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3G, 4G and Enhanced MIMO cellular systems: LTE-Advanced

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ABSTRACT -This paper provides an in-depth view on the technologies being considered for Long Term Evolution-Advanced (LTE-Advanced). First, the evolution from third generation (3G) to fourth generation (4G) is described in terms of performance requirements and main characteristics. The new network architecture developed by the Third Generation Partnership Project (3GPP), which supports the integration of current and future radio access technologies, is highlighted. Then, the main technologies for LTE-Advanced are explained, together with possible improvements, their associated challenges, and some approaches that have been considered to tackle those challenges.

Index Terms- 3G, 4G, LTE, MIMO, RAN, SAE, ITU-R, SINR

1 INTRODUCTION

The fourth generation (4G) of wireless cellular systems has been a topic of interest for quite a long time, probably since the formal definition of third generation (3G) systems was officially completed by the International Telecommunications Union Radio communication Sector (ITU-R) in 1997. A set of requirements was specified by the ITU-R regarding minimum peak user data rates in different environments through what is known as the International Mobile Telecommunications 2000 project (IMT-2000).

The requirements included 2048 kbps for an indoor office, 384 kbps for outdoor to indoor pedestrian environments, 144 kbps for vehicular connections, and 9.6 kbps for satellite connections. With the target of creating a collaboration entity among different telecommunications associations, the 3rd Generation Partnership Project (3GPP) was established in 1998.

It started working on the radio, core network, and service architecture of a globally applicable 3G technology specification. Even though 3G data rates were already real in theory, initial systems like Universal Mobile Telecommunications System (UMTS) did not immediately meet the IMT- 2000 requirements in their practical deployments. Hence, the standards needed to be improved to meet or even exceed them. The combination of High Speed Downlink Packet Access (HSDPA) and the subsequent addition of an Enhanced Dedicated Channel, also known as High Speed Uplink Packet Access (HSUPA), led to the development of the technology referred to as High Speed Packet Access (HSPA) or, more informally, 3.5G. Motivated by the increasing demand for mobile broadband services with higher data rates and Quality of Service (QoS), 3GPP started working on two parallel projects, Long Term Evolution (LTE) and System Architecture Evolution (SAE), which are intended to define both the radio access network (RAN) and the network core of the system, and are included in 3GPP Release 8. LTE/SAE, also known as the Evolved Packet System (EPS), represents a radical step forward for the wireless industry that aims to provide a highly efficient, low-latency, packet-optimized, and more secure service. The main radio access design parameters of this new system include OFDM (Orthogonal Frequency Division Multiplexing) waveforms in order to avoid the inter-symbol interference that typically limits the performance of high-speed systems, and MIMO (Multiple-Input Multiple-Output) techniques to boost the data rates. At the network layer, an all-IP flat architecture supporting QoS has been defined. The world's first publicly available LTE service was opened by Telia Sonera in the two Scandinavian capitals Stockholm and Oslo on December 14, 2009, and the first test measurements are currently being carried out.

However, by the time the standard development started, the ITU-R framework for 4G systems was not in place, and later research and measurements confirmed that the system did not fully comply with ITU 4G requirements. For this reason, the term has been widely used with the expectation of their evolving towards official 4G status in due course. Before 3GPP started working in the real 4G wireless technology, minor changes were introduced in LTE through . In particular, femtocells and dual-layer beam forming, predecessors of future LTE-Advanced technologies, have been added to the standard. The formal definition of the fourth generation wireless, known as the International Mobile Telecommunications Advanced (IMT Advanced) project, was finally published by ITU-R through a Circular Letter in July 2008 with a call for candidate radio interface technologies (RITs) [1]. By backward compatibility, it is meant that it should be possible to deploy LTE-Advanced in a spectrum already occupied by LTE with no impact on the existing LTE terminals. Other candidate technologies are IEEE 802.16m and China's Ministry of Industry and Information Technology TD-LTE-Advanced (LTE-Advanced TDD specification) [3,4]. The set of IMT-Advanced high-level requirements established by the ITU-R in [5] is as follows.

A high degree of commonality of functionality worldwide while retaining the flexibility to support a wide range of services and applications in a cost-efficient manner.

- Compatibility of services within IMT and with fixed networks.
- Compatibility of internetworking with other radio access systems.

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- High-quality mobile devices.
- User equipment suitable for worldwide use.
- User-friendly applications, services, and equipment.

The requirements for LTE-Advanced were accordingly set to achieve or even enhance IMT-Advanced. However, as stated in [6], the target for average spectrum efficiency and cell-edge user throughput efficiency should be given a higher priority than the target for peak spectrum efficiency and Voice-over-IP (VoIP) capacity. Therefore, the solution proposals of LTE-Advanced, the main ones of which are covered by this paper, focus on the challenge of raising the average and cell-edge performance. The relationship among the requirements of LTE, LTE-Advanced, and IMT Advanced are shown in Table 1. Other important requirements are the already mentioned backward compatibility of LTE-Advanced with LTE and the spectrum flexibility, i.e., the capacity of LTE Advanced to be deployed in different allocated spectra since each region or country has different regulations. The main issue now is to develop the appropriate technologies that allow LTE-Advanced to meet the proposed targets. From a link performance perspective, LTE already achieves data rates very close to the Shannon limit, which means that the main effort must be made in the direction of improving the Signal-to-Interference-and-Noise Ratio (SINR) experienced by the users and hence provide data rates over a larger portion of the cell.

2 Network Architecture

3GPP specified in its Release 8 the elements and requirements of the EPS architecture that will serve as a basis for the next-generation networks [7]. In Fig. 1, we provide an overview of the EPS, other legacy Packet and Circuit Switched elements and 3GPP RANs, along with the most important interfaces. In the services network, only the Policy and Charging Rules Function (PCRF) and the Home Subscriber Server (HSS) are included, for simplicity. In the context of 4G systems, both the air interface and the radio access network are being enhanced or redefined, but so far the core network architecture.

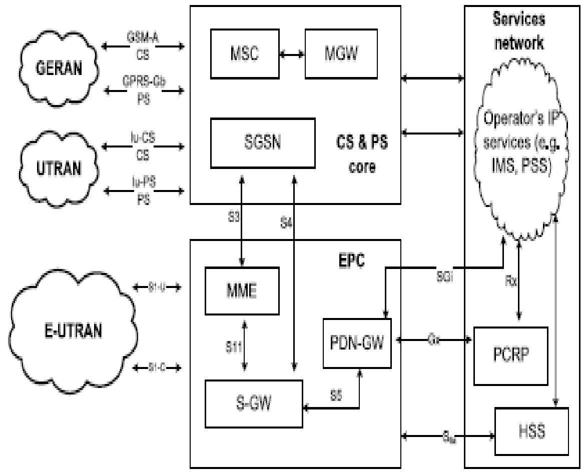

Fig. 1. Overview of EPS for 3GPP accesses (non-roaming architecture).

3 LTE-Advanced E-UTRAN Overview

In Fig. 2, we show the architecture of E-UTRAN for LTE Advanced. The core part in the E-UTRAN architecture is the enhanced Node B (eNodeB or eNB), which provides the air interface with user plane and control plane protocol terminations towards the UE. Each of the eNBs is a logical component that serves one or several E-UTRAN cells, and the interface interconnecting the eNBs is called the X2 interface. Additionally, Home eNBs (HeNBs, also called femtocells), which are eNBs of lower cost for indoor coverage improvement, can be connected to the EPC directly or via a gateway that provides additional support for a large number of HeNBs.1 Further, 3GPP is considering relay nodes and sophisticated relaying strategies for network performance enhancement. The targets of this new technology are increased coverage, higher data rates, and better QoS performance and fairness for different users. As mentioned earlier, eNBs provide the E-UTRAN with the necessary user and control plane termination protocols. Fig. 3 gives a graphical overview of both protocol stacks. In the user plane, the protocols that are included are the Packet Data Convergence Protocol (PDCP), the Radio Link Control (RLC), Medium Access Control (MAC), and Physical Layer (PHY) protocols. The control plane stack additionally includes the Radio Resource Control (RRC) protocols.

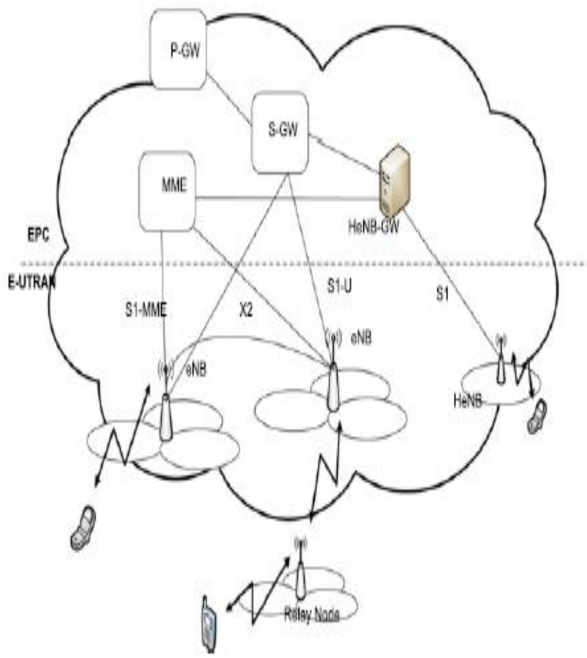

Fig. 2. LTE-Advanced E-UTRAN architecture.

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Table 1 LTE, LTE-Advanced, and IMT-Advanced performance targets for downlink (DL) and uplink (UL).

Item	Tx. Path	Antenna	LTE (Rel. 8)	LTE- Advanced	IMT- Advanced
Peak data rate	DL	8 X 8	300 Mbps		1Gbps
	UL	4 X 4	75 Mbps	500	–
Peak Spectrum (bps/Hz)	DL	8 X 8	15	30	15
	UL	4 X 4	3.75	15	6.75
Capacity (bps/Hz/cell)	DL	2 X 2	1.69	2.4	–
		4 X 2	1.87	2.6	2.2
		4 X 4	2.67	3.7	–
	UL	1 X 2	0.74	1.2	–
		2 X 4	–	2.0	1.4
Cell-edge user throughput (bps/Hz/cell/user)	DL	2 X 2	0.05	0.07	–
		4 X 2	0.06	0.09	0.06
		4 X 4	0.08	0.12	–
	UL	1 X 2	0.024	0.04	
		2 X 4	–	0.07	

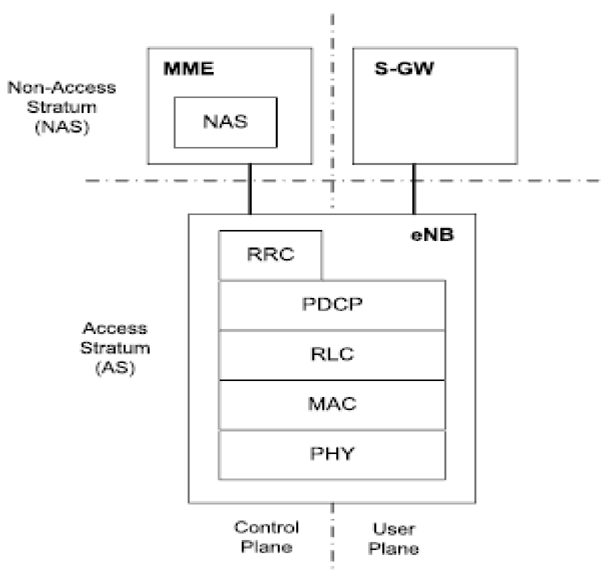

Fig. 3. Protocol stack.

The main functionalities carried out in each layer are following.

- NAS (Non-Access Stratum)
  - Connection/session management between UE and the core network.
  - Authentication.
  - Registration.
  - Bearer context activation/deactivation.
  - Location registration management.
- RRC (Radio Resource Control)
  - Broadcast system information related to Non-Access Stratum (NAS) and Access Stratum (AS).
  - Establishment, maintenance, and release of RRC connection.
  - Security functions including key management.
  - Mobility functions.

  - QoS management functions.
  - UE measurement reporting and control of the reporting.
  - NAS direct message transfer between UE and NAS.
- PDCP (Packet Data Convergence Protocol)
  - Header compression.
  - In-sequence delivery and retransmission of PDCP Session Data Units (SDUs) for acknowledge mode radio bearers at handover.
  - Duplicate detection.
  - Ciphering and integrity protection.
- RLC (Radio Link Control)
  - Error correction through Automatic Repeat request (ARQ).
  - Segmentation according to the size of the transport block and re-segmentation in case a retransmission is needed.
  - Concatenation of SDUs for the same radio bearer.
  - Protocol error detection and recovery.
  - In-sequence delivery.
- MAC (Medium Access Control)
  - Multiplexing/demultiplexing of RLC Packet Data Units (PDUs).
  - Scheduling information reporting.
  - Error correction through Hybrid ARQ (HARQ).
  - Local Channel Prioritization.
  - Padding.

4 Enhanced MIMO

Multiple-Input Multiple-Output (MIMO) is a key technique in any modern cellular system that refers to the use of multiple antennas at both the transmitter and receiver sides. Base stations and terminals are therefore equipped with multiple antenna elements intended to be used in transmission and reception to make MIMO capabilities available at both the downlink and the uplink. Next-generation cellular systems will have to provide a large number of users with very high data transmission rates, and MIMO is a very useful tool towards increasing the spectral efficiency of the wireless transmission.

Enhanced MIMO is considered as one of the main aspects of LTE-Advanced that will allow the system to meet the IMT-Advanced rate requirements established by the ITU-R. The majority of the MIMO technologies already introduced in LTE are expected to continue playing a fundamental role in LTE-Advanced, namely beam forming, spatial multiplexing and spatial diversity. However, further improvements in peak, cell-average, and cell-edge throughput need to be obtained to substantially increase performance.

The aforementioned techniques require some level of channel state information (CSI) at the base station so that the system can adapt to the radio channel conditions and significant performance improvement can be obtained. TDD systems this information is easily gathered from the uplink, provided the channel fading is sufficiently slow, due to the fact that the same carrier frequency is used for transmission and reception. On the other hand, due to the asymmetry of FDD systems, feedback information over the reverse link is required. Full CSI could cause an additional overhead that might be excessive, so quantization or statistical CSI are preferable in practice. In addition, terminal mobility can pose serious difficulties to the system performance as the channel information arriving to the eNB may be outdated. Multi-antenna techniques in a multi-user scenario have the role of delivering streams of data in a spatially multiplexed fashion to the different users in such a way that all the degrees of freedom of a MIMO system are to be utilized. The idea is to perform an intelligent Space Division Multiple Access (SDMA) so that the radiation pattern of the base station is adapted to each user to obtain the highest possible gain in the direction of that user. The intelligence obviously lies on the base stations that gather the CSI of each UE and decide on the resource allocation accordingly.

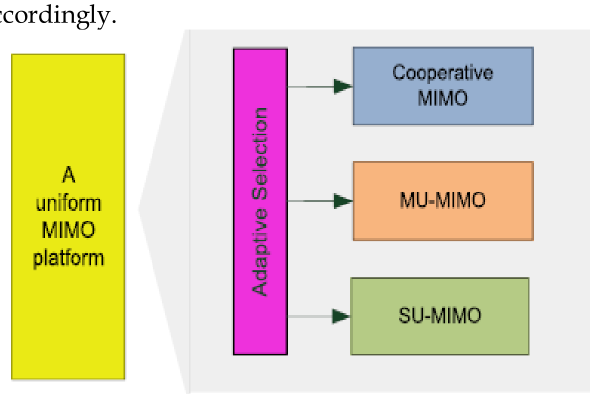

Fig 4. MIMO adaptive switching scheme

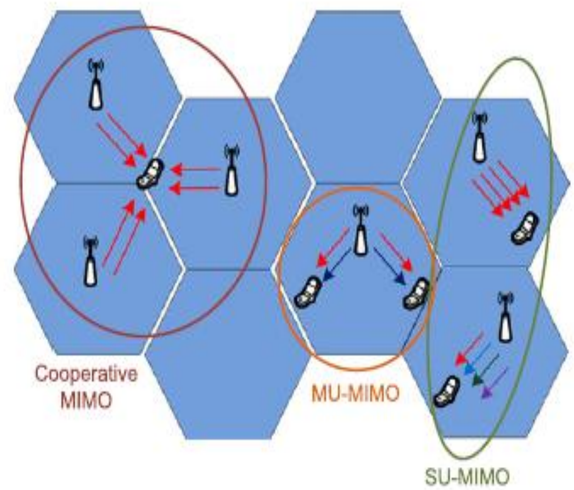

Fig 5. LTE-Advanced main MIMO modes

5 Cooperative Multipoint Transmission and Reception of LTE-Advanced

Future cellular networks will have to simultaneously provide a large number of different users with very high data rates, and the capacity of the new radio access systems needs to be increased. Traditionally, in cellular systems each user is assigned to a base station on the basis of criteria such as signal strength. At the terminal side, all the signals coming from the rest of base stations in the form of interference dramatically limit the performance. The user also communicates with a single serving base station while causing interference to the rest of them. Due to the interference limitation of cellular systems, the task of high data delivery cannot be accomplished by simply increasing the signal power of the transmission. Each base station processes in-cell users independently, and the rest of the users are seen as inter-cell interference whose transmission power would also be increased. One strategy to reduce the performance-limiting interference is to reduce the inter-cell interference with the help of cooperative transmission. Cooperative Multipoint (CoMP) transmission and reception is a framework that refers to a system where several geographically distributed antenna nodes cooperate with the aim of improving the performance of the users served in the common cooperation area. It encompasses all required system designs to achieve tight coordination for transmission and reception.

Cooperation among eNBs is characterized by the need of an interconnection among the different nodes in the form of very-high-speed dedicated links. Optical fiber, wired backbone connection or even highly directional wireless microwave links could be some feasible examples. These low-latency links are essential for the success of the cooperative communication, although its design is a very challenging issue due to the large amount of data that may

need to be exchanged among the nodes. LTE-Advanced will use the standardized interface X2 for these purposes.
CoMP in the context of LTE-Advanced involves several possible coordinating schemes among the access points. Coordinated beam forming/scheduling is a simpler approach where user data are transmitted only from a single cell. Joint processing techniques; however, requires multiple nodes to transmit user data to the UE. Two approaches are being considered: joint transmission, which requires multi-user linear preceding, and dynamic cell selection, where data are transmitted from only one cell that is dynamically selected. This section of the paper presents a broad overview of the architectures, approaches, and main challenges regarding CoMP in the context of LTE-Advanced. It is necessary to mention that most of these ideas are currently being studied and therefore may change throughout the standardization process.

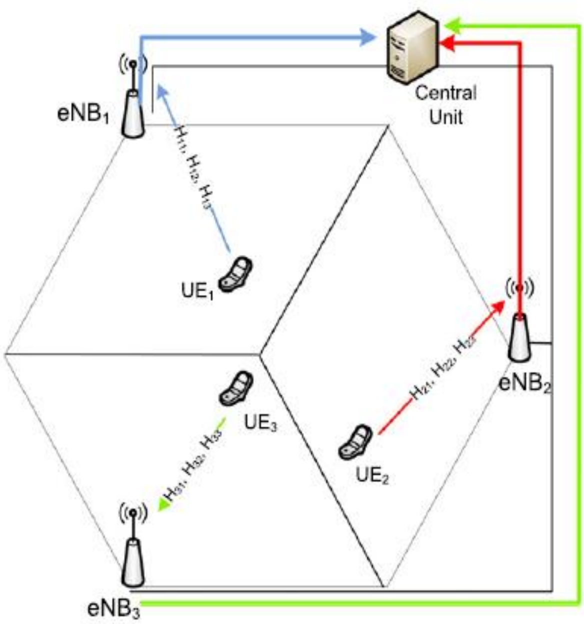

Fig 6. Centralized CoMP approach

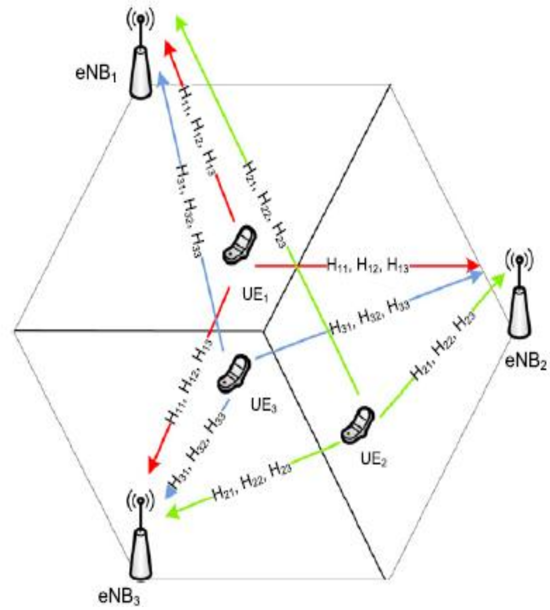

Fig 7. Distributed CoMP approach.

6 Conclusions

LTE-Advanced, the backward-compatible enhancement of LTE , will be fully specified in 3GPP. It has already been submitted as 3GPP's 4G candidate radio interface technology to ITU-R. We have described its main technologies: carrier aggregation, enhanced MIMO, cooperative multipoint transmission and reception, and relays. For each one, we have examined their benefits, challenges, and some existing approaches to tackle these challenges. However, several issues in each of them are still open and require further research. It is the combination of these technologies, and not just a single one, that will enable achieving the target performance requirements established by IMT-Advanced. The development and integration of this elements will not end with 3GPP, but will provide the starting point for their implementation.
In addition to the elements that we have examined in this paper, it is also expected that the use of femto cells will drive the evolution of current and future mobile wireless networks.

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