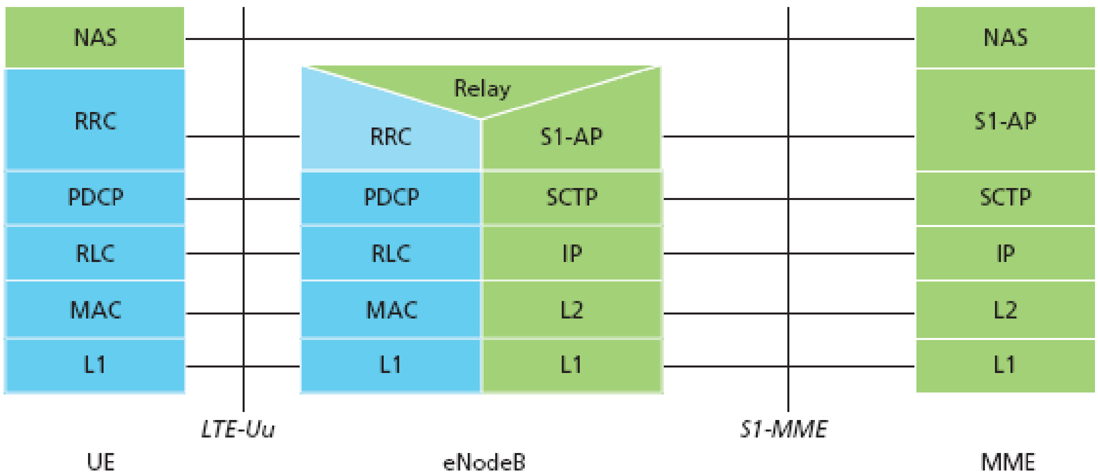


Figure. 2.31. The Control plane protocol stack.

- **Network Deployment**

The number of mobile operators who have committed to deploy LTE advanced mobile broadband systems has more than doubled in the past year. There are now 64 operators committed to LTE network deployments in 31 countries, according to the Global mobile Suppliers Association (GSA) as confirmed in the April 2010 update of its Evolution to LTE report. This compares to 31 network commitments identified by GSA in a similar study 12 months earlier. LTE networks are now being installed or planned for commercial service in Armenia, Australia, Austria, Bahrain, Brazil, Canada, China, Estonia, Finland, France, Germany, Hong Kong SAR, Ireland, Italy, Japan, Jordan, Netherlands, New Zealand, Norway, The Philippines, Portugal, Russia, Saudi Arabia, Singapore, South Africa, South Korea, Sweden, Taiwan, UAE, USA, and Uzbekistan. LTE systems were commercially launched in December 2009 in Norway and Sweden.

Moreover, GSA forecasts that up to 22 LTE networks will be in commercial service by end 2010, and expects this figure to grow to 39 or more LTE networks commercially launched by end 2012. The Evolution to LTE report also confirms there are 24 additional operators who have decided to undertake technology tests or trials of LTE, from which additional commitments to deploy commercial systems are expected to follow in due course. These trials are taking place, or firmly scheduled to be undertaken, in 11 additional countries – Argentina, Belgium, Chile, Czech Republic, Hungary, Indonesia, Kazakhstan, Slovak Republic, Spain, UK and Ukraine.

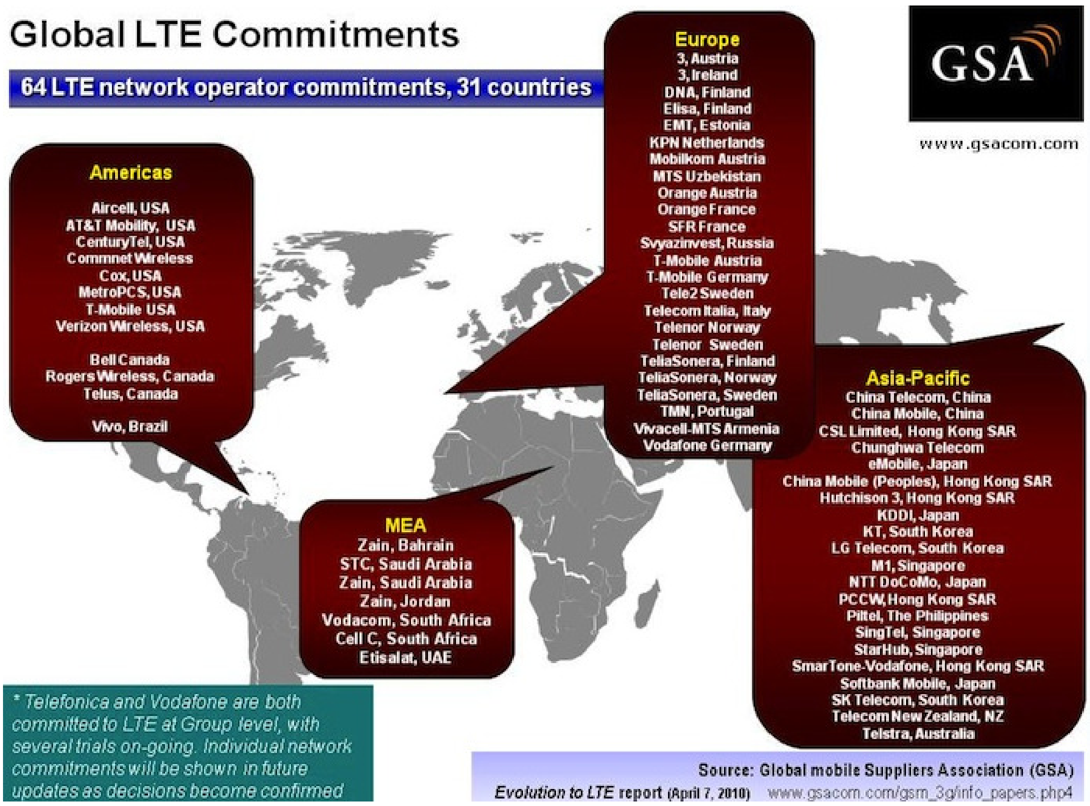


Figure. 2.32. Illustration of the Global LTE commitments.

Alan Hadden, President, GSA said: "A total of 88 operators in 42 countries have now committed to deploy LTE systems or are engaged in trials or other planning/preparatory activities. Mobile broadband is a global success, driven by HSPA. While HSPA+ systems are meeting the challenge to deliver higher data capacities today, LTE brings the opportunity for additional spectrum, more capacity, lower cost, and is essential to take mobile broadband to the mass market.”

Information is included in the report on the growing eco-system, which includes an expanding range of platforms and user devices.

Moreover, the key findings from extensive independent drive test evaluations of the commercial LTE networks in Stockholm and Oslo are provided which confirm that LTE already outperforms many fixed broadband connections.

2.8. 3G HSPA vs. LTE comparison

There has been a lot of press lately about next-generation LTE and the speeds it will bring to wireless broadband. There has also been a lot about networks upgrading to 3G HSPA and HSPA+ to achieve similar data speeds. There are a lot of recent reports which are showing in great details how much money a network operator could save by upgrading to HSPA+ and not moving to LTE at this point in time, or moving in LTE and saving more CAPEX and OPEX without upgrading to HSPA+.

One of the great things about competition is that network operators can make choices based on their own perceptions of the two technologies, their customer base, existing demand for data, and their projections for increased broadband usage over time. The decision also needs to be based on the amount of spectrum available to be dedicated to HSPA+ or LTE. LTE can operate in bandwidths of 1.4, 3, 5, 10, or 20 MHz while HSPA+ is designed to be deployed in 5 MHz of spectrum.

Moreover, a core battle raging between the two technologies concerns the often-inflated claims about data speeds and capacities in a given amount of spectrum. HSPA+ specifications state that data rates up to 56 Mbps down and 22 Mbps up are possible using MIMO (dual antenna) systems. LTE claims data rates of 43 Mbps down to devices in 5 MHz of spectrum and 29 Mbps for an uplink. However, all of these data rates are theoretical in nature.

Furthermore, let we see the differences between 3G HSPA and LTE network architecture and advantages/disadvantages of each technology. In Figure 2.33 the architecture of 3G HSPA and LTE RANs is given, and moreover, in Figure 2.34 is shown how the network intelligence in LTE is pushdown from access gateway to eNodeB entity.

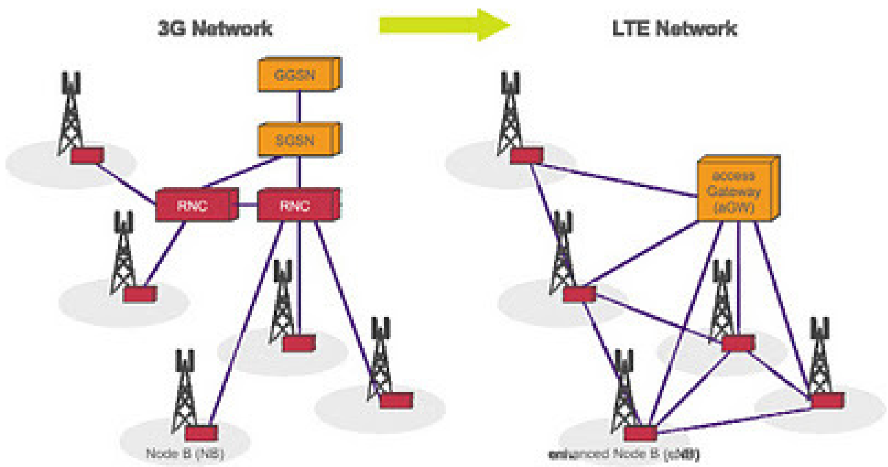


Figure 2.33. Comparison of 3G HSPA and LTE access networks.

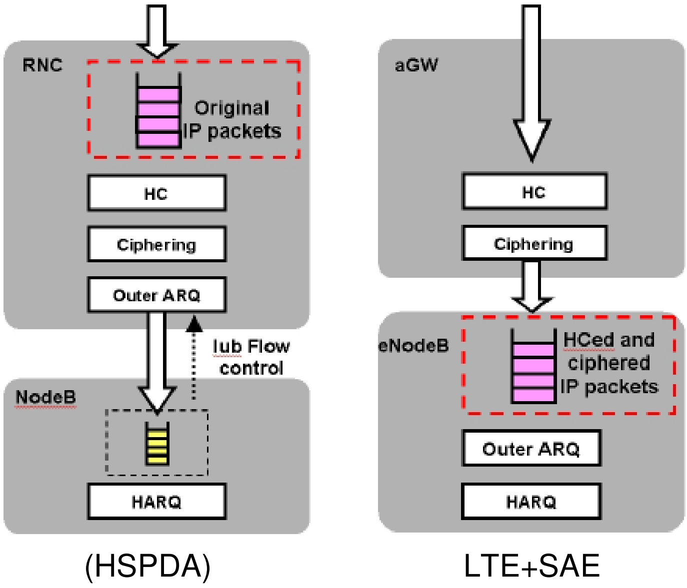


Figure 2.34. Differences between HSPDA and LTE/SAE Access Networks.

Moreover, the main advantages of LTE over 3G HSPA and HSPA+ are the following:

- ✓ Flexible Spectrum usage possible with LTE: LTE will be the same whether the bandwidth available is 5MHz or 20MHz. Of course the data rate will increase when the BW is increased. With HSPA+ only 5MHz bandwidhts possible. Similalrly with HSPA+ only FDD mode of operation is possible whereas with LTE FDD or TDD mode is possible.
- ✓ Spectrum Effeciency: Better spectrum effeciency, by a factor of 2 atleast over HSPA+
- ✓ Simpler Architecture: LTE has a much simpler and relatively flat architecture compared to the legacy UMTS network in HSPA+
- ✓ Higher Data Rates: LTE gives DL data rates of 144Mbps and UL of 57Mbps. HSPA+ gives 42Mbps in DL and 11Mbps in UL
- ✓ Ultra Low Latency: 10ms instead of 50ms for HSPA+
- ✓ Short TTI: 0.5ms instead of 2ms for HSPA+

On the other hand, the key advantages of 3G HSPA and HSPA+ over LTE are the following:

- ✓ HSPA is ready much before LTE: HSPA+ technology is available in Q1 2009 whereas the earliest LTE (Release 8) is became available in 2010.
- ✓ Much less investment in infrastructure: Since HSPA+ is evolution of HSPA which is already being deployed, it would be easier and less costly to upgrade. With LTE since its based on OFDM a lot of new components will be required. Also in case of LTE the number of components is reduced but since they work in a different way, new components will be required.

Finally, in the Table 2.6 are summarized above mentioned advantages of 3G/HSPA/HSPA+ and LTE technologies.

Table 2.6. 3G/HSPA/HSPA+ and LTE comparisons

	WCDMA (UMTS)	HSPA HSDPA / HSUPA	HSPA+	LTE
Max downlink speed bps	384 k	14 M	28 M	100 M
Max uplink speed bps	128 k	5.7 M	11 M	50 M
Latency round trip time approx	150 ms	100 ms	50ms (max)	~10 ms
3GPP releases	Rel 99/4	Rel 5 / 6	Rel 7	Rel 8
Approx years of initial roll out	2003 / 4	2005 / 6 HSDPA 2007 / 8 HSUPA	2008 / 9	2009 / 10
Access methodology	CDMA	CDMA	CDMA	OFDMA / SC-FDMA

In addition to this, LTE is an all IP based network, supporting both IPv4 and IPv6. There is also no basic provision for voice, although this can be carried as VoIP. After all, LTE can be seen for provide a further evolution of functionality, increased speeds and general improved performance.

So while the battle between HSPA+ and LTE continues to rage on within the wireless marketplace, the customers, who don't care what the faster technology is called, will benefit from faster speeds and more capacity. Faster data speeds are coming, or are here in some cases. They are not as fast as many in the industry would like us to believe, but they are a lot faster than anything we have been able to have previously. It won't matter whether your network operator's choice is HSPA+ or LTE for the next few years, the migration to LTE will undoubtedly continue to take place over the next three years and as these networks are being built, later releases of the standard will add even more speed and capacity to the networks at very little additional cost to the operator. Wireless broadband services are shared with other customers within the same cell sector, but having faster data speeds and increased capacity will benefit all of us, whichever technology is deployed and whichever network we subscribe to. Another bright spot is that all of today's 2G and 3G spectrum can be converted to LTE over time if demand warrants it. As more video is sent and received over the wired Internet and then over the wireless Internet, the additional speed and capacity will help us get on and off the networks faster, freeing up the bandwidth for others.

The battle over moving toward with either HSPA or LTE will continue to be waged by network operators; that is what they do. They look for advantages to attract more customers and keep the ones they already have. The cost of providing wireless broadband will continue to come down as these more efficient technologies are deployed, and customers will benefit from the higher speeds. In the meantime, the industry needs to be more realistic in its claims about data speeds and capacity. Customers who know what to expect will be happier than customers who feel they were promised data speeds that cannot be delivered in the real world, no matter what technology is deployed.

2.9. Regulation of LTE

Regulation of the telecommunications industry has traditionally focused on the supply side of the industry, chiefly the retail segment of the market. Since liberalization of the industry has begun, regulation has gradually shifted to the wholesale segment of the market. The regulatory agencies have intervened to regulate access and facilitate entry and, hopefully, investment in infrastructure. This asymmetric regulation has had mixed results. As an answer to that some regulatory agencies have abandoned wholesale regulation (the case of the USA) and some others have shifted from light- handed regulation to heavy- handed regulation with mandatory unbundling of the local loop (the case of Australia). Other regulatory agencies have moved to a more gradual type of wholesale deregulation on the grounds that competition in this segment of the market has not yet fully developed, but as it grows the need for regulation is reduced (the case of Europe and Canada).

From a regulatory perspective, the deployment of NGMN (including LTE deployment) is linked with two main pillars of the electronic communications framework: spectrum management and the triangle "**investment – competition – innovation**". Together, they form what we could name as "the model" for the future mobile industries from the public perspective. Both of them are currently under review due precisely to their impact on the deployment of NGMNs.

Moreover, the regulatory model chosen may impact positively or negatively on investment in LTE/SAE broadband infrastructure. Additionally, ubiquitous broadband and mobile applications create new needs for spectrum availability and spectrum management becomes an important function of the regulatory agencies, particularly at this time of rapid evolution of the mobile technologies. The LTE/SAE require a new distinctive regulatory and policy framework which will deal explicitly with the issues and opportunities of the next phase of wireless technologies.

However, the regulation evolves and its evolution is the result and the impetus of change of the telecommunications industry structure and performance. As the industry becomes more mature and incumbents and new entrants get more familiar with the rules of the game, they become able to develop strategies which increase the value of the firm. In a competitive context telecommunications firms will invest only if their investment achieves an average return which is greater than the weighted average cost of capital (WACC). Projects with positive net present values (adjusted for specific risks) are value accretive and therefore it is worth undertaking them. They will bring more wealth to stakeholders through dividends and capital gains. In a regulatory context the investment decisions, particularly for projects of high risk (sunk investments in broadband and LTE, for instance) may not occur or may be 'unreasonably' delayed. Thus, under specific regulatory frameworks, deployment of LTE technologies may not be optimal, LTE may not roll out adequately or optimally, consumers may be “impaired” or harmed; and these are not necessarily the results the regulatory authorities have sought to achieve in the first place. Regulation thus has a role in an evolving global telecommunications industry.

On the other hand, LTE networks will need new spectrum if a truly ubiquitous broadband connectivity is to be achieved in a competitive environment. To emphasize, the total budget of spectrum for NGMNs and especially for LTE will depend on the availability of spectrum, on the level of competition (that is, the number of mobile network operators in the market) and on the expected return on investments. Higher quality of service will need more spectrums per user. In Figure 2.35 the spectrum management relations with ITU-R, Operators, with foreign administration bodies and with regulation authority are shown.

In fact, many national authorities in charge of spectrum management, the European Commission or the ITU, have released documents supporting the modification of the current spectrum management models and defending the inclusion of market mechanisms. Therefore, that the radio-electric spectrum needs a new management model – or at least a renewed one – is an assertion over which there exists a consensus among public administrations, players with interest in the market and researchers. The new ways of managing the spectrum intend to increase flexibility and transparency, as well as the speed of the response to technological innovations. The actual demand and the value given by the market to each band of frequencies are new governing criteria. Obviously, any change should improve global resource usage efficiency, while maintaining certain inalienable technical requirements.

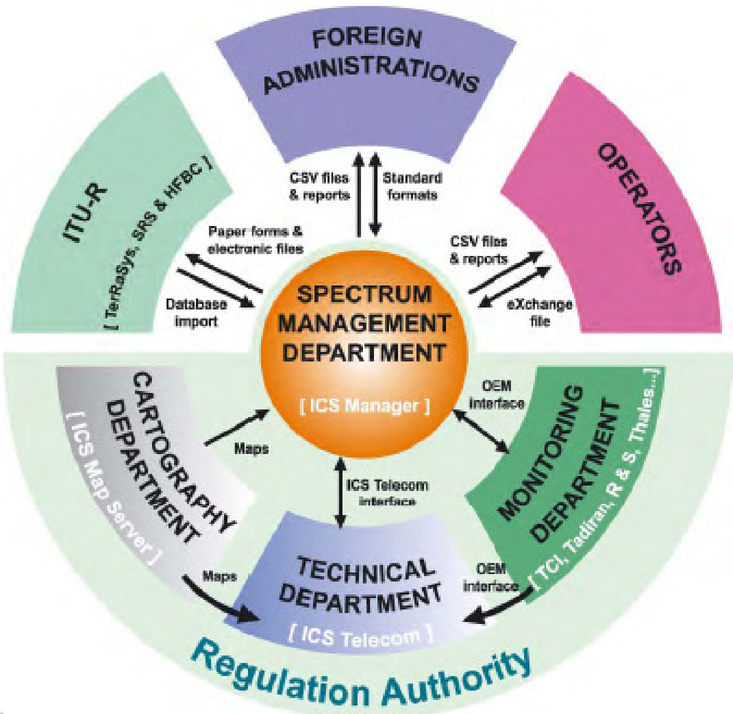


Figure 2.35. Illustration of Spectrum management relations with regulation authorities.

There are three possible steps leading to change. These are listed in ascending order in the process of assignment of the spectrum usage rights:

- ✓ Modifications in the conditions of the license: relaxation of some clauses but, especially, authorization of the transmission of rights (secondary spectrum trade).
- ✓ Modifications in the license-assignment mechanisms: usage of auctions.
- ✓ Modifications in the definition of the licenses: avoiding binding the license to specific technologies – technological neutrality; or even to specific services – service neutrality.

In addition to making more flexible and decreasing the costs of NGMN deployment, it is worth mentioning that an efficient spectrum framework would increment the number of potential mobile network operators in the market and the overall level of competition in the electronic communications domain. Equivalently, given a certain amount of available frequencies, spectrum management will determine the initial level of competition and the rules for its evolution.

Furthermore, future is almost present – for LTE and other mobile and wireless access technologies will need more efficient access to broader-spectrum bands to be able to compete in the ubiquitous broadband landscape. Therefore, the reform of spectrum management has a prime role. Spectrum management, however relevant, is only one part of the equation. It should be framed in a larger perspective: policy- makers and regulators should define a scenario for LTE deployment as the cornerstone to stimulate innovation that is transferred to markets and users in the form of new services, applications and businesses. There are two minimum conditions for this scenario to be achieved:

- ➢ stability, since the time required for the return on investments for the deployment of LTE (and generally for NGMNs) will be longer than for previous generations of mobile and wireless technologies;
- ➢ and coherence, in the sense of the definition of a model – comprised policies on spectrum management, investment, innovation and competition in NGN – for mobile operators.

Beyond these minimum conditions there could be more ambitious and challenging objectives. These additional objectives are related not to the LTE (or to NGMN) deployment as such, but to the still to be fully understood innovation which could originate from a ubiquitous mobile broadband infrastructure. The new mobile innovation would require:

- ✓ more open ecosystem (see the Figure 2.36 -each segment of the ecosystem has a role to play in LTE's success) to decrease the barriers of an heterogeneous and fragmented ecosystem in particular when compared with the Internet;
- ✓ making the most of the new role of users;
- ✓ and reviewing the institutional framework that supports it, including some additional pieces of the regulatory framework like the intermittently debated convergence with audiovisual.

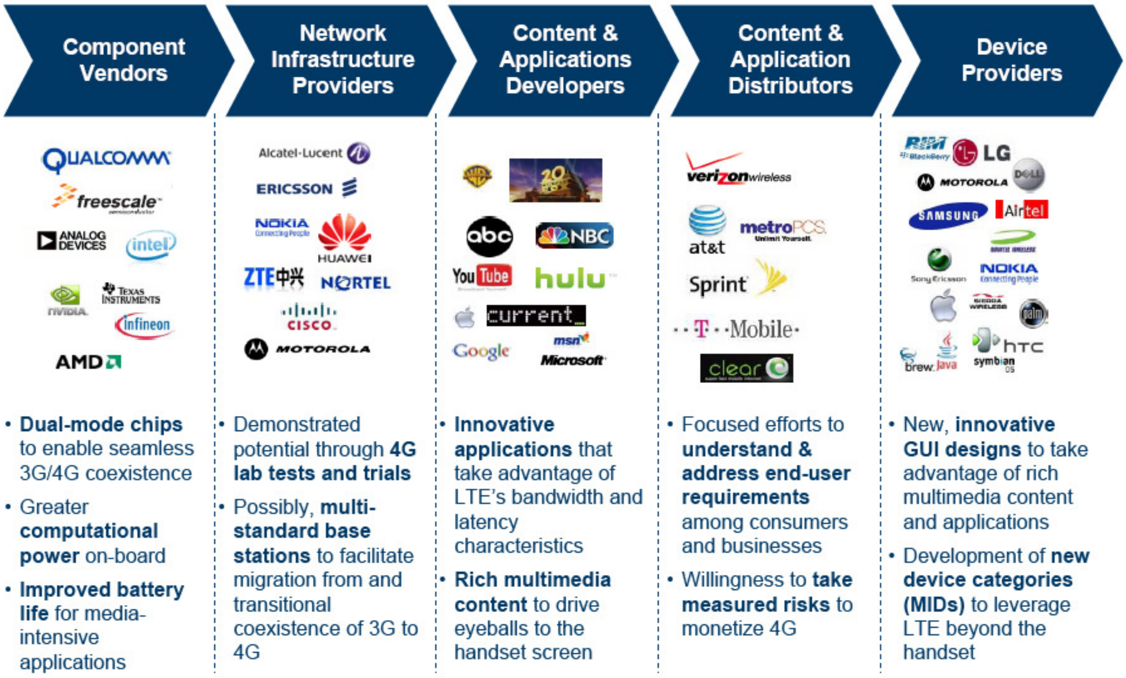


Figure 2.36. LTE ecosystem.

The final challenge consists of meeting these goals while the mobile operators are still in the process of investing in LTE/SAE networks.

In conclusion, both elements of reform – spectrum management and regulatory policy framework – have been on the agenda since the stage for the initial liberalization of electronic communications was – approximately – met in about 2002–03 in Europe, though they have never reached actual and complete implementation.

From our opinion, the window of opportunity for mobile operators' deployment of NGMNs is and will be open up to the medium term and, to a great extent, it will be independent of regulation as the LTE deployment commitments of operators have proved even during times of economic crisis. However, the regulatory policy framework severely impacts the intensity and speed of the LTE deployment and, through the ubiquitous broadband this will provide, of a long-awaited new wave of applications and societal empowerment.

2.10. LTE business case

LTE is still technically a pre-standard technology and yet is seeing unprecedented interest from vendors and operators alike. The question is: can operators who are only just starting to see returns from their 3G licenses really justify investing in what is essentially a new replacement technology? This section gives the main technical and market dilemmas faced by operators and vendors in their migration to LTE, examining the LTE business case in the context of a converging communications world. However, there is a huge challenge and in the same time a great risks associated with the upgrade to a totally new technology and the progress made by the principal vendors and standards bodies involved. The transition to LTE promises to fundamentally change the mobility ecosystem and enable new capabilities well beyond traditional voice and data services. As the migration to LTE gains momentum, all members of the ecosystem – carriers in particular – are taking a closer look at the LTE business case, together with the critical factors for LTE deployments to succeed. It is more then obvious that success rests on business case, and underlying economic drivers, for LTE.

As it is well known, LTE's economic benefits are grounded in the new capabilities it has to offer. Higher-bandwidth and lower-latency will significantly improve the user experience for bandwidth-hungry content and applications. LTE's all-IP architecture, spectral efficiency, and bandwidth flexibility, promise to improve overall network economics. To understand how these capabilities will impact the LTE business case, it's useful to consider their potential impact on subscriber economics: Average Revenue per User (**ARPU**), Cash Cost per User (**CCPU**), Cost per Gross Addition (**CPGA**), churn, and adoption.

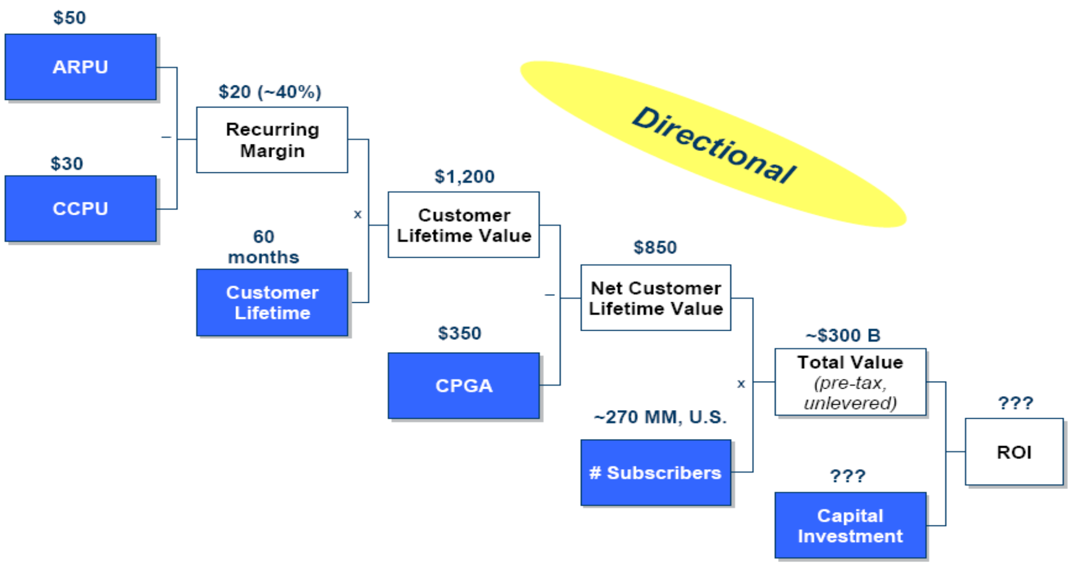


Figure 2.37. LTE Business case.

Moreover, in Figure 2.37 the LTE business case steps, factors and direction are illustrated. ARPU or sometimes average revenue per unit, usually abbreviated to ARPU is a measure used primarily by consumer communications and networking companies, defined as the total revenue divided by the number of subscribers. It has been trending flat to down in recent years, falling from roughly $52 at the end of 2005, to nearly $50 today on a blended basis. During this same period, data ARPU roughly doubled from $5 to $10, helping offset a nearly 15% decline in voice ARPU. LTE promises to reverse these declines by accelerating adoption of high-speed data services and innovative new content and applications. The dilemma for carriers, however, is that LTE's all-IP architecture will create a more open environment for Over The Top (OTT) applications, including third-party VoIP services, which threaten to further commoditize the network. To overcome this threat and realize revenue gains from LTE, carriers will need to partner with content and application providers, develop application store-fronts such as Apple's App Store, and perhaps deploy APIs that expose LTE's value-added network capabilities to third-party application and content developers for a fee. On the other hand, value-added applications offset ARPU declines in other price components (just consider the opportunity cost of inaction in Figure 3.38).

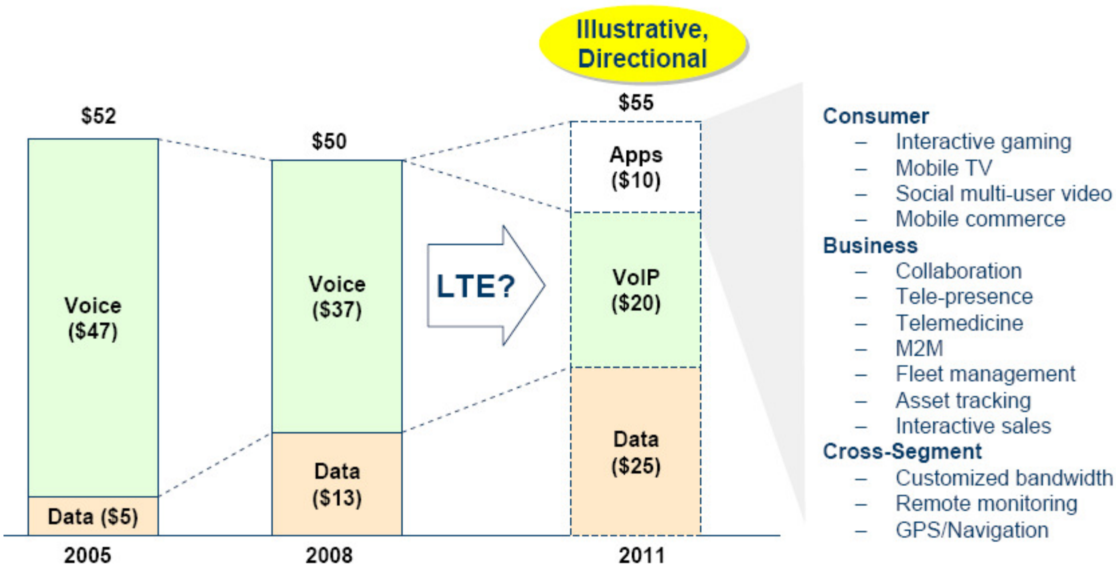
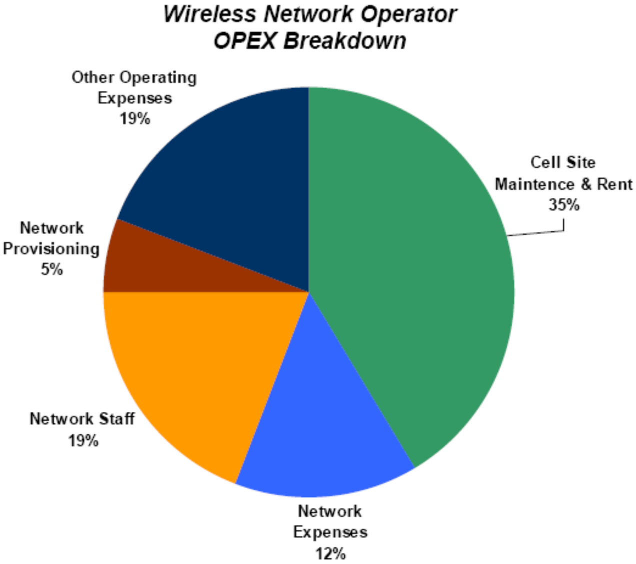


Figure 3.38. Illustration of the Average ARPU Components.

Furthermore, CCPU averages about 50% of ARPU today. LTE's IP architecture and greater use of Ethernet backhaul could significantly reduce transport costs per Megabit, a key component of CCPU, relative to comparable 3G networks. Moreover, LTE's greater spectral efficiency, bandwidth flexibility, and use of 700 MHz spectrum, should reduce the number of cell sites and related costs required to serve subscribers (long story-short: we have significantly reduced network expenses). In Figure 3.39 Wireless Network Operator OPEX Breakdown and LTE OPEX impacts are plotted. However, over time, these benefits are likely to diminish as demand for bandwidth-intensive services grows, and carriers are compelled to boost cell density and backhaul capacity to maintain network coverage and performance.



LTE OPEX Impacts	
Cell Site	• Fewer sites and radios • Reduced maintenance and part replacement costs
Network Expenses	• Reduced switching and transport costs • Better able to handle bursts of data • Reduced backhaul costs (50% by some estimates)
Network Staffing	• More remote (i.e., online) maintenance • Fewer network elements (when fully converted)
Network Provisioning	• Fully IP networks may simplify provisioning

Figure 3.39. Illustration of the Wireless Network Operator OPEX Breakdown and LTE OPEX Impacts.

Furthermore, when we talk about Customer Lifetime phase, we must not forget the Small and Midsize Business (SMB) and Enterprises. In that way, in Figure 3.40 are given some business and technology issues and concerns which affect the SMB and enterprises.

Figure 3.40. Business and technology issues and concerns.

CPGA comprises two key components – device subsidies and sales and marketing costs. Despite the trend toward more expensive smartphones, economies of scale eventually should drive down subsidies as 3GPP device volumes grow and component and manufacturing costs fall. Competition from new device entrants, including PC manufacturers and traditional consumer electronics companies, should place additional downward pressure on price. However, sales and marketing costs, which can represent over 50% CPGA, will almost certainly increase as wireless penetration approaches 90% and competition for subscribers intensifies.

Next step in the LTE business case is determination or prediction of the number of UEs (subscribers). In Figure 2.41, a forecast for the number of LTE subscribers in period between 2010 and 2015 is given. As can be seen, by 2013, the forecast number of global subscribers to LTE will be around 110 millions, with European operators making up 48.8 million of this number, followed by 21.5 million in Asia Pacific and 17.5 million in North America.

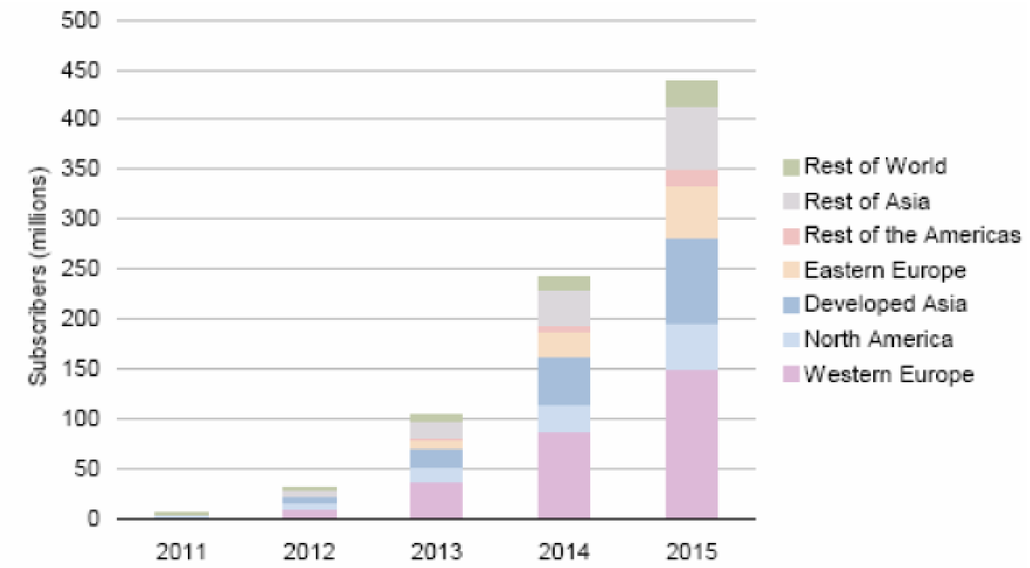
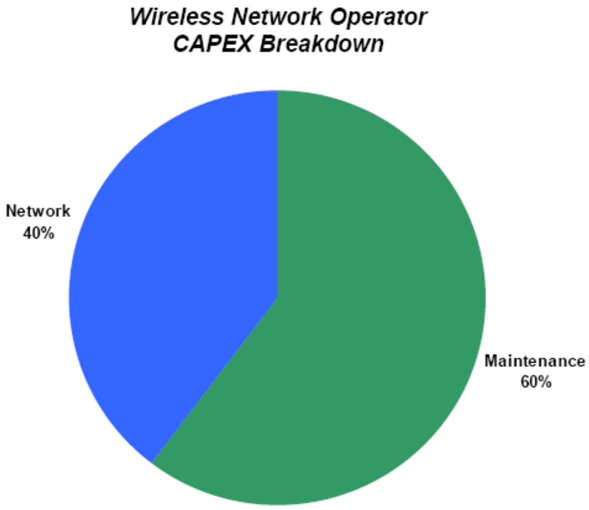


Figure 2.41. Forecasted LTE Subscribers 2010-2015.

Finally, in the final step (Capital Investments) we have great achievements with using LTE technology: the standardized, IP-based network equipment for LTE will reduce capital costs. And moreover, improved spectral efficiency of LTE promises to further enhance the capital efficiency of LTE investments. In Figure 2.42 the Wireless Network Operator CAPEX breakdown and LTE CAPEX impacts are given.

Also, at just under 2% today, churn could increase in the near-term as the race to deploy 3.5G/4G networks creates periods of network disparity among carriers. Open-access environments may worsen the situation by breaking down switching barriers among providers. Longer-term, however, innovative new services and improved network performance should enhance customer loyalty and retention, and also may help to accelerate adoption by encouraging new performance-sensitive segments, particularly business segments, to subscribe.

Device penetration per subscriber also will increase as more consumer electronics devices, such as Amazon’s Kindle and in-vehicle systems, become wirelessly enabled and drive further adoption.



LTE CAPEX Impacts	
Cell Site	• Improved spectrum efficiency • Propagation benefits of 700 MHz spectrum • Spectrum flexibility (channel width, FDD/TDD)
Network Maintenance	• Simpler network architecture • Lower equipment costs resulting from standardization
Network Expansion	• Lower equipment costs resulting from standardization • Simpler network architecture

Figure 2.42. Wireless Network Operator CAPEX breakdown vs LTE CAPEX impacts.

So, what does this (above discussed) mean for the LTE ecosystem, and what must each segment do to ensure LTE’s success?

For equipment providers, the focus should be on understanding the needs of their customers’ customers. They must anticipate the types of services, applications, and content that will be demanded by end users in a 4G environment, and incorporate the required functionality into their equipment for service enablement by carriers.

Service providers should define new business models and marketing strategies to drive acquisition and retention of subscribers, as well as adoption of high-value content and applications. As described earlier, carriers will need to partner with content and application providers, develop application storefronts, and possibly create value-added network APIs. They also will need to define the right channel and pricing strategies to simplify the adoption of new service categories.

Application and content developers will need to create services that take advantage of LTE’s capabilities. Applications such as real-time multi-user video gaming and multi-media remote health monitoring are just two examples. Developers should consider how LTE will change the mobility value proposition, and determine how best to leverage LTE’s capabilities to enhance the 4G experience.

Finally, device manufacturers will play a critical role in the success of LTE. Improved displays and user interfaces, for instance, will be necessary to facilitate interaction with advanced applications and content. Additionally, new device categories, including mobile internet devices (MIDs), in-vehicle systems, and machine-to-machine devices, should be developed to fully leverage LTE’s improved performance and network coverage. All of these advances must be realized with more on-board computational power and longer battery life.

LTE's new capabilities promise to essentially change how we think about mobility, from core voice and data services to high-value-added content and applications. However, for the LTE business case to prove-out, all segments of the ecosystem must enable the capabilities necessary for end users to reap the full benefits of LTE. In the end, with the last figure (Figure 2.43) of this module, we illustrate one possible data revenues from LTE in the period 2010-2015.

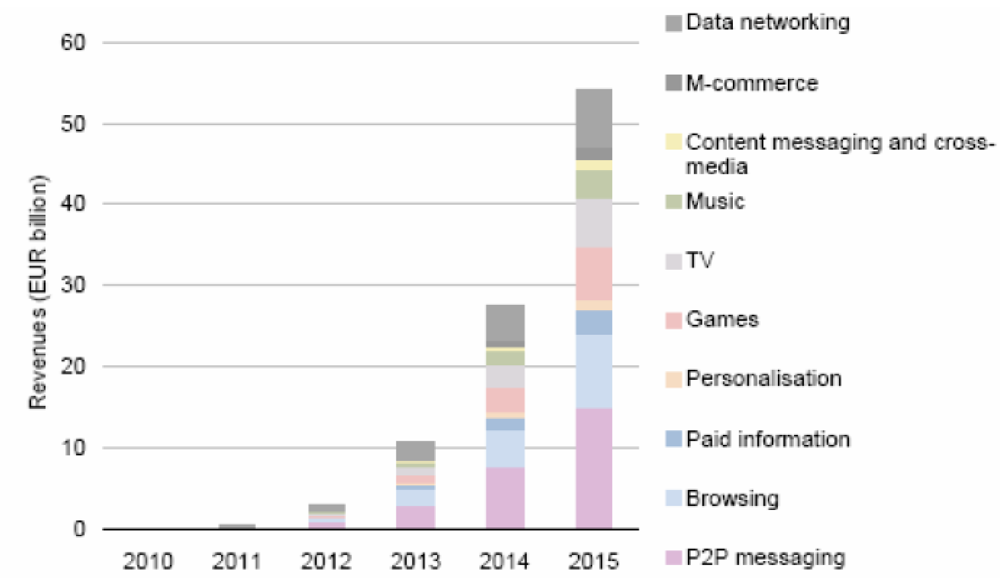


Figure 2.43. Data Revenues from LTE 2010-2015.

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