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LTE-Advanced Radio Access Enhancements: A Survey

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Abstract Long Term Evolution Advanced (LTE-Advanced) is the next step in LTE evolution and allows operators to improve network performance and service capabilities through smooth deployment of new techniques and technologies. LTE-Advanced uses some new features on top of the existing LTE standards to provide better user experience and higher throughputs. Some of the most significant features introduced in LTE-Advanced are carrier aggregation, enhancements in heterogeneous networks, coordinated multipoint transmission and reception, enhanced Multiple Input Multiple Output (MIMO) usage and deployment of relay nodes in the radio network. Mentioned features are mainly aimed to enhance the radio access part of the cellular networks. This survey article presents an overview of the key radio access features and functionalities of the LTE-Advanced radio access network, supported by the simulation results. We also provide a detailed review of the literature together with a very rich list of the references for each of the features. An LTE-Advanced roadmap and the latest updates and trends in LTE markets are also presented.

Keywords LTE-Advanced, Carrier Aggregation, MIMO, Heterogeneous Network, Relay Nodes, CoMP Transmission and Reception

1 Introduction

Wireless mobile data traffic has increased tremendously in the last few years and is expected to increase 13-fold between 2012 and 2017 [1]. The leading driver for this increased growth of wireless data traffic, especially in cellular communications, is smartphones as shown in Fig. 1 [1] and Fig. 2 [2]. This increasing demand is pushing the existing wireless mobile networks towards their limits, causing a reduction in data throughput, decreasing the availability of resources and increasing data transmission delay.

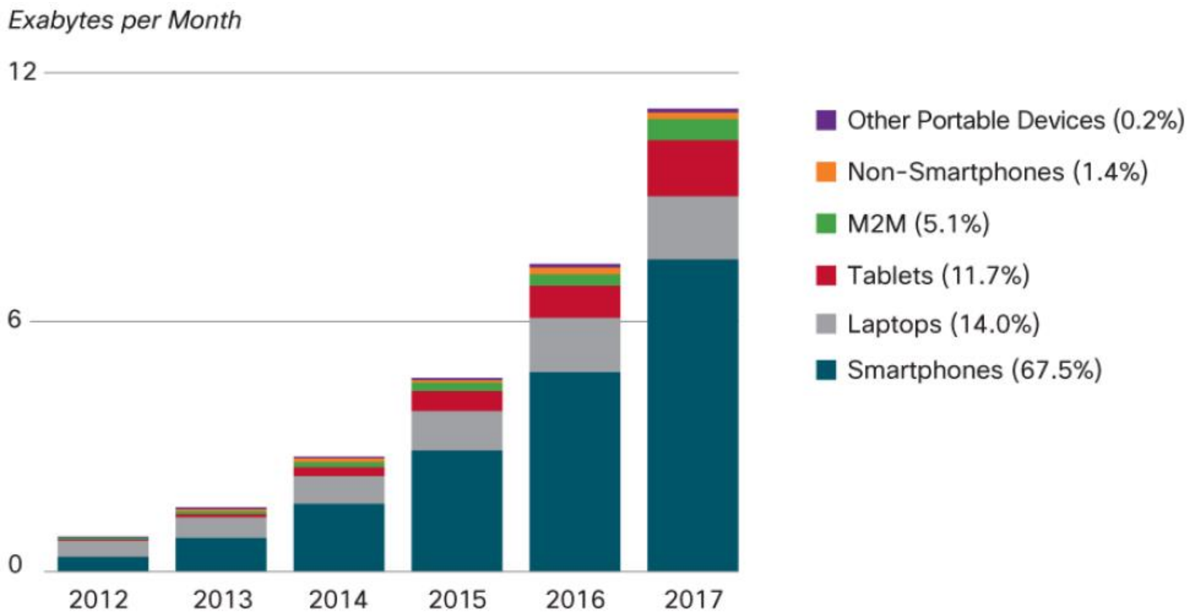

Fig. 1 Mobile data traffic growth **[1]**

Long Term Evolution of 3G (LTE) is one of the strongest candidates proposed by the 3rd Generation Partnership Project (3GPP) for deploying globally as the next generation of wireless mobile networks (i.e. 4G). LTE has been the fastest developing mobile system to date and as of July 2014, 318 operators have commercially launched LTE systems worldwide [3]. The LTE expansions forecast illustrated in Fig. 3 [2] indicates that the LTE deployment trend will continue to increase in the coming years.

LTE standardisation was started in 3GPP release 8 with basic features such as Multiple Input Multiple Output (MIMO) support. The next release of LTE (i.e. release 9) did not introduce major changes in the radio capability of the LTE systems. Some complementary features, e.g. positioning and enhanced Multimedia Broadcast Messaging Service (MBMS) were enabled, but the offered data rates and capacity remained unchanged. In release 10 (also referred to as LTE-Advanced), significant modifications have been made in the radio capabilities and the peak and achievable data rates improved significantly.

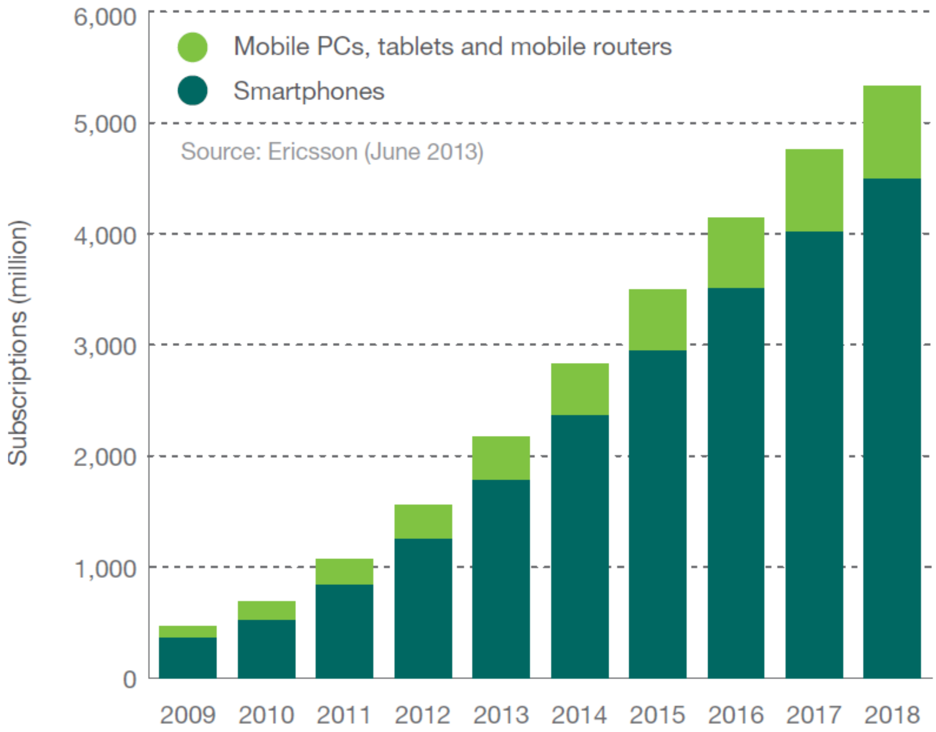

Fig. 2 Subscriptions with cellular connection [2]

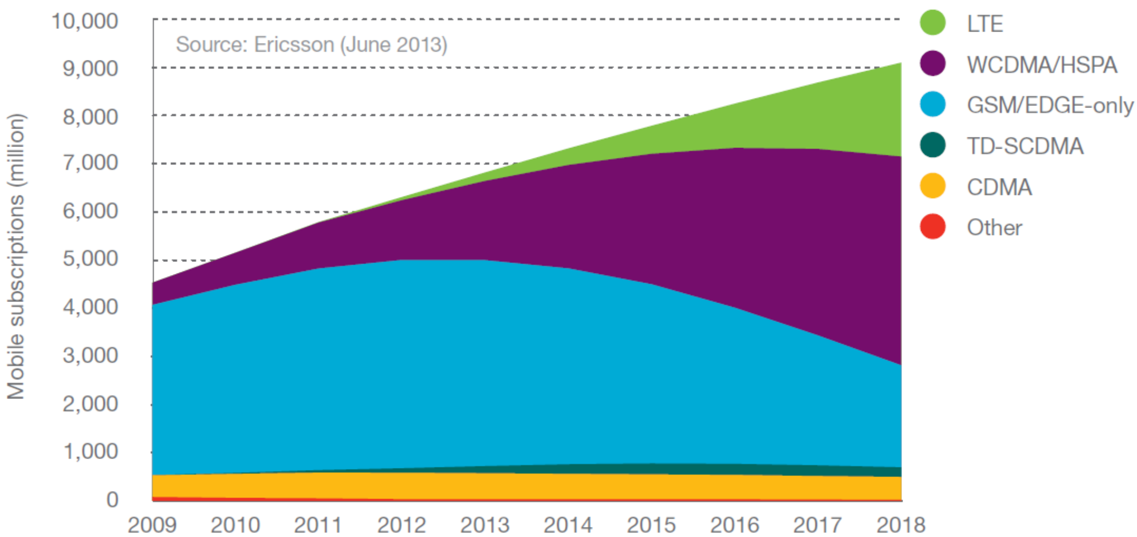

Fig. 3 Mobile subscriptions by technology [2]

LTE-Advanced is meant to fulfil the requirements of International Telecommunication Union – Radio communication sector (ITU-R) for International Mobile Telecommunication - Advanced (IMT-Advanced). The Key IMT-Advanced requirements are summarised as follows [4]:

- 100 Mbps and 1 Gbps peak data rates for high and low mobility cases respectively;
- Minimum 40 MHz transmission bandwidth (and up to 100 MHz is under consideration);
- Interworking with other radio access technologies and systems;
- Enabling high quality mobile services;
- Capability of worldwide roaming;
- Up to 350 km/h mobility support;
- Voice Over IP (VoIP) capacity from 30 to 50 users/sector/MHz depending on the scenario;

- Spectral efficiency from 0.7 bits/Hz/cell to 3 bits/Hz/cell depending on the scenario;
- Cell edge user spectral efficiency from 0.015 bps/Hz to 0.1 bps/Hz depending on the scenario;

Main features and techniques deployed in LTE-Advanced physical layer can be summarised as follows [5-13]:

- More transmission bandwidth using Carrier Aggregation (CA);
- Using more antennas and enhanced antenna techniques in the uplink and downlink transmission (MIMO enhancement);
- Cooperation between cells and Coordinated Multi Point (CoMP) transmission and reception;
- Using small cells and relays;

In this article, these LTE-Advanced key features are briefly explained, and a comprehensive list of references is provided to forward readers directly to more details regarding the current state of the art (SOTA). The improvements from LTE to LTE-Advanced are also illustrated and highlighted through link level simulation results. To the best of authors' knowledge, none of the existing articles (e.g. see [5-8]) provide such a comprehensive survey related to LTE-Advanced radio access features. In addition, the latest evolution trends and updates in LTE markets together with discussions regarding the current challenges and the future roadmap of LTE-Advanced are presented, which have rarely been discussed in the existing articles. Hence, it could have a significant contribution as a comprehensive survey article.
In section 2, the specifications of LTE and LTE-Advanced are overviewed, following with a specific section for each of the mentioned features of LTE i.e. Carrier aggregation (section 3), MIMO enhancement (section 4), Heterogeneous Network (section 5), Relaying (Section 6) and CoMP (section 7). Simulation results and discussions on the future road map of LTE-Advanced enhancements are presented in section 8 and section 9 respectively. Finally, the article is concluded in section 10.

2 LTE Systems Overview

LTE was started as a study by 3GPP and first reported at a workshop in Canada in November 2004. The first complete set of standardisation was ready in March 2009. It was designed by 3GPP for years 2010 to 2020 and beyond and to compete with WiMAX technology introduced by IEEE. Some of the main drivers that push the different aspects of the LTE requirements are summarised in Table 1.

Table 1 LTE main drivers

Driver	Aspect
Wireline Evolution	Data Rate
Extensive Wireless Data Usage	Capacity
Flat Rate Pricing	Cost Efficiency
Other Wireless Technologies	New Capabilities

Orthogonal Frequency Division Multiple Access (OFDMA) is used in LTE downlink with subcarrier spacing of 15 KHz (7.5 KHz subcarrier spacing is also supported for MBMS services). Resource assignment is done through assigning the sets of 12 consecutive subcarriers, called Resource Blocks (RB), to the users by scheduler. Considering the 15 KHz spacing between subcarriers, the bandwidth of each RB is 180 KHz (12×15 KHz = 180 KHz). Number of RBs per cell is ranging from 6 to 100 corresponding to 1.4 MHz to 20 MHz bandwidth as shown in Table 2. Scalable bandwidth facilitates the deployment of LTE technology for mobile network operators. Small bandwidths can conveniently be used for refarming in lower frequencies such as 900 MHz, while higher bandwidths are basically suitable for refarming in higher frequencies to provide high data rates.

Table 2 LTE bandwidths

Bandwidth	No. of Resource Block	No. of Data Subcarrier	FFT Size	Sampling Rate
1.4 MHz	6	72	128	1.92 MHz
3 MHz	15	180	256	3.84 MHz
5 MHz	25	300	512	7.68 MHz
10 MHz	50	600	1024	15.36 MHz
15 MHz	75	900	1536	23.04 MHz
20 MHz	100	1200	2048	30.72 MHz

It can be seen from Table 2 that the sampling rates for all LTE bandwidths are set to be the multiplication of 3.84 MHz in order to provide backward compatibility with WCDMA systems and facilitate the implementation of terminals that can support both LTE and WCDMA systems.
In the uplink, LTE uses Single Carrier-OFDMA (SC-OFDMA) technique. The main advantage of SC-OFDMA over OFDMA is the 6 to 9 dB lower Peak to Average Power Ratio (PAPR) that results in less power consumption, less complex and less expensive Radio Frequency (RF) amplifiers in the user terminals. In addition, using only one carrier protects the system from interferences caused by frequency errors and the imperfect orthogonality between the subcarriers.
The main techniques that differentiate LTE radio access from other 3GPP technologies can be summarised as:

- OFDMA in downlink
- SC-FDMA in uplink
- Scalable bandwidth
- MIMO technology (HSPA systems also support MIMO technology in principle)
- Frequency domain scheduling

LTE release 8 and 9 meet the IMT-Advanced requirements in several areas such as high mobility support and latency. However, 3GPP set tight requirements for LTE-Advanced compared to IMT-Advanced in order to meet all the IMT-Advanced requirements confidently and also provide considerable improvements from release 8 and 9 to release 10 [14]. Table 3 compares LTE and LTE-Advanced fulfilments against IMT-Advanced and 3GPP requirements.

Table 3 Requirements and LTE fulfilments

	IMT-Advanced Requirements	3GPP LTE-Advanced Requirements	LTE Release 8 Achievements	LTE-Advanced Release 10 Achievements
Downlink Peak Spectrum Efficiency (bps/Hz)	15 (max 4 antennas)	30 (max 8 antennas)	16	16 (4x4 antenna configuration) 30 (8x8 antenna configuration)
Uplink Peak Spectrum Efficiency (bps/Hz)	6.75 (max 2 TX antennas)	15 (max 4 TX antennas)	4	8.1 (2x2 antenna configuration) 16.1 (4x4 antenna configuration)
User Plane Latency (ms)	10	10	4.9	4.9

Some of the main physical layer features in release 10 and subsequent releases of LTE-Advanced (i.e. release 11 and 12) are summarised in Table 4.

Table 4 LTE-Advanced features

Release 10	Release 11	Release 12 (Study Items)
Carrier Aggregation	Carrier Aggregation enhancement	MIMO enhancement
Advanced MIMO	CoMP Transmission/Reception	CoMP enhancement
Heterogeneous Network and eICIC	Further eICIC (FeICIC)	Small Cells enhancement
Relay Nodes	Enhanced Downlink Control Channel (E-PDCCH)	

At the time of writing this article, release 12 has not been finalised and documentation of specification started in September 2013 and will be completed by June 2014. Release 10 and 11 are already finalised.
Regarding the User Equipment (UE), LTE-advanced has defined three new classes in addition to the five classes in LTE release 8 and 9. Table 5 and 6 summarise LTE and LTE-advanced UE categories [15].

Table 5 LTE UE Category

	Category 1	Category 2	Category 3	Category 4	Category 5
Peak Data Rate Downlink	10 Mbps	50 Mbps	100 Mbps	150 Mbps	300 Mbps
Peak Data Rate Uplink	5 Mbps	25 Mbps	50 Mbps	50 Mbps	75 Mbps
RF Bandwidth	20 MHz	20 MHz	20 MHz	20 MHz	20 MHz
Modulation Downlink	64 QAM	64 QAM	64 QAM	64 QAM	64 QAM
Modulation Uplink	16 QAM	16 QAM	16 QAM	16 QAM	64 QAM
MIMO Downlink	Optional	2x2	2x2	2x2	4x4
MIMO Uplink	No	No	No	No	No

Table 6 Categories added in LTE-Advanced

	Category 6	Category 7	Category 8
Peak Data Rate Downlink	300 Mbps	300 Mbps	3000 Mbps
Peak Data Rate Uplink	50 Mbps	100 Mbps	1500 Mbps
RF Bandwidth	40 MHz	40 MHz	100 MHz
Modulation Downlink	64 QAM	64 QAM	64 QAM
Modulation Uplink	16 QAM	16 QAM	64 QAM
MIMO Downlink	2x2 with CA 4x4 without CA	2x2 with CA 4x4 without CA	8x8
MIMO Uplink	No	2x2	4x4

As of the date of writing this article, the majority of the LTE devices in the market are in category 3. A few mobile phones in category 4 have started to appear since the beginning of 2013. The first UE chipset that supports carrier aggregation was launched by Qualcomm in June 2013. It is used in category 4 UEs and supports two carriers with up to 10 MHz of bandwidth each (10 MHz + 10 MHz).

3 Carrier Aggregation

3.1 Overview

CA is considered to be the most important and effective feature of LTE-Advanced. The key idea in CA is to provide wider bandwidth for users by aggregating two or more release 8 LTE carriers as illustrated in Fig. 4 [16]. In LTE-Advanced, backward compatibility is achieved by aggregating several LTE carriers to increase transmission bandwidth without any significant changes to the LTE carriers. With CA, it is also possible to aggregate different carriers from different bands. Carrier aggregation is exciting for mobile network operators as large continuous bandwidths (i.e. on the order of 100MHz) are scarce in several countries, including the United Kingdom. The network operators can aggregate several small bandwidths distributed among different frequency bands and provide larger bandwidths and the required QoS.

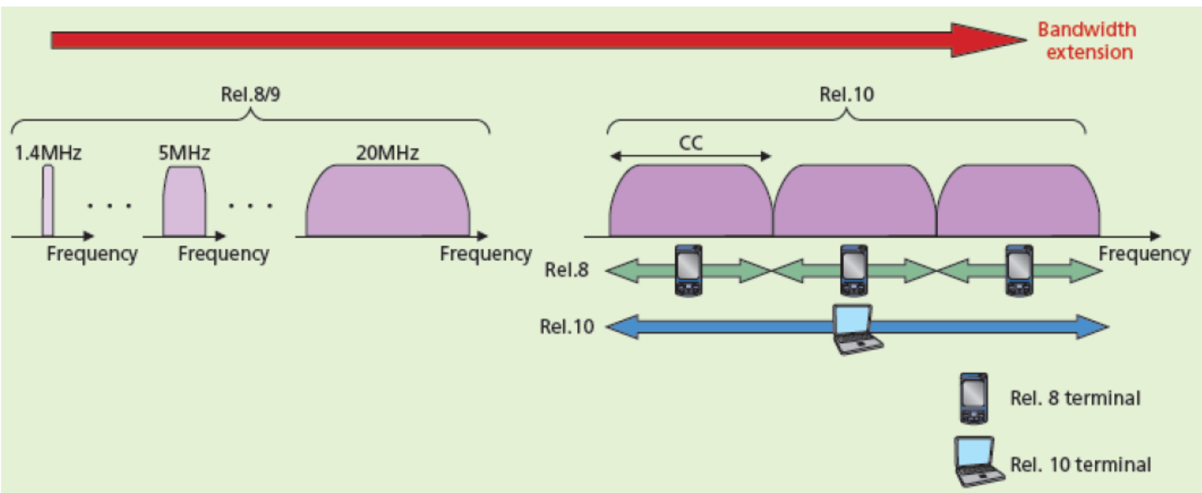

Fig. 4 Concept of LTE-Advanced CA [16]

From the theoretical point of view, release 10 signalling supports aggregation of up to five carriers and have a bandwidth of 100 MHz (5×20 MHz). Due to the practical limitations of the devices, only the aggregation of two carriers is currently considered in release 10. CA can be applied on uplink and downlink independently, but the number of uplink Component Carriers (CCs) should not be more than the downlink CCs. This is due to the fact that each of the uplink CCs is scheduled via its corresponding downlink CC. The performance evaluation for the asymmetric bandwidth allocation between uplink and downlink was examined via experiments in [17,18]. In the mentioned experiments, two CCs (40 MHz) in the uplink and five CCs (100 MHz) in downlink were considered and based on the results, improvements in the Block Error Rate (BLER) of Uplink Control Information (UCI) were seen.

3.2 Technical Aspects

General aspects and performance analysis of CA are detailed in [19-27]. CA can improve the performance of the frequency domain scheduling. Several studies have been carried out regarding CC selection and scheduling in LTE-Advanced systems with CA [28-43]. In the case of CA, the scheduler can assign better resources by considering more than one carrier. In previous LTE releases that support only one carrier, the scheduler assigns the best resource block in the carrier by considering Channel State Information (CSI) and Channel Quality Indicator (CQI) feedback. By combining CA and frequency domain scheduling, the scheduler will receive the feedback from more than one carrier, therefore it is more likely to find a suitable RB for the transmission. In addition, when the aggregated carriers are from the different bands, more flexible and efficient management is possible. For instance, UEs that only support lower frequency bands can be moved to the lower frequency, and higher frequency bands can be assigned to the UEs capable to work in high frequency bands. Also, it would be possible to assign more suitable frequency bands to the cell edge users and provide them with higher data rates and better channel conditions [30,41,42]. Based on these aspects of this feature, it is concluded that CA is not only able to increase the data rate for the users close to the Base Station (BS), but also can improve cell edge user throughput as well. However, it should be noted that in principle, CA does not offer any spectral efficiency or overall throughput improvement for a fully loaded network. Hence, the average throughput gain achieved by CA feature is decreased by increasing the number of users [44].

From the protocol point of view, impact of CA is limited to Medium Access Control (MAC) layer and the physical layer and has no impact on the core network. Core network would not know what is going on in the radio side and it only senses that the data rate exceeds the usual values. Thus, CA is not visible to the layers above the MAC layer and data is divided between CCs in MAC layer. As illustrated in Fig. 5, each CC has its own physical layer, therefore non-CA capable UEs can be easily served by any of the CC independently.

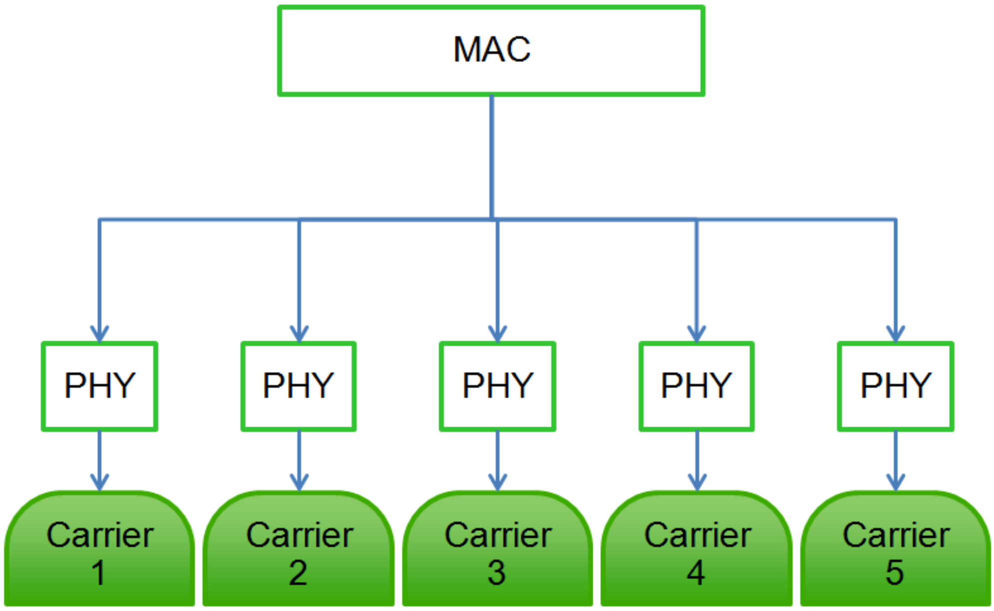

Fig. 5 CA structure

For UE attachment signalling procedure in the presence of the CA feature, the UE provides information about its CA capabilities, including information about its Primary CC (PCC) and any additional CC/CCs called Secondary CC (SCC). Once the Radio Resource Control (RRC) reconfiguration is completed, the MAC layer can activate and configure the SCC. In the case of lack of activities, a specific timer can be set to deactivate the SCC and prevent the UE from sending CSI and CQI measurement for the deactivated SCC. This reduces energy consumption in UEs and prolongs battery life.

4 MIMO Enhancement

4.1 Overview

MIMO is a key technology in wireless communications that has potential to increase the channel capacity by using multiple transmitter and receiver antennas. The term comes from the fact that the transmission antennas are handled as the input to the propagation channel (which is the air interface), whereas receiver antennas are the output of it. The very basic ideas behind MIMO were introduced in 1970 [45], but MIMO technology had not been deployed in wireless communications till 1990. This feature is currently used in IEEE 802.11n, 802.16d/e systems and supported by LTE release 8. It has already been deployed widely in LTE networks and further enhancements were proposed in release 10. In LTE-Advanced, Single User MIMO (SU-MIMO) is extended to support eight transmit antennas while in release 8, the maximum number of transmit antennas is four. In [46], performance evaluation of a single carrier LTE-Advanced system using 8 by 8 MIMO and 20 MHz of bandwidth shows that in an indoor scenario the median throughput of 335 Mbps can be achieved. The eight transmit antennas at the base station can also be deployed in the transmission diversity scenarios [47]. General review of the multi antenna transmission techniques in 3GPP technologies from GSM to LTE-Advanced is presented in [48]. References [49-51] focus on MIMO techniques in LTE-Advanced system.

Furthermore, LTE-Advanced brings some enhancements of Multi User MIMO (MU-MIMO). MU-MIMO can increase the network capacity, which is not achievable in SU-MIMO systems [52]. Many studies on different aspects of LTE-Advanced MU-MIMO such as performance evaluation [53-59], interference and channel estimation [60-62], feedback and signalling design and improvement [63-66], scheduling [67-69], beamforming [70,71], techniques to improve the throughput [72], and its deployment alongside other LTE-Advanced features such as CA [73,74] and CoMP [75] have been done.

4.2 Technical Aspects

In LTE-Advanced release 10, new techniques such as improved feedback and pre-coding, interference cancellation at the receiver and more flexibility in frequency domain scheduling were introduced. In addition, new techniques in reference signals were also introduced in release 10 [76,77]. An adaptive design method for the reference signals in LTE-Advanced was also proposed in [78]. Typically, by increasing the number of antennas, the number of required reference symbols and system overhead increase while power efficiency decreases. As the number of MIMO antennas supported in LTE-Advanced increased to eight, 3GPP decided to come up with a new reference signal structure to minimise the overhead. In the new structure, the reference signal is divided into two different signals. The first one is called Channel State Information Reference Symbol (CSI-RS) and used for CQI, Precoding Matrix Indicator (PMI) and Rank Indicator (RI) measurement and reporting. The second one is Demodulation Reference Symbol (DM-RS) which is used for channel estimation and data demodulation. DM-RS is a user specific signal and it is proportional to the number of users. It means in release 10, unlike the previous generations and technologies, each user has a specific reference symbol that can also be used for other purposes such as beamforming. CSI-RS transmission occurs less frequently than DM-RS and deploying these two types of reference symbols instead of the legacy LTE reference symbol reduces the total overhead.

Feedback signalling was also modified in release 10 and a new codebook for 8 transmit antennas was added based on double codebook principle [79,80]. The feedback is divided into short-term and long-term feedback to reduce overall feedback transmission. Long-term feedback contains information about long term parameters, while the short term feedback is relevant to SU-MIMO operation.

Regarding the uplink, in release 8 it was only possible to have MU-MIMO, while release 10 supports SU-MIMO as well. In addition, MU-MIMO is enhanced due to the enhancement of the uplink reference signal in LTE-Advanced [81]. An overview of uplink MIMO in LTE-Advanced is presented in [82]. A combination between the collaborative system and the precoded MIMO using a space frequency block codes (SFBC) for the uplink is also proposed in [83].

LTE-Advanced uses closed loop precoder selection and the base station provides feedback to the terminal. Some experimental evaluation results of the uplink SU-MIMO with closed loop precoding can be found in [84,85]. The network can also obtain CSI based on the Sounding Reference Symbols (SRS) sent by UE.

The uplink multiple access scheme in LTE and LTE-Advanced, i.e. SC-OFDMA, is also regarded as Discrete Fourier Transform Spread OFDMA (DFT-S-OFDMA). LTE-Advanced supports clustered DFT-S-OFDM technique as the standard technology in the uplink which works closely with uplink MIMO [86-89]. In this technique, a maximum of 2 non-contiguous frequency clusters can be allocated to a UE. Multi-cluster transmission provides higher average cell throughput by offering more flexibility in frequency scheduling and higher frequency diversity gain [90].

While the typical detection algorithm for MIMO detection in LTE and LTE-Advanced systems is Order Successive Interference Cancellation (OSIC), an alternative Adaptive Hybrid Interference Cancellation (AHIC) in uplink is proposed in [91].

5 Heterogeneous Network (HetNet)

5.1 Overview

In general, a simple solution for capturing the high traffic increase trend and having more capacity and coverage is to have more base station in the network. One approach is to use small cells rather than adding more macro base stations. HetNet refers to a network that contains macro base stations as well as small base stations (e.g. Micro, Pico and Femto base stations). Such small base stations are typically deployed within the umbrella of macro cell coverage as illustrated in Fig. 6. For details and a more comprehensive introduction of HetNet, readers may refer to [92-98]. More specifically, studies on different aspects of the Pico and Femto cell deployments in LTE-Advanced networks can be found in [99-105] and [106-124] respectively. Small cells increase the capacity of the networks with an acceptable overall power consumption increase. Thus, HetNets are also interesting from an energy efficiency viewpoint, especially when power saving features like sleep mode are deployed [125-127].

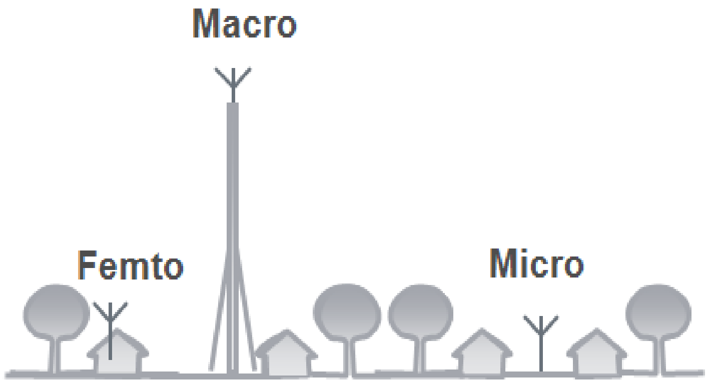

Fig. 6 Concept of HetNet

One of the main challenges in HetNet is to find suitable spectrums for small cells. Since all the available spectrum is usually assigned to the macro cells, different cell layers often have to use the same frequency [128]. This may cause interference issues which should be managed effectively in HetNets. Another concern is the amount of the traffic carried by the small cells. Typically, small cells have low output power and the received signal from small cells at UE is not strong enough, in comparison with macro cells, to attract enough users to the small cells.

5.2 Technical Aspects

Release 10 has come up with solutions to solve mentioned issues through a feature called enhanced Inter Cell Interference Coordination (eICIC), also referred to as Time Division Multiplexing ICIC (TDM-ICIC) [102,129,130]. In this feature, macro and small cells are coordinated in the time domain and inter cell interference is avoided by preventing simultaneous transmission. Time synchronisation among base stations is required for this feature and can be provided e.g. using GPS or IEEE 1588 phase sync. eICIC introduces muted sub-frames known as Almost Blank Subframe (ABS). ABSs are inserted to the macro cell frames, and the small cell uses these gaps to serve the UEs that are receiving strong signals from the macro cell, as seen in Fig. 7. The necessary information regarding ABS is exchanged between macro cell and small cell through the X2 interface. Having an ABS causes loss of the capacity of the network as it does not carry any user data. However, some information is still transmitted in ABS to provide backward compatibility for legacy UEs. Therefore, it does not offer full protection and still produces interference. More details about eICIC and its functionality can be found in [131-137]. Other methods to mitigate interference in LTE-Advanced heterogeneous networks are detailed in [138-148].

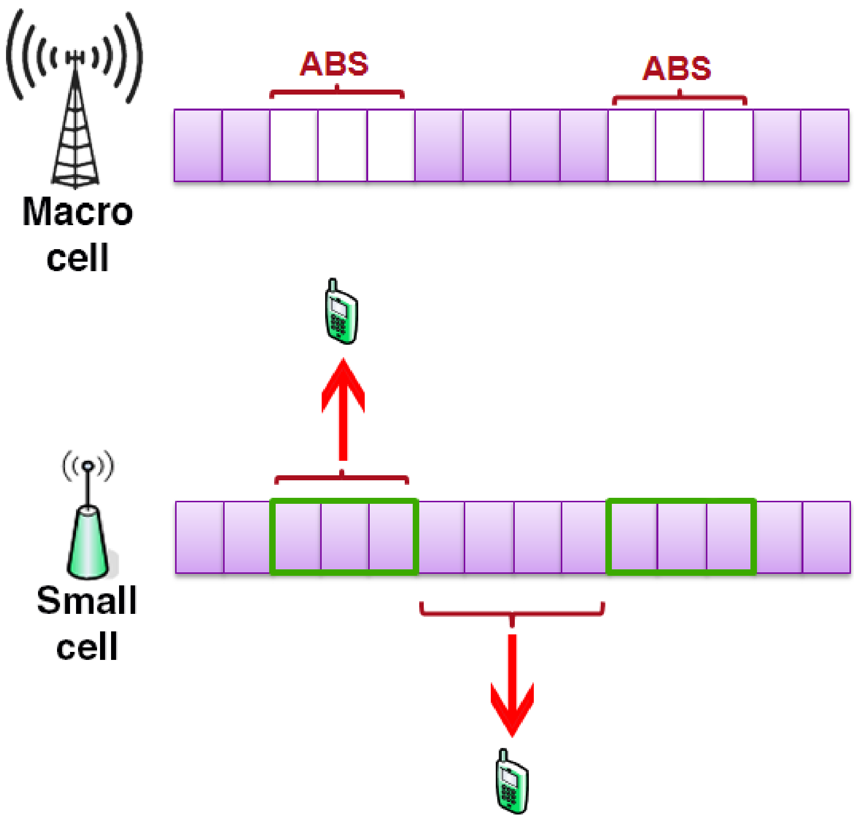

Fig. 7 eICIC functionality

Another issue in HetNet is that the small cells normally do not carry desirable amount of traffic as they typically have low output power. The footprint of the small cell can be extended in LTE-Advanced by modifying the mobility parameters under a feature called Range Extensions (RE). When RE is in place, positive offsets are applied to the small cell measurements and the UE will camp to it in worse radio conditions than without RE. Fig. 8 shows that RE increases the footprint of the small cell.

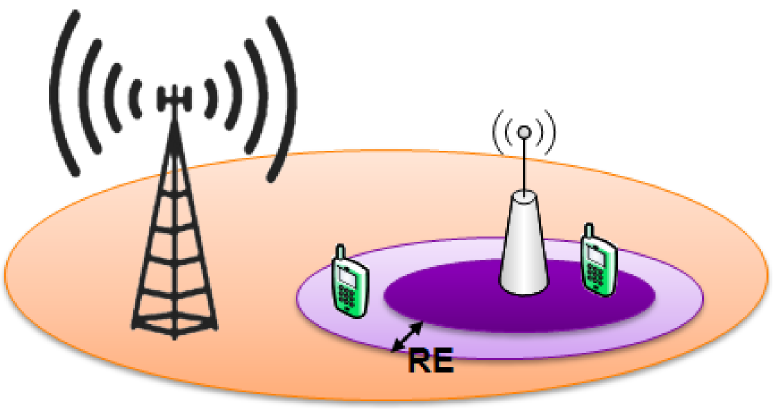

Fig. 8 Range Extension

However, it can result in a relatively bad performance in the UEs camped to the small cell, unless it is used together with interference mitigation features like eICIC. Without eICIC feature, these UEs receive strong interfering signals from the close-by macro cells. Hence, eICIC is one of the key features for enabling RE deployment in LTE-Advanced. Small cell's UEs in the RE area or cell edge may experience a high interference from the macro cell due to the co-channel deployment. The problem becomes more severe as the difference between macro and small cell transmit power increases. Having eICIC feature, larger RE values can be applied in the small cell. For more discussion, readers may refer to [149-153].

6 Relaying

6.1 Overview

Relay Node (RN) is a small site that operates between base station and UE. The main characteristic of the RN is that it does not need a separate backhaul and it is a self-backhauling base station. Relay nodes can be used in situations where providing backhaul is impractical or expensive. Installing RNs on mobile vehicles such as buses or in High Speed Railways (HSR) is another interesting application of the relays which is under consideration by 3GPP and ITU [154,155]. RN can also be considered as a special case of the small cell deployment and RNs can be compared with Pico and Femto cells in terms of performance, cost and energy efficiency [156-158]. Like small cell, techniques such as interference coordination and range extension [159-163], and power control [164-168] are required for optimising the relaying network.

From the UE point of view, RN seems as a normal base station. From the base station viewpoint, relay acts as a UE with some special features, and core network considers RN as an additional sector for the base station. The intention of relaying is to increase data rates by reducing transmitter-to-receiver distance. The link between the relay node and the UE is referred to as the access link or Uu, and the link between the base station and relay node is referred to as the backhaul link or Un [169]. The architecture of the LTE-Advanced relaying network is shown in Fig. 9.

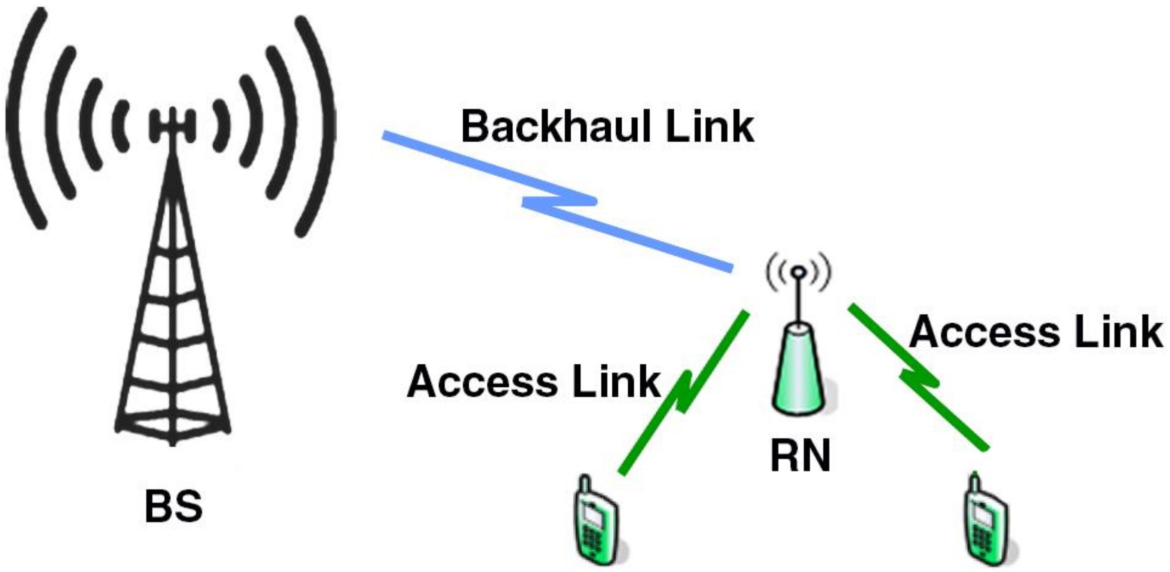

Fig. 9 RN deployment architecture

The access and backhaul links can use either Time Division Duplexing (TDD) or Frequency Division Duplexing (FDD) to distinguish between the uplink and downlink. Therefore, four links exist as illustrated in Fig. 10. In all cases, release 8 UEs are able to connect to the base station (donor cell), and backward compatibility is provided [170].

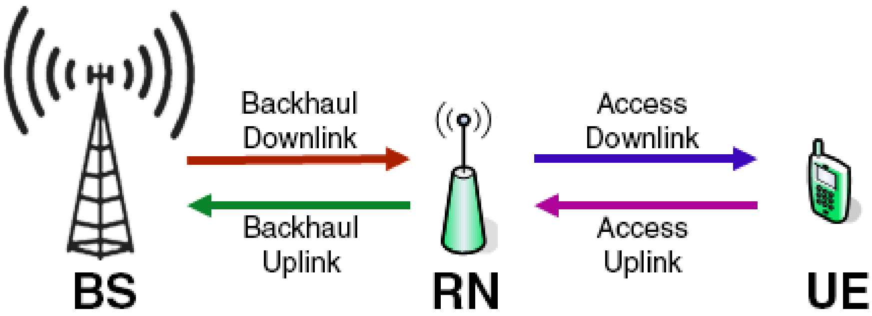

Fig. 10 RN four different links

If the split between the access link and the backhaul link is done in the frequency domain, the relay is called an outband relay. If the same frequency band is used for the both links and the split is done in the time domain, then it is called an inband relay. There are several studies for the appropriate resource sharing between backhaul and access links and mitigation of interference using the proper resource scheduling techniques [171-184]. CA feature can provide more flexible resource allocation in relaying networks [185,186].
An RN is generally more intelligent than a repeater and can act as a base station. One of the advantages of the RN over repeater is that, the responsibility of delivering signals from RN to UE is with RN and base station will be freed up immediately after delivering the signal to the RN. Repeaters are amplifying whatever they receive and hence, they amplify the noise and interference as well. Some studies have been done concerning the deployment of the repeaters in LTE-Advanced networks [187,188].
Relays can be categorised into transparent and non-transparent. In transparent relaying, the UE is not aware of the existence of the RN. In this case, the RN does not have a unique cell identity (Cell ID) and at least some parts of the Radio Resource Management (RRM) are done in donor base station. Hence, it is not creating a new cell in the network. In non-transparent relaying, RN has its own Cell ID and UE can distinguish whether it is connected to donor cell or the RN.
Relays can perform in two modes: Decode-and-Forward (DF) relay and Amplify-and-Forward (AF) relay. If the relay decodes and re-encodes the received signal before sending it to the receiver, it is known as the DF relay. In case the relay just amplifies and forwards the received signals, it is referred to as the AF relay. The performances of the DF and AF relays were compared in [189-191] and concluded that DF relays are more suitable for the LTE-Advanced system. The following types of DF, namely Layer 3 (L3) relays, can be categorised as [192]:

- Type 1a: It is a non-transparent outband relay and uses different frequencies in access and backhaul links. The implementation of this type of relays is easy and has little impacts on the network topology.
- Type 1b: In this type, adequate isolation between access and backhaul antennas is provided, thus no split between the two links is needed. It is considered as inband relay, as the access and backhaul links use the same frequency. Its implementation is easy and almost same as type 1a. It is a non-transparent relay.
- Type 1: it is a non-transparent inband relay and uses the same frequency for access and backhaul links. Therefore, time division multiplexing of the links is required. Some changes should be made in the frame structures for implementing this type of the relay.
- Type 2: it is a transparent inband relay. It is not considered in release 10. This type of the RN would be used mainly in CoMP scenarios [193].

6.2 Technical Aspects

General performance analysis and system architecture of the relay-enhanced LTE-Advanced network is presented in [194-200]. Network planning in LTE-Advanced relaying networks is one of the challenging areas that still has several open research problems e.g. finding the optimum RNs placement methods. One such method is Enhanced tree (E-Tree) algorithm [201] in which the coverage problem is formulated based on Integer Linear Programming (ILP). By using E-tree algorithm, both elements of the two-hop relaying networks would be placed at the location which has the lowest construction cost. Hence, this technique is suitable for large scale network planning where the cost efficiency is an important issue, and it can help undeveloped countries to implement the infrastructures with lower time complexity and less construction cost. Some other methods and strategies regarding the site planning and RN placement were introduced in [202-205]. The effects of the antenna height on the propagation channel in relaying were also discussed in [206,207].

Deployment of RNs brings many benefits such as coverage, capacity and cell edge throughput enhancements to the LTE-Advanced network [208,209]. At the expense of deployment cost [210,211], achievable gains in relaying networks substantially depend on the location and number of deployed relay nodes. In [212], three scenarios were proposed based on the number of relays per cell (RPC), and network performance was evaluated using Monte-Carlo simulation. The results show that two relays-per-cell can lead to a good compromise between capacity improvements and cost, while in three relays-per-cell scenario achieved gains cannot justify the cost in comparison with two relays-per-cell scenarios. Also, it can be seen that best performance is obtained in six relays-per-cell scenario. But it should be considered that the deployment of more relays per cell will significantly increase the implementation cost.

System performance evaluations by deploying RNs in LTE-Advanced systems have been performed in indoor [213], urban [214], and suburban [215,216] deployments. An evaluation has been done in an LTE-Advanced network in London, UK and the downlink channels performance of RNs was compared with the use of micro base stations [217]. In this study, inband relay was considered and the user data rate of 1024 kbps was set as the minimum target. The results illustrate that in order to enhance network coverage and remove the coverage gaps, inband RNs are good choices. But they do not offer a desirable improvement in terms of network capacity due to the limitation of wireless backhaul links. It can be seen from the results of this study that micro site deployment can boost capacity of the network up to 5 times, without any degradation in the network footprint.

Another important aspect of the relaying network is the energy efficiency [218-221]. RN deployment can bring power savings in the uplink, and prolonging battery lifetime of the UE. The theoretical analysis and computer simulation results on effects of relaying by considering fixed RNs show that for the path-loss index of 4, power reduction of more than 50% (4 to 5 dB) can be achieved [222]. The simulation shows high power efficiency achievement while maintaining an acceptable level of signal to noise ratio (SNR). Also, it was discussed that the optimum number of relays in terms of energy minimisation would be 12-24 per cell.

The increasing number of RNs increases interference between nodes. In addition, a new interference can be seen in relaying networks between the access link of an RN and backhaul link of another RN, which is referred to as relay-to-relay interference and addressed in [223]. Optimising the transmit power of the UE is an effective way to defeat the interference problem in relaying system. Reference [224] is discussed whether current employed power control parameters in LTE release 8 can be applied to both RN and base station in the LTE-Advanced relaying network. As predicted, deployment of relays even with current parameter settings shows a great enhancement in system performance. However, it is shown that it is not the best possible performance and better performance and more improvements can be achieved by optimising the relevant power control parameters.

Optimising output power and bandwidth allocation in relaying networks, considering type 1 relays are investigated in [225,226]. It is shown that deploying the bandwidth sharing method in LTE-Advanced networks can provide about 3.5 dB gain in the transmit power in comparison with the case in which fixed bandwidth is allocated. This considerable achieved gain can be used to increase coverage area, and provide a new way to enhance LTE-Advanced systems by deploying type 1 relays.

More advanced deployments of the relays such as cognitive relays [227], self-organising relays [228,229] coordinated/cooperative relay systems [230-233], and opportunistic relaying [234] have been studied and are expected to be used in future mobile communications networks.

7 CoMP Transmission and Reception

7.1 Overview

This framework offers different techniques for having tight coordination between multiple locally distant radio access network nodes such as base stations and RNs. The coordination can be among the cells served by the same base station (intra base station), or the cells served by different base stations (inter base station). The synchronisation between base stations is obviously a necessity for having CoMP. In the case of inter base station CoMP, this synchronisation and coordination would be realised via the X2 interface between the base stations. CoMP was supposed to be considered as part of the Release 10 at the beginning, but due to the complexity and unclear realistic gain it was excluded later and moved to release 11 and beyond.

The idea of CoMP is that data will be sent (downlink) or received (uplink) not only by one cell, but by multiple cells and base stations. At the first sight, it looks the same as the soft and softer handover in 3G systems but CoMP is more intelligent and can make the channel adaptation very faster. As discussed in [235], CoMP and soft handover can be deployed together and provide more enhancements in LTE-Advanced networks. In some cases, CoMP can be considered as a kind of MIMO, namely multi-cell MIMO, in which the antennas are located at the different base stations. Deploying CoMP provides higher cell edge and average data rate in LTE-Advanced networks [236-242], and also can bring considerable gains and improvements in HetNets [243-249].

7.2 Technical Aspects

Theoretically, two different versions of CoMP exist [250]. The simpler version is Coordinated Scheduling/Beamforming (CS/CB) in which the transmission is only done by one cell and the interference is minimised by coordination and proper scheduling among the surrounding cells. The more advanced CoMP is Joint Processing (JP) that also known as Cooperative MIMO (C-MIMO). In JP, multiple cells are involved in transmission and they are coordinated for active interference cancelation. Consequently, the interference is converted to a useful signal and theoretical channel capacity (Shannon Limit) is increased. In general, JP brings more system improvements that CS/CB [251]. User-plane transmission in JP can be done either from multiple points at a time (Joint Transmission) or one point at a time (Dynamic Cell Selection). The latter is also known as Transmission Point Selection (TPS). Different CoMP deployment architectures are illustrated in Fig. 11 [252].

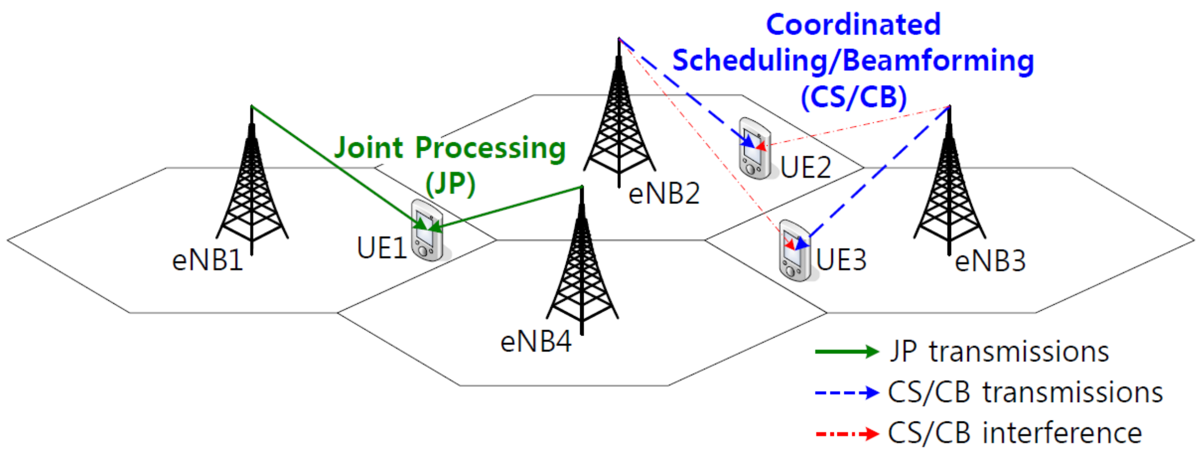

Fig. 11 CoMP architectures [252]

CoMP deployment can also result in energy savings in LTE-Advanced networks [253]. The energy savings gains can be boosted using the technique introduced in [254]. In this framework, power consumption of the network is reduced by toggling the transmission points between sleep and active modes based on their traffic.

There are some practical challenges in using this feature; In order to have an efficient transmission in the downlink, the UE should be able to estimate the channel fading not only from the serving cell but also from the other cells involved in CoMP transmission. This is more challenging when the received signal undergoes excessive fading and is relatively weak. In addition, excessive overheads and delays would be caused when all these measurements are sent to the network as feedbacks. A method for reducing these feedbacks and system overheads is proposed in [255].

8 Simulation results

8.1 Scenarios and results

In this article, typical LTE and LTE-Advanced scenarios with one base station and one UE are defined and downlink data throughputs of the user are simulated for different Signal to Noise Ratio (SNR) values. The general simulation parameters for all the LTE and LTE-Advanced cases are set according to the 3GPP specifications, and key parameters are summarised in Table 7.

Table 7 General simulation parameters

Parameter	Value
Carrier Frequency	2.5 GHz
Max No. of HARQ Retransmissions	3
Cyclic Prefix	Normal
Channel Type	Flat Rayleigh
UE Channel Estimation Method	Perfect
Number of Simulated Subframes	800

Firstly, four moderate cases are simulated for both LTE and LTE-Advanced. The UE is assumed to have two receiving antennas which is currently the case in almost all the practical situations. The results, shown in Fig.12 and Fig.13, are for two different bandwidths and MIMO configurations. Table 8 summarises the key simulation parameters for these cases.

Table 8 Simulation parameters used for Fig. 12 & 13

Parameter	Value
CQI	7
Modulation	16QAM
Bandwidth	10 MHz 20 MHz
MIMO	2x2 , Transmission Diversity (TxD) 4x2 , Open Loop Spatial Multiplexing (OLSM)

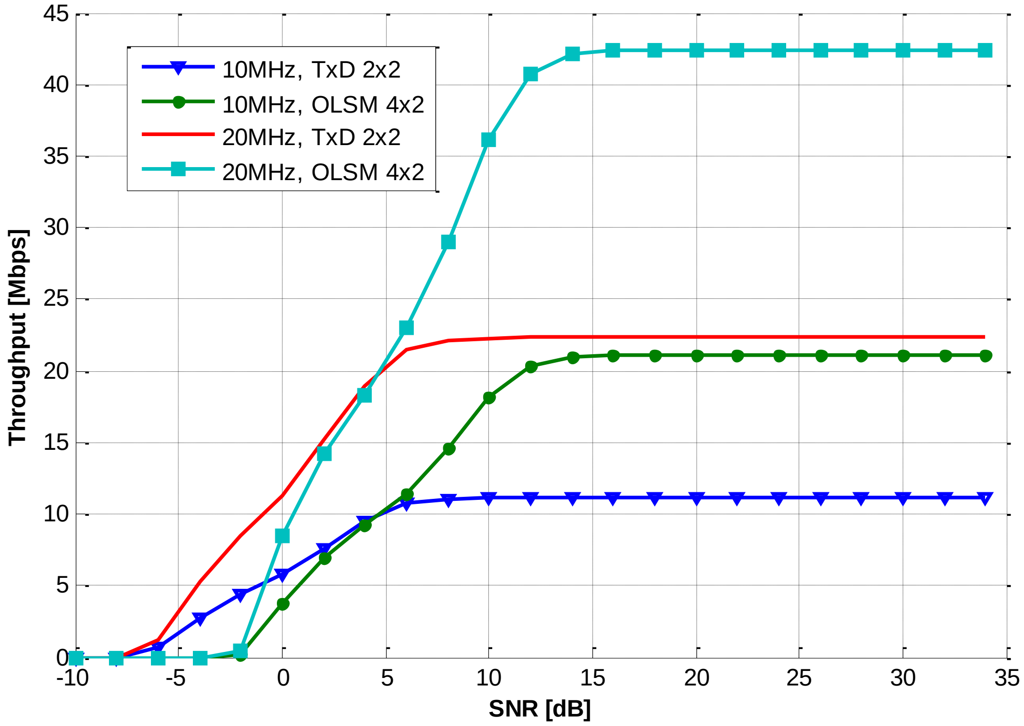

Fig. 12 LTE Simulation Results

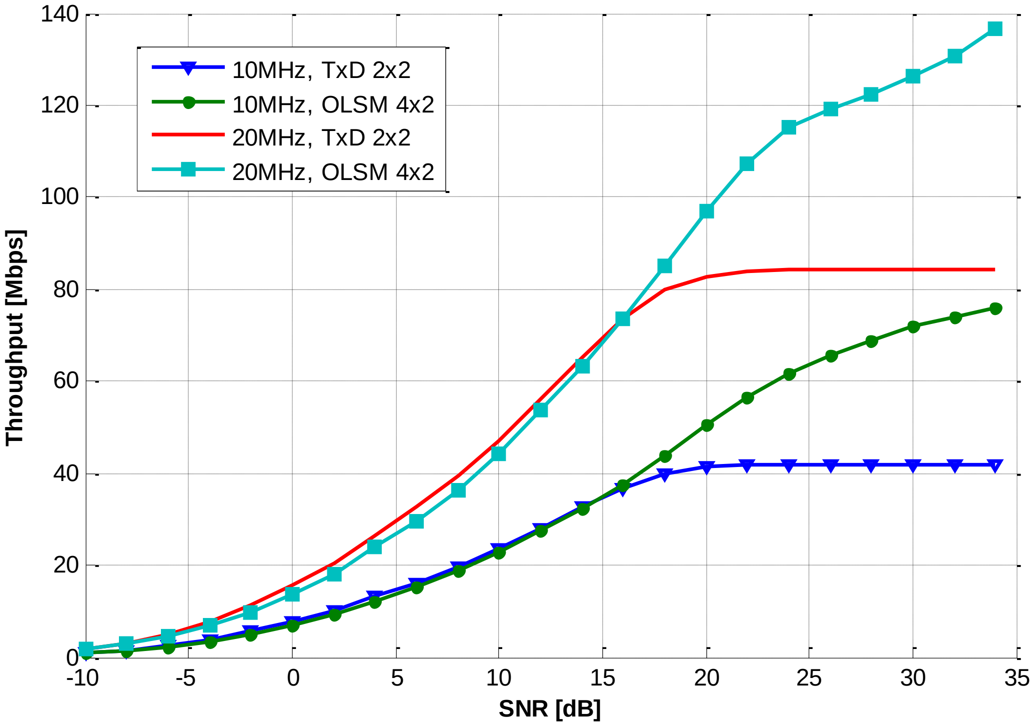

Fig. 13 LTE-Advanced Simulation Results

Secondly, for better illustration of the LTE-Advanced capabilities, a few more cases are defined (summarised in Table 9) and simulated using the system level simulation. In these cases, the highest CQI value is used (i.e. 15), the base station has eight transmission antennas, and the MIMO operation is in the Closed Loop Spatial Multiplexing (CLSM) mode. Simulation results are presented in Fig. 14.

Table 9 Simulation parameters used for Fig. 14

Parameter	Value
CQI	15
Modulation	64QAM
Bandwidth	20 MHz
MIMO	8x2 8x4 8x8

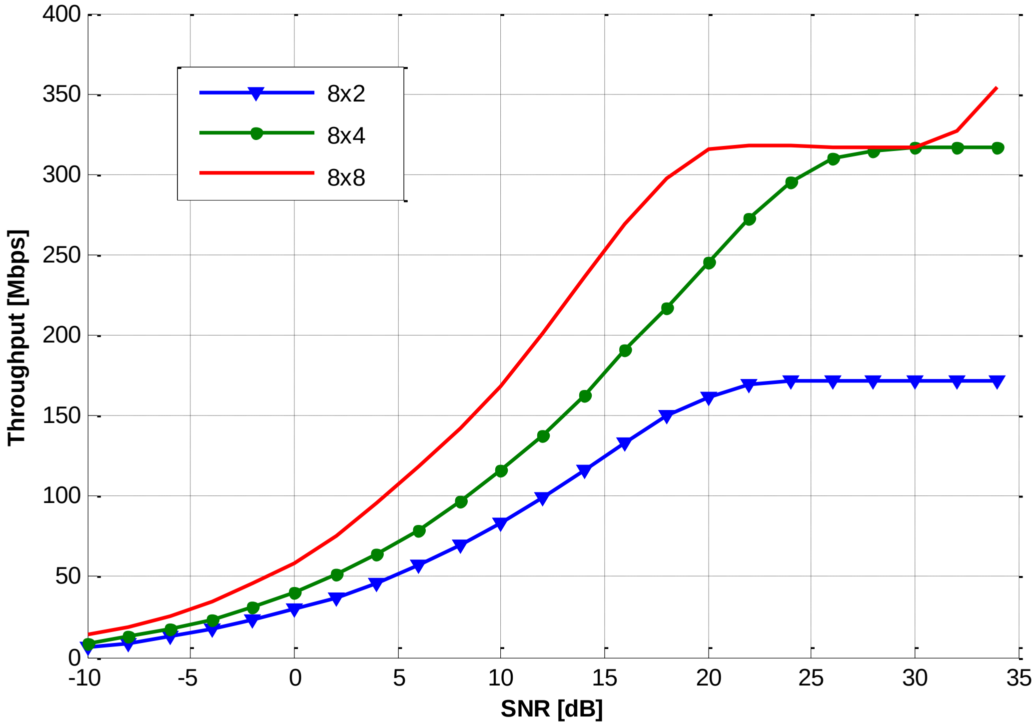

Fig. 14 LTE-Advanced simulation results

8.2 Discussions on results

The throughput can be achieved in LTE-Advanced, as illustrated in Fig. 14, is significant. The improvement in throughput from LTE to LTE-Advanced is quite visible from Fig. 12 and Fig. 13 and LTE-Advanced can be considered is a bold step towards meeting the fast-growing users' demands. It is seen that the advantages of LTE-Advanced over LTE are more substantial for higher SNR and any features that enhance the link quality can help to get more out of LTE-Advanced technology. The features discussed in this article add more enhancements in different aspects such as peak, average and cell edge data throughput and spectral efficiency.

9 Challenges and road map

The actual data rate experienced by users are becoming at the centre of attention rather than the peak data rates. Despite all the improvements in LTE-Advanced system, cell-edge user data rate is far less than the peak data rate and the difference between cell-edge and peak data rates is still too high. The actual data throughputs are currently limited by inter-cell interference and dramatically depend on the link quality. Although frequency reuse-1 systems like LTE and LTE-Advanced are highly efficient in terms of overall efficiency, they suffer from high inter-cell interference at the cell boundaries. Hence, more developments on the interference management features like eICIC and CoMP transmission and reception are necessary. Furthermore, more enhancements in the small cell deployments are needed as they can improve the radio link quality of the users.

The first commercial LTE-Advanced network launched in October 2012 although no LTE-Advanced UE was available at the time. After releasing the first LTE-Advanced chipset in June 2013, several mobile network operators such as SK Telecom and LG Uplus have started to offer LTE-Advanced services to their customers. However, according to the current trends, LTE-Advanced systems are less likely to appear as the mainstream in the markets before 2016.

While 3GPP focuses on the release 12 finalisation, the release 13 study items are getting together and as of now a few items such as Radio Access Network (RAN) sharing enhancements have been set. On the other hand, studies on the beyond-LTE-Advanced systems for the future wireless mobile communications networks - known as 5G have already started. Considering the previous trends and the timeframe between the generations, 5G is predicted to be in the picture by 2020 and LTE-advanced technology would have to compete with it as well.

ITU-R estimations show that at least 1280 MHz of spectrum bandwidth are required for the future development of IMT-2000 and IMT-Advanced by the year 2020 [256]. The required bandwidth can be provided by allocating new spectrums in higher frequency bands to the cellular networks. This may bring new challenges due to the special characteristic of the shorter wavelength signals. Another solution for dealing with the spectrum scarcity issues is to use Cognitive Radio (CR) technology in the networks in order to enable terminals to opportunistically access the spectrums which are being underutilised. CR technology offers flexible and efficient usage of the existing spectrum bandwidth and CR deployment seems inevitable for further evolution of LTE-Advanced networks. It will also play a more important role in 5G systems.

10 Conclusion

Five key features in LTE-Advanced systems are discussed in this article. Each of them brings some advantages to the wireless mobile networks for both operators and users. CA can provide higher peak data rate and cell edge user experience improvements. MIMO enhancement techniques do the same as well as average data rate enhancement, depending on the MIMO configurations and methods. CoMP transmission and reception can improve coverage in noise limited scenarios. HetNet enhances average and cell edge data rates. Regarding the RNs, their achievements depend on the situation they are deployed in. For instance, they can provide coverage for some locations that other kinds of base station cannot do, and therefore come up with a huge gain. These features are likely to be enhanced further and considered in future 3GPP releases and future wireless mobile technologies.

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