3GPP LTE/SAE: An Overview

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***Abstract*—3GPP LTE/SAE is a next generation radio access system that supports future end-user requirements. The fundamental aim of long-term evolution (LTE) is to improve the service provisioning and reduce user and operators cost, which will be fulfilled by improving data rates, coverage, system capacity and reducing latency. The paper presents the technical overview of Long Term Evolution (LTE)/ System Architecture Evolution (SAE), the QoS provisioning aspects of Evolved Packet System (EPS), the key research challenges and the ongoing work to provide solutions. The discussion also provides an insight into 3GPP LTE-Advanced, which is the future of LTE on the roadway to 4G. The paper provides the valuable and concise information to the researchers in the area of 3GPP LTE and 4G.**

***Index Terms*— EPS, E-UTRAN, LTE-Advanced, OFDMA.**

I. INTRODUCTION

3GPP LTE/SAE is a next-generation radio access system designed to support the future end-users requirements [1], [4]. The motivation for technological evolution in mobile communication comes from the globalization of markets and increased vendor competence, popularization of IEEE 802 wireless technologies in mobile communication domain, and the demand for advanced mobile services. The increased use of mobile services such as high-speed internet access, Multimedia Online Gaming (MMOG), Mobile TV, Web 2.0, wireless DSL and voice substitution contribute huge traffic in the networks. The challenge for next-generation wireless networks is to provide wireless broadband at a better cost and performance, while maintaining seamless mobility, service control and Quality of Service (QoS) provisioning. This provoked the Third Generation Partnership Project (3GPP) to launch the project LTE (Long Term Evolution)/ SAE (System Architecture Evolution), as the two key work items of 3GPP Release 8. The standardization work has lead to the specifications of the Evolved Packet Core (EPC) and LTE-Radio Access Network (RAN). The Evolved Packet System (EPS) includes EPC and Evolved Universal Mobile Telecommunications system (UMTS) Terrestrial RAN (E-UTRAN) as shown in Fig.1.

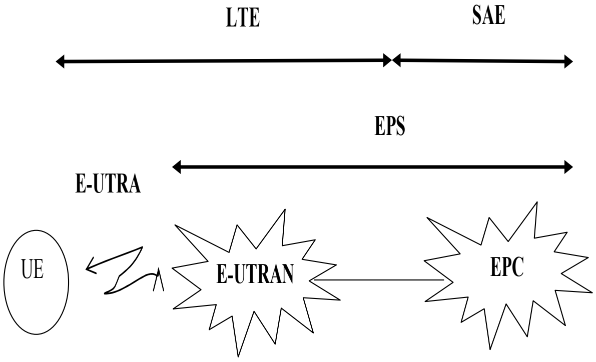

Figure 1. Evolved Packet System.

The EPC is a flat network architecture, IP based multi-access core network that supports the operation of a common packet core network for 3GPP radio accesses, non-3GPP radio accesses and fixed accesses. The EPC provides access to external IP networks and performs various functions like QoS, security, mobility and terminal context management for idle and active terminals. The LTE-RAN performs all terminal related radio interface functions. The LTE uses Orthogonal Frequency Division Multiplexing (OFDM) as its radio access technology, together with advanced antenna technologies. It supports different carrier bandwidths (1.4 - 20 MHz) in both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes. The EPS employs network-initiated and class-based QoS concept, aligned with 3GPP's Policy and Charging Control (PCC) framework. Table I summarizes the 3GPP standards and the major features with each release [7].

ITU-R gave the definition of future 4G mobile, which is referred to as International Mobile Telecommunications (IMT)-Advanced [3]. In the race towards IMT-Advanced, the 3GPP has divided this work into two phases: first completion

TABLE I. 3GPP STANDARDS AND FEATURES

Release	Important Features
Rel-99	Basic 3.84 Mcps WCDMA (TDD and FDD), First deployable version of UMTS. EDGE
Rel-4	Low chip rate TDD (1.28 Mcps), Multimedia messaging support, Initial step towards IP Core Network.
Rel-5	HSDPA, IMS Phase-1, Full ability to use IP-based transport instead of ATM.
Rel-6	HSUPA, WCDMA/WLAN internetworking, MBMS, IMS Phase-2, Initial VoIP capability.
Rel-7	GPRS enhancements with evolved EDGE, HSPA+ (64-QAM DL, 16-QAM UL, MIMO), LTE & SAE basic study items.
Rel-8	LTE (OFDMA based air interface), SAE (New IP core network), EDGE Evolution, Enhancements to HSPA+.
Rel-9	HSPA and LTE enhancements including HSPA multi-carrier operation.
Rel-10	LTE Advanced specifications to meet requirements of IMT-Advanced.

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of LTE standard (Release 8), then adapt LTE to the requirements of IMT-Advanced through the specification of LTE-Advanced (Release 9 and 10).

The paper focuses on the technical overview of LTE/SAE. The organization of this paper is as follows. Section II discusses the LTE enabling technologies. Section III discusses the LTE/SAE system architecture and Radio interface protocol architecture. In section IV, the QoS related aspects of EPS are dealt. Section V discusses the LTE research challenges and related works. Section VI gives an insight into LTE-Advanced. Section VII concludes the paper.

II. LTE ENABLING TECHNOLOGIES

LTE aims at better spectral flexibility, higher data rates, low latency, improved coverage and better battery lifetime [7], [9]. Table II lists the key targets of LTE. To achieve the targets, LTE employs the enabling technologies: Orthogonal Frequency Division Multiple Access (OFDMA), Single Carrier Frequency Division Multiple Access (SC-FDMA) and Multiple Input Multiple Output (MIMO). LTE employs OFDMA is for downlink and SC-FDMA for uplink data transmissions.

A. OFDM and OFDMA

OFDMA [13] is a variant of Orthogonal Frequency Division Multiplexing (OFDM) [2], which is a digital multi-carrier modulation scheme widely used in wireless systems. In an OFDM system, the available spectrum is split up into a number of sub-carriers, which are orthogonal to each other. Each of these sub-carriers is independently modulated by a low data rate stream. The conventional modulation schemes such as QPSK, 16-QAM or 64-QAM are employed to modulate each sub-carrier at a low symbol rate. The sub-carriers are combined to produce data rates similar to conventional single-carrier modulation schemes in the same bandwidth. Fig.2. shows the key features of OFDM signal in time and frequency domain for 5 MHz bandwidth, the principle of which is same for the entire E-UTRA bandwidth. The frequency domain consists of a number of sub-carriers independently modulated with data. In time domain, the guard intervals are inserted between each of the symbols to combat Inter-symbol interference (ISI) caused by multi-path delay spread in the radio channel.

TABLE II. LTE PERFORMANCE REQUIREMENTS

Metric	Requirements
Spectral Flexibility	1.4, 3, 5, 10, 15 and 20 MHz
Peak data rate	1. Downlink (2 Ch MIMO): 100 Mbps 2. Uplink (Single Ch Tx): 50 Mbps (20 MHz ch)
Supported antenna configurations.	1. Downlink: 4x2, 2x2, 1x2, 1x1 2. Uplink: 1x2, 1x1
Spectrum efficiency	1. Downlink: 3 to 4 times HSDPA Rel. 6 2. Uplink: 2 to 3 times HSUPA Rel. 6
Latency	1. Control-plane: Less than 100 msec to establish U-plane 2. User-plane: Less than 10 msec from UE to server
Mobility	1. Optimized for low speeds (0-15 km/hr) 2. High performance at speeds up to 120 km/hr 3. Maintain link at speeds up to 350 km/hr
Coverage	1. Full performance up to 5 km 2. Slight degradation 5 km – 30 km 3. Operation up to 100 km should not be precluded by standard

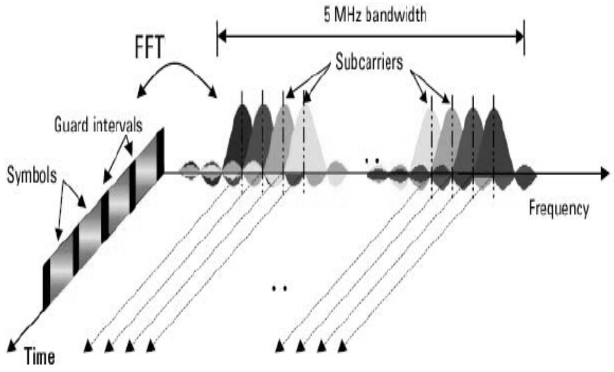

Figure 2. OFDM signal in frequency and time domain [13].

Compared to Code Division Multiple Access (CDMA), OFDM has the benefits of robustness against frequency selective fading, superior spectral flexibility, bandwidth scaling and efficient receiver architecture. OFDM is better suited for MIMO. The drawback of OFDM lies in its sensitivity to frequency errors and phase noise (mainly due to closely spaced sub-carriers), and generation of high Peak-to-Average Ratio (PAR) signals. Compared to CDMA the operation of OFDM at the cell boundaries is more difficult. CDMA uses scrambling codes to provide immunity against inter-cell interference (ICI) at the cell boundaries. As OFDM has no such features, the frequency reuse planning at the cell edges is required.

The pure OFDM can suffer from narrowband fading and interference. Hence OFDMA is used for downlink, which allows subsets of the sub-carriers to be allocated dynamically among the different users on the channel. It results in a more robust system with increased capacity [7].

B. SC-FDMA

LTE uplink requirements differ from those of downlink due to low power consumption requirement at User Equipment (UE). SC-FDMA [5] is chosen for uplink because it combines the low PAR techniques of single-carrier transmission systems, such as CDMA with the multi-path resistance and flexible frequency allocation of OFDMA.

The SC-FDMA signal generation is done as follows. The incoming bit stream is first converted to single carrier symbols (BPSK, QPSK, or 16-QAM depending on channel conditions). Then, data symbols in the time domain are converted to the frequency domain using a Discrete Fourier Transform (DFT); then they are mapped to the desired band in the overall channel bandwidth before being converted back to the time domain using an Inverse Discrete Fourier Transforms (IDFT). Finally, the Cyclic Prefix (CP) is inserted, which is used to effectively eliminate ISI. The digital signal is converted to analog, up-converted to radio frequency (RF) and transmitted. Fig.3 shows the block diagram of SC-FDMA signal generation and reception [7].

C. MIMO

3GPP LTE uses different multiple antenna schemes to fulfill the requirements on coverage, robustness, capacity and high data rates. Beam-forming is a technique used to

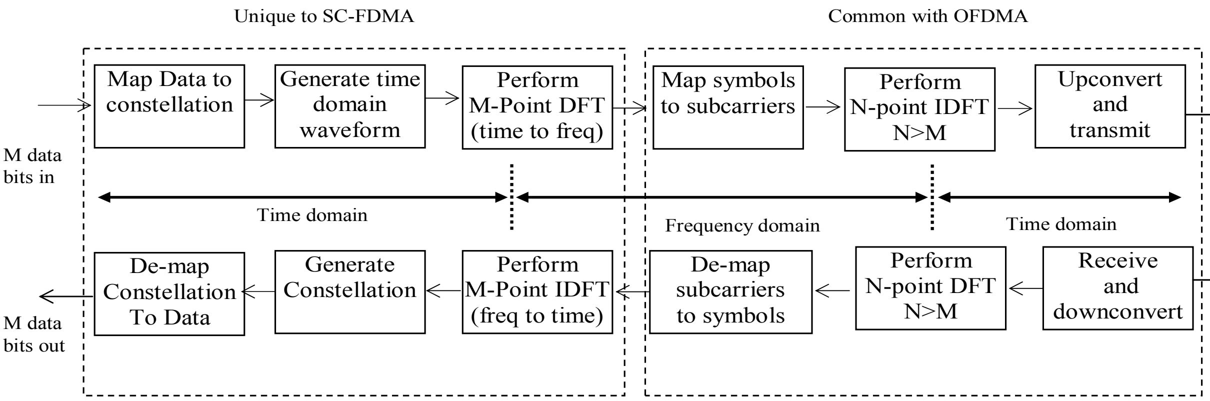

Figure 3. SC-FDMA signal generation and reception [7].

increase the coverage and/or capacity. MIMO [6] is used to enhance the data rates (up to 20 Mbps), by exploiting the spatial diversity in radio channels. MIMO systems are the work items in Release 6 specifications, which refer to the use of multiple antennas at transmitter and receiver side.

Fig.4. illustrates a 2x2 MIMO system. At the transmitter, the information bits are divided into several bit streams (S1, S2) and transmitted through different antennas. The channel mixes the streams so that at the receiver each antenna has the combination of the streams in the received signal. The transmitted information bits are recovered from the received signals at multiple receive antennas by using an advanced receiver, which analyses the unique pattern corresponding to each transmitter and then recovers the stream. Due to the high data rate transmission, the trade off between complexity and system performance becomes an important issue, especially for the UE designs.

The combined use of OFDM and MIMO improves the spectral efficiency and capacity of the wireless network. It maximizes the usage of limited available spectrum, which is typically controlled by regulatory bodies.

III. LTE / SAE ARCHITECTURE

A. LTE/SAE Evolved Architecture

The architectural evolution of 3GPP LTE [17], [19] involves the migration from traditional hierarchical system to flat architecture as shown in Fig.5. It reduces the number of nodes and distributes the processing load, in order to achieve reduction in latency in the network. The user plane comprises of only two nodes (instead of four), while control plane is separated with an entity called Mobility Management Entity (MME).

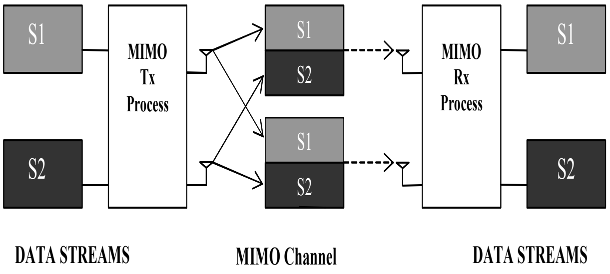

Figure 4. MIMO system

The simplified LTE/SAE architecture is shown in Fig.6. Based on the functionality, the architecture is split into two parts: a radio access network (E-UTRAN) and a core network (EPC). The E-UTRAN supports all services, including real-time multimedia services over shared packet channels. It contains new network elements called enhanced NodeBs (eNBs), which provide E-UTRA user plane and control plane termination towards the UE. The functions of eNBs include radio resource management, IP header compression and encryption, selection of MME at UE attachment, routing of user plane data towards S-GW, scheduling and transmission of paging messages and broadcast information, measurement and reporting configuration for mobility and scheduling [25].

The EPC consists of the functional entities [14].

(i) The Mobility Management Entity (MME), which is responsible for the control plane functions related to subscriber and session management. The MME performs the distribution of paging messages to eNBs, security control, idle state mobility control, SAE bearer control, ciphering and integrity protection of Non-Access Stratum (NAS) signaling.

(ii) The Serving-Gateway (S-GW), handles the user-plane packet data termination towards E-UTRAN. It acts as local mobility anchor, exchanging packets with eNB, where UEs are served. It serves as routing node towards other 3GPP technologies.

(iii) The Packet Data Network (PDN)-Gateways (P-GW), interfaces with the external PDNs. It performs IP related functions like address allocation, policy enforcement, packet classification and routing. It also acts

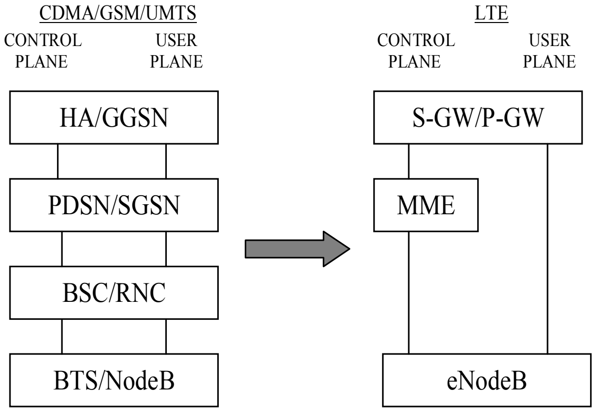

Figure 5. Evolution from hierarchical to flat EPS network.

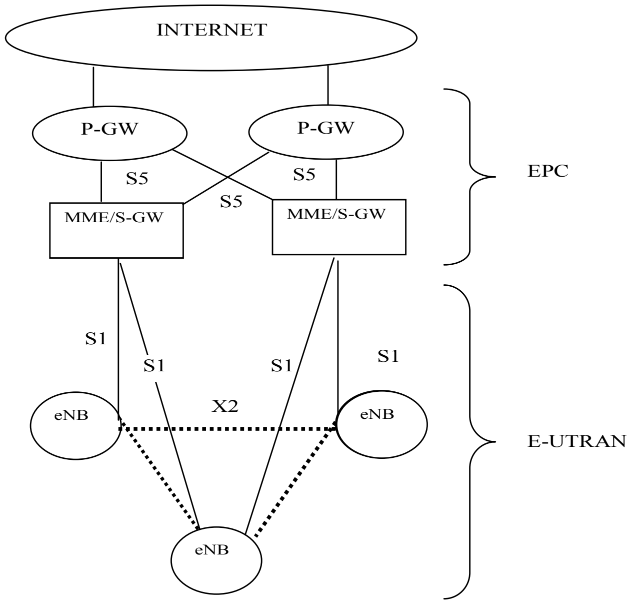

Figure 6. Simplified LTE architecture.

as mobility anchor for non-3GPP access networks.

(iv) The Policy and Charging Rules Function (PCRF) controls the charging and the IP Multimedia Subsystem (IMS) configuration of each user.

The interface X2 enables direct communication between the eNBs. S1 interfaces the E-UTRAN and the EPC by connecting eNBs to MME and S-GW elements through a many-to-many relationship. S5 provides an interface between the two gateways- S-GW and P-GW.

B. *LTE Radio Interface Protocol Architecture*

The overall radio interface protocol architecture is shown in Fig.7 [20]. Layer 1 (Physical layer) provides data transport services to the higher layers using transport channels. Transport channels are characterized based on the way the information is transferred over the radio interface, while logical channels define the type of information transferred. The functions of physical layer include - Error detection on the transport channels, Encoding/decoding of the transport channels, Hybrid automatic repeat request (HARQ) soft-combining, Rate matching and mapping of coded transport channels to physical channels, Physical channel modulation and demodulation, Frequency and time synchronization, radio characteristics measurements, MIMO antenna processing, Transmit diversity, Beam forming, RF processing etc. The physical layer specifications are categorized into four main sections: Physical channels and modulation [21], Multiplexing and channel coding [22], Physical layer procedures [23], Physical layer measurements [24].

The MAC layer performs the mapping between the transport channels and logical channels [25], scheduling of UEs and their services (based on their relative priorities), selecting the appropriate transport format. The RLC is used to format and transport traffic between eNB and UE. RLC provides sequenced delivery of service data units (SDUs) to higher layers, and eliminates duplication of SDUs. RRC is responsible for setting up and maintenance of radio bearers. RRC makes handoff decisions based on the neighbouring cell measurements. The requirements for

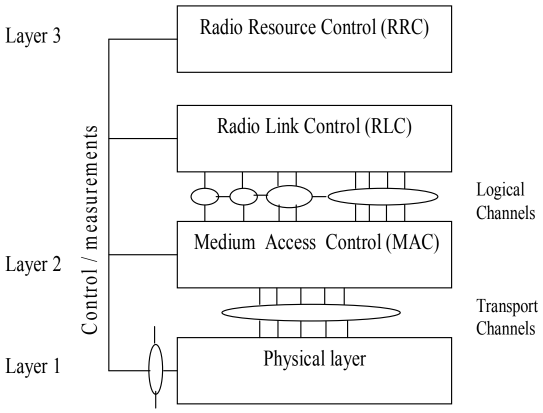

Figure 7. LTE Radio interface protocol architecture

Radio Resource Management (RRM) is defined in [26]. RRM covers the procedures and performance requirements for the efficient utilization of radio resources.

IV. QOS PROVISIONING IN 3GPP EPS

A. *Principles of 3GPP EPS QoS Provisioning*

The QoS provisioning has been a major issue in the mobility management of wireless networks, which include wireless LAN, wireless ATM [29], cellular networks etc. The 3GPP standards for UMTS QoS concepts and architecture are proposed in [27], [28]. The 3GPP Release 8 has standardized QoS concept of the EPS. In the EPS QoS concept [10], [11], the bearer is the basic level of granularity for QoS control. An EPS bearer carries data between P-GW and UE. It uniquely identifies packet flows corresponding to a QoS treatment between the UE and the gateway, which are specified by scheduling policy, queue management policy, rate shaping policy etc. There are two types of bearers: Guaranteed Bit-Rate (GBR) and Non- Guaranteed Bit-Rate (n-GBR) bearers. In GBR bearer, the dedicated network resources with corresponding GBR QoS value associated with it are permanently allocated during bearer establishment/modification. The service using GBR bearer assumes that the congestion related packet losses do not occur. It is suitable for conversational services like voice call. A non-GBR bearer does not have guaranteed bit rate and the corresponding services should be prepared for congestion related packet losses. Such bearers are suitable for background services like e-mails. The bearer can be either a default or a dedicated bearer. A default bearer is established when the UE connects to a PDN and it remains throughout the lifetime of PDN connection, providing UE with an always-on IP basic connectivity to that PDN. The default bearer is a non-GBR bearer and the QoS level of the default bearer is assigned based on the subscription data. Any additional EPS bearer established for the same PDN connection is termed as a dedicated bearer. A dedicated bearer can be either a non-GBR or a GBR bearer. The operator can control mapping of packet flows onto the dedicated bearer and the corresponding QoS level through policies as specified by Policy and charging resource function (PCRF) [12]. An end-to-end IP packet entering the system at different system interfaces is attached with a tunnel header, which contains the bearer identifier to associate a node with appropriate QoS parameters. In the transport network, the tunnel header also includes a DiffServ Code Point (DSCP) value as shown in Fig.8 [10].

The EPS QoS concept is based on two fundamental principles - Network initiated QoS control and Class based mapping of operator services to user plane packet forwarding treatment. These two principles provide access network operators and service operators with a set of tools to enable service and subscriber differentiation. While the service differentiation includes Public Internet, corporate VPN, peer-to-peer (P2P) file sharing, video streaming, IMS and non-IMS voice, mobile TV etc., the subscriber differentiation includes pre-paid/ post-paid, business/ standard, roamers etc [10]. In the network initiated QoS control, only network can make the decision to establish or modify a bearer. It specifies a set of signaling procedures for managing bearers and for controlling their associated QoS. The advantages of the network-initiated QoS control include its ability to support QoS provisioning in access-QoS unaware client applications and in the split-terminal case, where the client application resides in a node that is physically separated from the terminal. It enables the deployment of more consistent exception-handling policies.

The EPS QoS concept is class-based, wherein each bearer is assigned a scalar *QoS Class Identifier (QCI)*. The QCI specifies the user-plane packet forward treatment associated with bearer. The standardized QCI characteristics for the bearer traffic between UE and the gateway are specified in terms of bearer type (GBR or non-GBR), priority, packet delay budget, and packet error loss rate [18]. Apart from QCI, QoS parameters defined in EPS also include Allocation and Retention Priority (ARP), Maximum Bit-Rate (MBR) and Guaranteed Bit-Rate (GBR). The ARP enables the EPS system to decide about the acceptance of a new bearer establishment/ modification request and rejection of established bearers in case of limited resources. GBR specifies the long-term average bit-rate that can be expected to be provided by a GBR bearer, while MBR specifies the upper limit for bit-rate offered by GBR bearers. In release 8, MBR is set equal to GBR, while MBR greater than GBR may be relaxed in future releases [18]. The Aggregated Maximum Bit-Rate (AMBR), defined per group of non-GBR bearers, enables the operator to limit the total amount of bit-rate consumed by a single user.

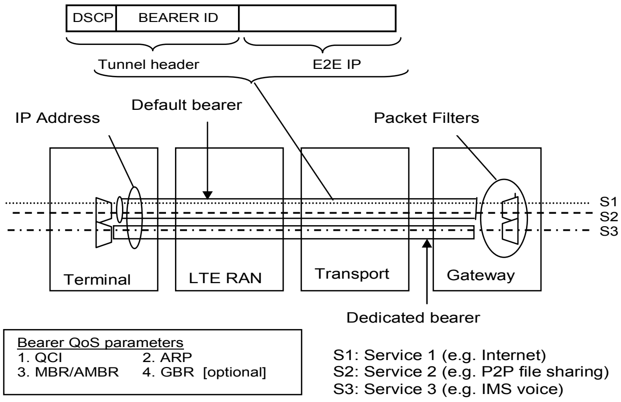

Figure 8. The 3GPP Bearer and QoS parameters [10].

B. 3GPP EPS QoS Control Mechanism

The QoS provisioning mechanism can be divided into control-plane signaling procedures and user-plane functions as follows [10].

(i) *Control Plane Signaling Procedures:* The policy controller (using policy and charging control rules) in the network determines the handling of each packet flow for each subscriber in accordance with the associated QoS parameters. The UL/DL packet filters are used to describe the packet flow. The bearer level request is forwarded to LTE RAN and UE. A high-level view of the EPS signaling flow to control QoS functions is shown in the Fig.9.

(ii) *User Plane Functions:* The User plane QoS functions are carried out by the configuration of the network nodes through 3GPP specified signaling procedures and through an operation and maintenance (O & M) system. These functions are classified into functions operating at packet flow level, bearer level, or DSCP level. The packet flow level functions use deep-packet inspection techniques to identify packet flows and implements rate-policing to regulate the bit-rates.

At bearer level, UL and DL packet filtering is done by terminal and gateway respectively to map packet flows to appropriate bearers. The gateway and LTE RAN implements the functions related to admission control and pre-emption handling, and rate policing. In addition, LTE RAN performs UL and DL scheduling to distribute the RAN resources among the bearers, and link-layer protocol configurations. The QCI to DSCP mapping is implemented by gateway and LTE RAN (based on operator policies) to enable traffic separation in the transport network. At the DSCP-level, the transport network nodes implement queue management schemes and scheduling algorithms for uplink and downlink traffic. These algorithms determine the individual packet forwarding treatment based on the DSCP value.

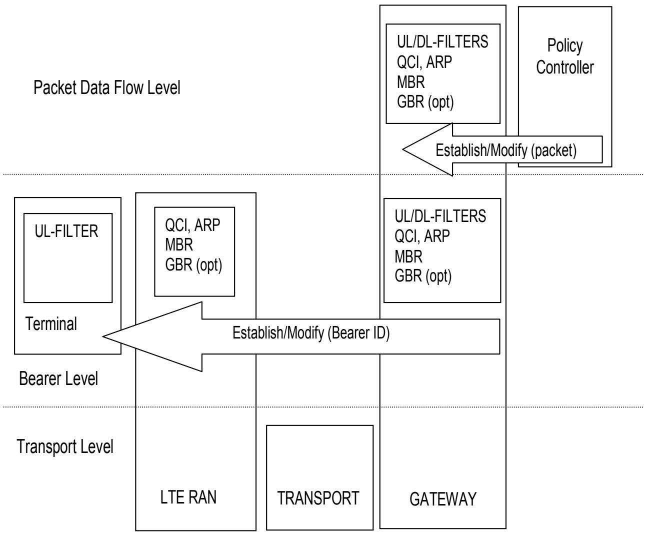

Figure 9. EPS signaling procedures to control QoS functions [10].

V. RESEARCH ISSUES AND RELATED WORKS

A. Scheduling

The scheduling does the task of dividing and allocating resources among users involved in data transmission. The scheduling algorithms aim at providing efficient resource sharing, better performance in terms of throughput, link utilization, fairness and complexity. In LTE, OFDMA is used for downlink (DL), while SC-FDMA is used for air interface in uplink (UL) taking into account power consumption issue of the mobile terminal. The Medium Access Control (MAC) scheduling in LTE can be categorized into persistent and dynamic scheduling. A persistent scheduling allocates fixed resources to the services without considering the link conditions. The dynamic scheduling allocates resources dynamically based on UE feedback about the link situation. The dynamic scheduling achieves flexible resource allocation at the cost of excessive control signals that can hinder data packet delivery. In hybrid approach *semi-persistent* scheduling [37], [38], the packets are not always scheduled dynamically, but the decision is taken for a fixed amount of time in future. This approach attains resource allocation flexibility, while costing lesser amount of control signals.

In LTE, DL needs the scheduler that can offer better performance at Flow class identifier (FC-ID) level. The method in [30] adopts a divide and conquers approach for DL scheduling of the Best Effort (BE), Guaranteed Bit-Rate (GBR) and Signaling (SIG) flows. It employs two-level schedulers: *the Inter FC-ID Scheduler (Inter S)* to sort different FC-IDs based on their policies and *Intra FC-ID Scheduler (Intra S)* to schedule the users within a given class. The complexity is split between the two levels. The Opportunistic Proportionate Fairness Scheduler (OPFS) for DL proposed in [31] aims at low packet loss probability, and good fairness in terms of user throughput and packet delay. The scheduler chooses a user with highest weighting factor taking into account buffer occupancies per queue, dynamic token value traffic class priority and channel conditions reported from access terminals. [32] proposes an optimal multi-user scheduler for DL in LTE cellular systems. The method shows that the system performance improves with increasing correlation among OFDMA sub-carriers and needs lesser feedback information to achieve better performance. It also proposes a suboptimal solution to handle complexity in multi-user environment. The Proportional Fair (PF) Multi-user Scheduler proposed in [33] provides superior fairness at low complexity, with modest loss of throughput.

The SC-FDMA technology requires the contiguous allocation of sub-carriers to a user. This limits the flexibility in resource allocation, making the design of scheduling algorithms for UL more computationally complex than that of DL. S. Lee in [34] investigates the adaptation of time-domain PF algorithm to scheduling objective of proportional fair criteria, under contiguous RB allocation constraint of UL. The paper analyses the NP hardness nature of the frequency-domain scheduling problem and presents a set of algorithms considering this problem. The paper [35] proposes an Extrinsic Information Transfer (EXIT) based scheduling and rate control scheme for multi-user MIMO system in uplink. The method aims at reducing the computational complexity, while maintaining high throughput efficiency. It focuses on convergence properties predicted by EXIT trajectory from channel transfer functions and window control. Three new channel-aware scheduling algorithms for SC-FDMA with different level of complexity have been presented in [36]. They allocate the resource blocks (RBs) by dividing the bandwidth to the users, based on better channel conditions. All the algorithms offer high level of fairness and outperform round-robin method.

B. *Inter-Cell Interference Mitigation*

In LTE, inter-cell interference limits the performance in terms of spectral efficiency and data rates, especially at the cell edge. Based on the approaches, Inter Cell Interference (ICI) mitigation techniques can be categorized into the following major classes: interference cancellation by receiver processing, interference randomization by frequency hopping using scrambling sequence, and interference co-ordination/avoidance through resource usage restrictions imposed by frequency and power planning. The LTE supports dynamic *Inter-Cell Interference Co-ordination* (ICIC), motivated by traffic and radio conditions, to control the ICI. ICIC can be applied to both UL and DL. In case of UL, the interference originates from UEs, whereas in DL interference originates from stationary base stations. The inter-cell coordination is aided by the exchange of *high-interference indicator* and *overload indicator* (in UL), and *narrow band relatively narrow power indicator* (in DL), using which resource alterations are done in different parts of spectrum [8].

There are different approaches of formulating ICIC problem. In one kind of approach, ICIC problem is formulated as *optimization task* with objectives of maximizing throughput in multi-cell system, subjected to power constraints, limitations of inter-cell signaling, fairness and minimum bit-rate requirements [44]-[46]. Another kind of approach develops *Collision models*, which considers ICI as collision between resource blocks [47]. The ICIC mechanism aims at reducing the collision probabilities and minimize signal-to interference and noise (SINR) degradation, and to enable better performance in terms of bit error rate and throughput of multi-cell systems. Xiang in [39] compares ICIC based resource reuse schemes: soft frequency reuse [48] and the partial frequency reuse scheme [49]. The paper proposes an average cell capacity estimation method for different resource reuse schemes and verifies the results for heterogeneous traffic load. It shows frequency reuse scheme performs better in enhancing cell edge throughput, without degrading average cell throughput. [40] reviews the recent advances in ICIC research and discusses the assumptions, advantages and limitations of several proposed mechanisms. It also discusses the architecture and protocol support for ICIC in the 3GPP LTE system. A Coordinated Inter-Cell Resource Allocation (CICRA) approach proposed in [41] uses a set of coordinated cell-specific resource allocation sequences in order to manage ICI over all the cells within a cell cluster. An ICI coordination technique based on users' ratio and frequency allocation is proposed in [42]. It employs the frequency resources allocation based on cell-edge users' ratio to the cell-edge users, and the rest resources to cell-center users with two levels of power. An interference avoidance scheme for LTE downlink in [43] uses dynamic inter-cell coordination facilitated through X2 interface among neighboring eNBs. The paper presents an approach to handle inter-cell intra-eNB interferer, using Hungarian algorithm by devising utility matrix in a multi-cell fashions.

C. Uplink Power Control

The power control (PC) enables setting of power levels with the goal of improving system capacity, coverage, data-rates and reduction in power consumption. In LTE, the orthogonality of SC-FDMA eliminates intra-cell interference, but the system is still susceptible to inter-cell interference. The PC plays a prominent role in providing the required SINR for the received signals, while controlling the inter-cell interference. The 3GPP standard has PC formulation with an open loop and a closed loop component. The open loop power control (OLPC) compensates for slow varying path-loss and shadowing, while the closed loop power control (CLPC) compensates for faster variations and reduces interference. In CLPC, UE adjusts its UL power level based on transmission PC commands sent by base stations. The closed loop SINR target results in a trade-off between the cell edge and mean bit rate. High SINR target results in high mean user bit rate, but lower cell edge bit rate, while lower SINR target results in low mean and high cell edge bit rate. Hence the design of a closed loop power control scheme should provide reasonable cell-edge bit rate, while providing high user received SINR and in turn high mean user bit rate. The conventional power control offers same SINR targets to all users and allows full compensation of path loss. LTE UL supports fractional power control (FPC), wherein the users close to the cell edges use relatively less transmit power, and thus generate relatively less interference to neighbor cells. FPC compensates for the fraction of the path loss.

The 3GPP specification [50] defines UE transmit power setting for PUSCH. [51] evaluates the impact of a FPC scheme on the SINR and interference distributions in providing a sub-optimal configuration tuned for interference and noise-limited scenarios. The methodologies in [52] employ aperiodic CLPC corrections to control/correct the UL power level. The transmission of aperiodic PC commands is done over DL by base stations based on the received power measurements. In accordance with the PC commands, the access terminals modify UL power level in subsequent UL transmissions. Simonsson [53] presents the 3GPP LTE power control mechanism constituting of a closed loop component operating around an open loop point of operation. The open loop component has a parameterized fractional path loss compensation factor. The paper highlights the advantages of LTE PC mechanism employing FPC compared to full path loss compensation PC mechanism (in terms of cell bit-rate and battery life time). An iterative distributed algorithm for power and rate control, specially tuned for delay tolerant traffic is proposed in [54]. The algorithm is based on sum-power constrained sum-rate maximization with upper (and lower) power and rate constraints. The feasibility and performance of the algorithm is evaluated in a cellular system, with focus on delay tolerant traffic. The results show better performance of the sum-rate vs. sum-power relation when compared to both *fixed power adaptive rate* and *fixed rate adaptive power* radio resource management. By silencing sub-optimal links, it manages reuse of resources.

D. Rate Policing

3GPP LTE requires rate policing on per bearer basis, and per subscriber basis for both uplink and downlink. In LTE, the upper limit for GBR bearers is provided by MBR, while that for a group of non-GBR bearers is provided by AMBR.

While several proposals [57]-[59] can provide possible solutions for rate policing per bearer, enforcing AMBR for a group of non-GBR bit rates in LTE is an important issue. The method for scheduling of UL resources in [55] discusses four AMBR handling mechanisms. They are based on radio bearer priority only, radio bearer priority and absolute priority per PDN connection, radio bearer priority and MBR per radio bearer, and radio bearer priority and UL rate control weighing parameters per radio bearer. The method for enforcing UL AMBR at network gateway is provided in [56]. In this method, when total bit-rate at a single P-GW due to multiple bearers from eNBs exceeds the threshold, P-GW informs to the eNBs about the overflow condition. The eNBs trigger action to reduce data-rates sent from UEs.

E. Preemption Handling for Radio Resource Allocation

Preemption method plays a very important role in the QoS provisioning in wireless networks, whenever there is congestion due to network overload. Based on QoS attributes and associated priorities, the higher priority services preempts the resources from the low priority bearers. Several preemption techniques have been proposed in literature for GSM/GPRS/UMTS networks. The invention in [60] discusses the radio resource management in GPRS (or UMTS) based on preemption method, wherein the high priority requests for the communication channel preempts the resources from lowest priority bearers, based on the QoS parameters – Allocation and retention priority (ARP), Traffic class and Traffic handling priority (THP). [63] proposes a method for determining priority of a UMTS bearer by finding the weighted sum QoS parameters ARP, Traffic class, THP, bit-rate etc. The soft preemption based on ARP information [61] in GPRS/UMTS network is proposed in [62].

While it is required that the high priority radio bearers (RBs) be better served than low priority RBs, it is also important to avoid/minimize the starving of the low priority RBs forever. [64] discusses two solutions for the starvation avoidance in the uplink scheduling; prioritized bit rate and priority alteration pattern. In both cases, the solution for starvation problem in lower priority RB involves sacrificing the QoS of higher priority RB. [65] considers the starvation avoidance proposal that guarantees a minimum bit rate to low priority flows, which is based on what was specified for HSUPA.

VI. LTE-ADVANCED: THE EVOLVED LTE

The LTE-Advanced is the further evolution of LTE, which aims at enhancing LTE radio access in terms of system performance and capabilities. LTE-Advanced targets to meet and even exceed the requirements of IMT-Advanced as defined by the ITU [16]. The work towards LTE-Advanced has been initiated in April 2008, with the specifications in [15]. LTE-Advanced is backward compatible with LTE Release 8. The initial phase of work on LTE-Advanced comprises of the following key components [8], [66]:

- *Carrier aggregation*: It involves aggregation (both for contiguous and non-contiguous spectrum) of multiple component carriers of 20 MHz (LTE Rel.8) to support wider transmission bandwidths of up to 100 MHz. The aggregation of the component carriers is done at MAC layer and above.
- *Advanced Relaying:* The deployment of advanced relaying solution enables the improvement in coverage and deployment cost reduction. It aims at reducing transmitter-to-receiver distance to allow higher data rates.
- *Extended multi-antenna transmission*: It enhances multi-antenna transmission with upto eight layers (using 8x8 antenna configuration) for DL and up to four layers (using 4x4 antenna configuration) in UL. It enables to improve the data rates.
- *Coordinated multipoint transmission/reception*: It consists of coordinating the transmission and reception of signal to/from one mobile terminal, jointly carried out from multiple cells. It improves cell-edge bit rates, reduces ICI and enhances received power at UE. It involves co-ordination of scheduling, multi-site beam-formation, information exchange for ICI cancellation. Its potential impacts occur in three areas: feedback and measurement mechanisms from the UE, receiver preprocessing schemes and reference signal design.

VII. CONCLUSION

The 3GPP LTE/SAE is a future-oriented radio access system designed to support huge traffic of future end user requirements like high speed internet, MMOG, Mobile TV etc. The 3GPP Release 8 has specified the IP-based flat multi-core network architecture called EPC and OFDM based radio access technologies called LTE. While LTE is designed for high data-rate, spectral flexibility, low latency, improved coverage and battery lifetime, EPC supports robust IP-based services with seamless mobility and advanced QoS mechanism. The 3GPP LTE provides a framework for standardization in the evolution towards 4G. The paper is focused on the technical overview of 3GPP LTE/SAE and provides a brief insight into the key components of LTE-Advanced.

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