



The evolution to 4G 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.

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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 Radiocommunication 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 TeliaSonera 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,

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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 3.9G 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 Release 9. In particular, femtocells and dual-layer beamforming, 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]. In October 2009, six technologies were submitted seeking for approval as international 4G communications standard. 3GPP's candidate is LTE-Advanced, the backward-compatible enhancement of LTE Release 8 that will be fully specified in 3GPP Release 10 [2]. 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.
- High-quality mobile devices.
- User equipment suitable for worldwide use.
- User-friendly applications, services, and equipment.
- Worldwide roaming capability.
- Enhanced peak rates to support advanced services and applications (100 Mbit/s for high mobility and 1 Gbit/s for low mobility were established as targets for research).

All the above requirements, except for the last one, are high level, i.e. they do not quantify the performance requirements; besides, they have largely been pursued by the industry already. When it comes to a detailed description of the IMT-Advanced requirements, explicit targets have been set for average and cell-edge performance in addition to the usual peak data rates. This was a necessary issue to be addressed since they define the experience for the typical user.

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.

The remainder of this paper is organized as follows. In Section 2, we provide an overview of the network architecture that will support the LTE and LTE-Advanced air interfaces. Then, we cover the concept and challenges of the four research categories that, according to 3GPP, constitute the pillars of the LTE-Advanced system. In Section 3, we present LTE-Advanced spectrum issues: bandwidth aggregation, a technology that aims at increasing the system bandwidth by aggregating different carriers, and spectrum sharing techniques for heterogeneous networks. The new enhanced MIMO techniques in both the downlink and the uplink for LTE-Advanced are introduced in Section 4. In Section 5, we describe enhanced Node B cooperation techniques in the framework of LTE-Advanced, grouped under the name of coordinated multipoint transmission and reception (CoMP). We present relaying strategies in Section 6. Finally, we conclude the paper with Section 7.

2. Network architecture

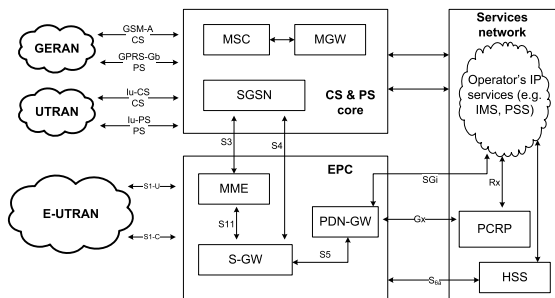
3GPP specified in its Release 8 the elements and requirements of the EPS architecture that will serve as a basis for the next-generation networks [7]. The specifications contain two major work items, namely LTE and SAE, that led to the specification of the Evolved Packet Core (EPC), Evolved Universal Terrestrial Radio Access Network (E-UTRAN), and Evolved Universal Terrestrial Radio Access (E-UTRA), each of which corresponds to the core network, radio access network, and air interface of the whole system, respectively. The EPS provides IP connectivity between a User Equipment (UE) and an external packet data network using E-UTRAN. 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, i.e. the EPC, is not undergoing major changes from the already standardized SAE architecture. Therefore, in this section we give an overview of the E-UTRAN architecture and functionalities defined for the LTE-Advanced systems and the main EPC node functionalities, shared by Releases 8, 9, and 10.

Table 1

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

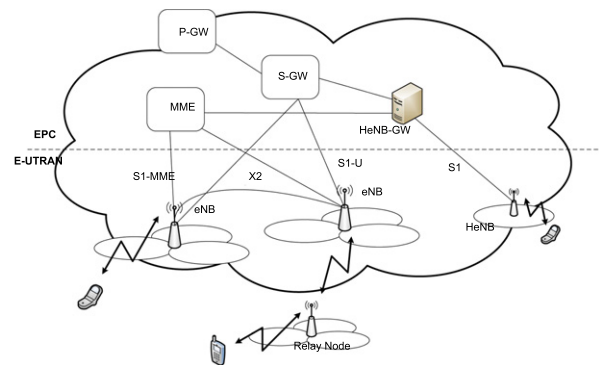
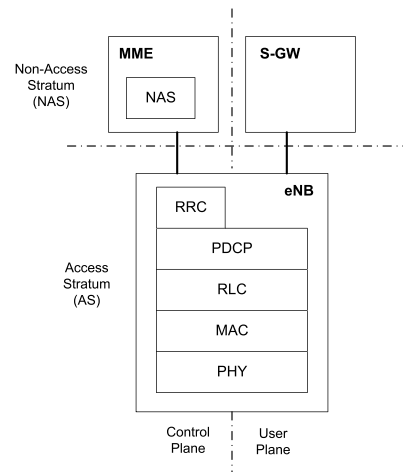
Item	Transmission path	Antenna configuration	LTE (Rel. 8)	LTE-Advanced	IMT-Advanced
Peak data rate	DL	8×8	300 Mbps	1 Gbps	1 Gbps
	UL	4×4	75 Mbps	500 Mbps	–
Peak spectrum efficiency (bps/Hz)	DL	8×8	15	30	15
	UL	4×4	3.75	15	6.75
Capacity (bps/Hz/cell)	DL	2×2	1.69	2.4	–
		4×2	1.87	2.6	2.2
		4×4	2.67	3.7	–
	UL	1×2	0.74	1.2	–
		2×4	–	2.0	1.4
		2×2	0.05	0.07	–
Cell-edge user throughput (bps/Hz/cell/user)	DL	4×2	0.06	0.09	0.06
		4×4	0.08	0.12	–
	UL	1×2	0.024	0.04	–
		2×4	–	0.07	0.03

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

2.1. 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.**Fig. 3.** Protocol stack.

The main functionalities carried out in each layer are summarized in the following [8–11].

- **NAS (Non-Access Stratum)**
 - Connection/session management between UE and the core network.
 - Authentication.
 - Registration.

¹ It is still under discussion which is the most appropriate solution.

- 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.

2.2. Evolved Packet Core overview

The EPC is a flat all-IP-based core network that can be accessed through 3GPP radio access (UMTS, HSPA, HSPA+, LTE) and non-3GPP radio access (e.g. WiMAX, WLAN), allowing handover procedures within and between both access types. The access flexibility to the EPC is attractive for operators since it enables them to have a single core through which different services are supported. The main components of the EPC and their functionalities are as follows.

- **Mobility Management Entity (MME)**
This is a key control plane element. Among other functions, it is in charge of managing security functions (authentication, authorization, NAS signalling), handling idle state mobility, roaming, and handovers. Also selecting the Serving Gateway (S-GW) and Packet Data Network Gateway (PDN-GW) nodes is part of its tasks. The S1-MME interface connects the EPC with the eNBs.
- **Serving Gateway (S-GW)**

The EPC terminates at this node, and it is connected to the E-UTRAN via the S1-U interface. Each UE is associated to a unique S-GW, which will be hosting several functions. It is the mobility anchor point for both local inter-eNB handover and inter-3GPP mobility, and it performs inter-operator charging as well as packet routing and forwarding.

- **Packet Data Network Gateway (PDN-GW)**
This node provides the UE with access to a Packet Data Network (PDN) by assigning an IP address from the PDN to the UE, among other functions. Additionally, the evolved Packet Data Gateway (ePDG) provides security connection between UEs connected from an untrusted non-3GPP access network with the EPC by using IPSec tunnels.

From a user-plane perspective there are only the eNBs and the gateways, which is why the system is considered “flat”. This results in a reduced complexity compared to previous architectures.

3. Spectrum and bandwidth management

In order to meet the requirements of IMT-Advanced as well as those of 3GPP operators, LTE-Advanced considers the use of bandwidths of up to 100 MHz in the following spectrum bands (in addition to those already allocated for LTE) [12].

- 450–470 MHz band (identified in WRC-07 to be used globally for IMT systems).
- 698–862 MHz band (identified in WRC-07 to be used in Region 2² and nine countries of Region 3).
- 790–862 MHz band (identified in WRC-07 to be used in Regions 1 and 3).
- 2.3–2.4 GHz band (identified in WRC-07 to be used globally for IMT systems).
- 3.4–4.2 GHz band (3.4–3.6 GHz identified in WRC-07 to be used in a large number of countries).
- 4.4–4.99 GHz band.

3.1. Carrier aggregation

In order for LTE-Advanced to fully utilize the wider bandwidths of up to 100 MHz, while keeping backward compatibility with LTE, a carrier aggregation scheme has been proposed. Carrier aggregation consists of grouping several LTE “component carriers” (CCs) (e.g. of up to 20 MHz), so that the LTE-Advanced devices are able to use a greater amount of bandwidth (e.g. up to 100 MHz), while at the same time allowing LTE devices to continue viewing the spectrum as separate component carriers. In Fig. 4 we illustrate the concept of Carrier aggregation in contiguous bandwidth.

It may not be always possible for an operator to obtain 100 MHz of contiguous spectrum. For this reason, the use

² Region 1: Europe, Africa, the Middle East west of the Persian Gulf including Iraq, the former Soviet Union, and Mongolia. Region 2: Americas, Greenland, and some of the eastern Pacific Islands. Region 3: most of non-former-Soviet-Union Asia, east of and including Iran, and most of Oceania.

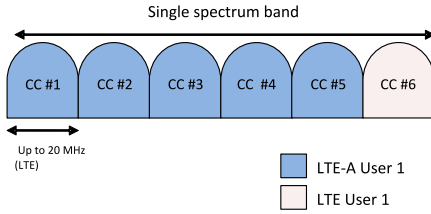


Fig. 4. Carrier aggregation in contiguous bandwidth.

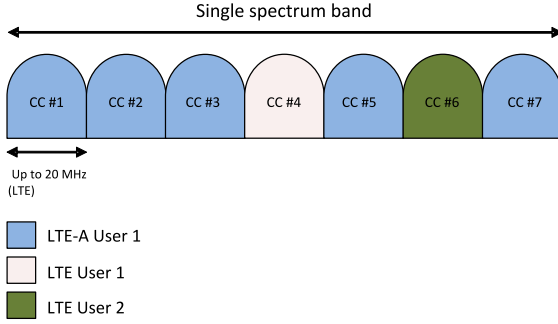


Fig. 5. Carrier aggregation in noncontiguous bandwidth, single band.

of noncontiguous carrier aggregation is also proposed. In this case, the component carriers that are going to be aggregated can be noncontiguous in the same spectrum band or noncontiguous in different spectrum bands. In either case, several challenges need to be addressed before carrier aggregation can be successfully introduced, as discussed later.

Fig. 5 illustrates the case of noncontiguous carrier aggregation in the same band. The figure shows two LTE devices using bandwidths of up to 20 MHz, coexisting with an LTE-Advanced device that is using noncontiguous aggregated bandwidth of up to 100 MHz.

Fig. 6 illustrates the case of noncontiguous carrier aggregation in different bands, which is a scenario that could result from the simultaneous use of the spectrum bands mentioned at the beginning of this section. The figure shows two LTE devices using bandwidths of up to 20 MHz, each one in a different spectrum band, coexisting with an LTE-Advanced device that is using noncontiguous aggregated bandwidth from different spectrum bands. The bands that are used can be dedicated bands or shared bands. In all the previous cases of carrier aggregation, the number of UL and DL component carriers, as well as their bandwidths, might be different. Even within a single eNB, different LTE-Advanced UEs will be configured with different numbers of CCs, according to their capabilities, channel conditions, data rate requirements, and QoS requirements.

Carrier aggregation not only helps to achieve higher peak data rates, but could also help to achieve better coverage for medium data rates. For medium data rates, it allows the use of lower orders of modulation and lower code rates, which would reduce the required link budget, transmission power, and interference.

As an initial approach for carrier aggregation, 3GPP specifies in [13,14] four deployment scenarios, which are

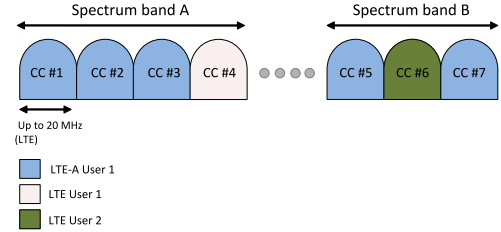


Fig. 6. Carrier aggregation in non-contiguous bandwidth, multiple bands.

shown in Table 2. These deployment scenarios cover both contiguous and non-contiguous carrier aggregation for single and multiple spectrum bands using time division duplexing (TDD) and frequency division duplexing (FDD) schemes.

3.1.1. Control channels

In order to utilize the available spectrum, devices must be able to access the control channels in the downlink and uplink frames (in addition to other reference signals). Hence, to keep backward compatibility with LTE devices, each component carrier must maintain its own control channels. On the other hand, if a service provider wants to support only LTE-Advanced devices, the control channels could be reduced from one set per component carrier (of up to 20 MHz) to one set per group of aggregated component carriers (of up to 100 MHz). The option of enabling/disabling the control channels and reference signals could allow a service provider to do a progressive migration from LTE to LTE-Advanced, by controlling which spectrum bands are accessible to LTE and which to LTE-Advanced devices. For example, in [15], a layered control signaling structure is proposed where the signaling structure depends on the assigned component carriers.

In terms of scheduling, the resource assignment information (for DL and UL) can refer to resources within the same CC in which it was sent, or to resources in another CC. The first case is suitable for scenarios where the UE is configured to receive resource assignment information at each CC, and it can reliably receive it in each CC. On the other hand, the second case is suitable for scenarios where the UE is not configured to receive resource assignment information at each CC, e.g. when the bandwidth of the extra CCs is small or is only available to LTE-Advanced devices. The second case is also suitable for cases when it is not reliable to send resource assignment information in some CCs.

3.1.2. Multiple access scheme

For the downlink, the scheme chosen for multiple access is to perform parallel transmission of transport blocks (TBs) at each CC, based on OFDMA, as in LTE. In each CC, a single TB (or two TBs in case of spatial multiplexing) is transmitted; also, each CC manages its own HARQ process. Furthermore, most of the upper-layer protocols of LTE are reused, since the multi-carrier nature of the physical layer is exposed as parallel paths up to the MAC layer. In this way, most of the development and investment done for LTE devices can be extended to LTE-Advanced.

Table 2

Primary LTE-Advanced deployment scenarios.

Scenario no.	Description	Transmission BWs of LTE-A carriers	No. of LTE-A CCs	Bands for LTE-A carriers	Duplex modes
A	Single-band contiguous spec. alloc. @ 3.5 GHz band for FDD	UL: 40 MHz DL: 80 MHz	UL: Contiguous 2×20 MHz CCs DL: Contiguous 4×20 MHz CCs	3.5 GHz band	FDD
B	Single-band contiguous spec. alloc. @ Band 40 for TDD	100 MHz	Contiguous 5×20 MHz CCs	Band 40 (3.5 GHz band)	TDD
C	Multi-band non-contiguous spec. alloc. @ Bands 1, 3 and 7 for FDD	UL: 40 MHz DL: 40 MHz	UL/DL: Non-contiguous 10 MHz CC@Band 1 + 10 MHz CC@Band 3 + 20 MHz CC@Band 7	Band 3 (1.8 GHz), Band 1 (2.1 GHz), Band 7 (2.6 GHz)	FDD
D	Multi-band non-contiguous spec. alloc. @ Bands 39, 34, and 40 for TDD	90 MHz	Non-contiguous $2 \times 20 + 10 + 2 \times 20$ MHz CCs	Band 39 (1.8 GHz), Band 34 (2.1 GHz), Band 40 (2.3 GHz)	TDD

In the uplink, LTE uses DFT-precoded OFDM. For LTE-Advanced there is one DFT per component carrier, supporting contiguous and frequency-non-contiguous resource allocation on each CC. As for the downlink, the objective is to reuse and extend most of what has already been developed for LTE [13].

3.1.3. Transceiver architecture

To utilize these wider spectrum bands, LTE-Advanced devices must use wideband transceivers. As described in [16], the two basic approaches for wideband communication transceivers are as follows.

- Multiple single-band transceivers:** For n spectrum bands, n transceivers are used, one for each spectrum band. In this case, the transceivers work simultaneously, allowing the use of all the spectrum bands simultaneously. As described at the beginning of Section 3, LTE-Advanced is considering the use of six spectrum bands, which would require at least six transceivers through this scheme. This concept is feasible in the sense that only requires the addition of parallel paths to process each spectrum band, as in current multi-band devices. However, this translates into an increase of the size and cost of the mobile device. There exists a point at which the transceivers join in the processing of the signals. In Fig. 7, we show an example of a high-level block diagram for a receiver [16], where the digital signal processing is the point of union of the parallel transceivers. The receiver has a single antenna, and several RF branches. Each branch has an RF band pass filter for a specific spectrum band, an RF frontend, and an analog-to-digital converter. In general, as the point of union moves toward the antenna the number of elements reduces, which translates into a reduction of the size and the cost of the device.
- Wideband transceiver:** In this case, a single transceiver processes all the spectrum bands of interest, and the filtering of each individual spectrum band is usually done in the digital domain. As described at the beginning of Section 3, LTE-Advanced would process the spectrum band from 450 MHz to 4.99 GHz through this scheme. In

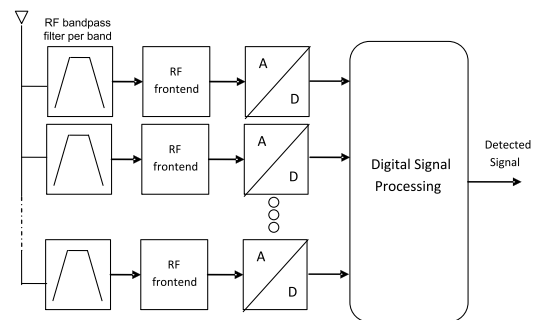
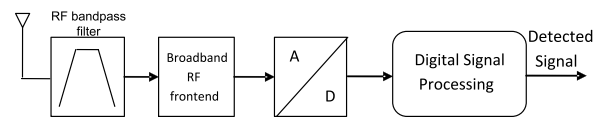
**Fig. 7.** Multiple single-band receivers [16].**Fig. 8.** Wideband receiver [16].

Fig. 8, we show an example of a wideband receiver high-level block diagram [16]. It is composed of an RF bandpass filter, RF frontend, analog-to-digital converter, and digital signal processing blocks. Due to the wideband nature of this type of transceivers, most of the RF components used need to be wideband. Since the RF signal is digitally filtered, very high-speed, high-resolution, and high-dynamic range linear analog-to-digital converters (ADCs) are needed.

Based on these two general classifications, 3GPP further specifies subclassifications of transceiver structures for LTE-Advanced, which can be found in [13].

3.2. Spectrum sharing

Carrier/spectrum aggregation allows a service provider to offer up to 100 MHz of bandwidth to its LTE-Advanced clients by aggregating dedicated spectra in order to increase performance. However, in certain scenarios, sharing of the spectrum becomes another attractive option to achieve this objective.

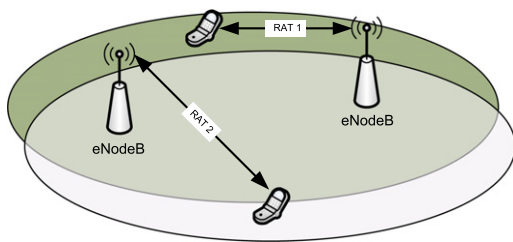


Fig. 9. Multi-RAT scenario.

Spectrum sharing could be done among radio access technologies (RATs), even though it is not currently specified by 3GPP. A service provider may offer more than one RAT to its users (e.g. LTE, HSPA, WiMAX) in a specific area. The reason for this is that the different clients of a service provider might use UEs that support different RATs. Hence, to provide coverage to all users, different RATs are deployed. It can also occur that specific UE supports several RATs. This gives the operator the flexibility of deciding to which RAT(s) the UE should attach to maximize spectrum utilization while providing the required QoS. In this case, the requirements in terms of spectrum resources will vary spatially and temporally for each RAT. This variation/diversity can be exploited in order to flexibly assign resources to the RATs that require them at each time and location.

In Fig. 9, each base station/eNB (they could be co-located), will manage the spectrum that is currently assigned to its RAT to serve its users, using a local radio resource management (RRM). At an upper layer, a joint RRM (JRRM) will be in charge of managing the sharing of spectrum between both RATs. The level of granularity at which the local RRM (which contains the scheduler) will work will usually be smaller than the JRRM (e.g. LTE and LTE-Advanced can define scheduling decisions each millisecond, so the JRRM could work in seconds or minutes granularity). For example, in [17], a fuzzy-neural methodology framework for JRRM treatment is proposed, considering UMTS, GERAN, and WLAN, where one of the RATs must be selected. Even though this type of sharing could occur not only in LTE-Advanced, LTE-Advanced adds a new level of complexity/degree of freedom by allowing the use of carrier aggregation. Hence, the LTE-Advanced network could borrow spectrum (contiguous or non-contiguous) from other RATs and use it for carrier aggregation. This will allow more flexibility in terms of the amount of spectrum that is assigned among RATs, potentially increasing the performance in each one. The JRRM and local RRM will work in a hierarchical way, where the spectrum that is managed by the local RRM will depend on the assignments done by the JRRM, which will depend on feedback information coming from the local RRM and external policies, as Fig. 10 shows.

The advantage of having a hierarchical RRM is that it allows the lower-level entities in the hierarchy to perform and communicate the RRM decisions faster and with less overhead than in a scheme that only depends on a central RRM entity. However, in cases of low network load or low number of local RRM entities, the JRRM use can be avoided if the local RRM entities are available to manage the

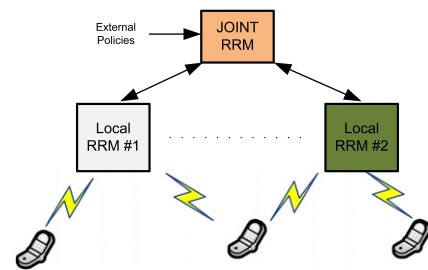


Fig. 10. Joint RRM and local RRM.

load effectively by themselves (probably exchanging information/measurements directly between them). This is the case of LTE and LTE-Advanced, where the X2 interface interconnects the different eNBs for coordination purposes, without a specific central JRRM. It has been suggested that the use of a central entity (JRRM) is only required and used when the local RRM entities are not able to further fulfill the network and user requirements [18]. [18] also analyzes the advantages and disadvantages of centralized and distributed admission control, scheduling and interference management. In general, distributed approaches are favored since they enable low delay, lower signaling, and lower cost, even though they risk losing some gains compared to their centralized counterparts. It has also been proposed to assign a greater part of the RRM decisions to the UE [19]; however, this approach requires more computation and power consumption from the UE (in addition to information from the RAN and core network).

In addition to spectrum sharing among RATs, spectrum sharing among service providers is also possible. This concept is supported by 3GPP [20,21], and it is called “network sharing”, since it also refers to the sharing of elements at the RAN and core networks. An LTE/LTE-Advanced UE must be able to decode the list of operators sharing a cell, which is broadcasted by the eNB. Once the UE selects a specific operator, the shared eNB forwards all data to the core network of the selected operator. Beyond this initial operator selection, the presence of network and spectrum sharing is transparent from a UE perspective.

When the available spectrum is limited (either in the low-frequency or high-frequency bands—with their intrinsic advantages and disadvantages), service providers may need to share a spectrum band. By enforcing this, the regulator increases the pool of the spectrum that can be used or aggregated by each service provider, without assigning spectrum exclusively to one of the service providers. In this way, no service provider will have the advantage of being the exclusive owner of more spectrum than other service providers. This is a feasible scenario in cases of scarce spectrum availability.

Spectrum and network sharing can also be catalysts for the introduction of LTE/LTE-Advanced. Since the investment required for an LTE/LTE-Advanced deployment is high, network sharing allows operators to reduce the initial investment that each one must do. As the number of LTE/LTE-Advanced UEs increases, each operator can later decide whether to keep the shared structure or deploy its own LTE/LTE-Advanced network. For example, in low UE density areas, the operators may favor keeping the shared

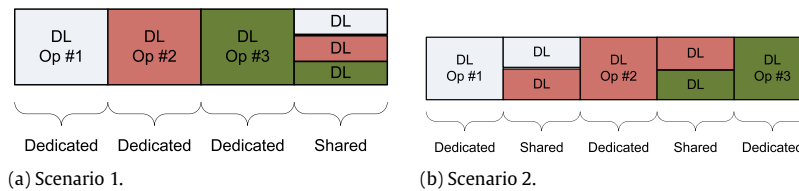


Fig. 11. Spectrum sharing scenarios.

scheme, while in high UE density areas they may favor a non-shared scheme.

In Fig. 11(a), three operators have their own dedicated spectrum, and at the same time they share a spectrum band. In this case, LTE-Advanced could take advantage by using non-contiguous carrier aggregation (either on the same or different spectrum bands). In Fig. 11(b), the spectrum is shared only between operators that are adjacent to the shared spectrum; in this way non-contiguous carrier aggregation is avoided which results in reduced complexity but also reduced flexibility. Effective ways to achieve spectrum sharing between several operators within the same spectrum band are required to make this type of scenario feasible, taking into account the performance and requirements of LTE-Advanced.

In either case, or any other scenario, an entity (or entities) will be in charge of coordinating and managing the spectrum sharing between the different operators, as shown in Fig. 12. The speed at which the spectrum is dynamically shared between operators will be slower than for JRRM and Local RRM.

The flexibility provided by the spectrum sharing between service providers gives an additional degree of freedom to the schedulers, allowing the realization of joint scheduling and RRM between service providers. These scenarios of spectrum sharing require further investigation in terms of adaptations at the core network and how they can be implemented, taking into account coordination between service providers. In addition, optimizing the allocation of users in the shared bands and analyzing the achievable gains through spectrum sharing must be further investigated.

Some sharing scenarios, similar to the ones mentioned, have been initially studied. In [20], general scenarios for multi-operator network sharing are identified by 3GPP. In [22], some of the possible dynamic sharing scenarios for FDD and TDD spectrum sharing are presented, while [23] proposes cooperation mechanisms for intra-system and inter-system interworking, taking into account radio resource management (RRM) with spectrum aggregation in the context of IMT-Advanced.

Another possible scenario for spectrum sharing is when the eNB (a primary network according to the terminology of cognitive radio networks) is not utilizing its entire available spectrum band and decides to lease part of this spectrum to a secondary network operator (e.g. a cognitive radio network), with the objective of maximizing its profit. This scenario can be further extended to include coordination in a cooperative and non-cooperative way between several primary networks and several secondary networks. The non-cooperative case has already been examined in the research community, assuming that the

primary network provides no support for the cognitive network. However, for mobile wireless networks it may be valid to assume some type of support for the cognitive network.

Even though cognitive radio networks (CRNs) [24] have become an area of extensive research in recent years, there is still a need for clear deployment scenarios, requirements, and constraints, where the benefits of using CRNs clearly outweighs all the complexity related to deploying, managing, and integrating the cognitive radio network with the primary network environment (at both the radio access network and the core network). IEEE 802.22 aims to use cognitive radio networks, but focused on the TV frequency spectrum. Therefore, there is still a lack of standardization for non-TV spectrum frequencies, which must be addressed in order to increase the commercial implementations of cognitive radio networks.

3.3. Research challenges

The use of wider bandwidths, multiple spectrum bands, and spectrum sharing introduces new challenges in terms of transceiver, signal processing, resource management, and error control mechanism design, among others.

3.3.1. Transceiver design

The design of wideband transceivers will be affected by several factors [16], such as the following.

- *Frequency-dependent path loss:* As higher frequencies are used, the path loss increases nonlinearly.
- *Doppler frequency and spectrum:* At higher frequencies, the Doppler effects affect the signals more severely, which would require faster adaptation algorithms, increasing the overhead.
- *Effective noise power:* As the bandwidth increases, the effective noise increases as well.
- *Receiver input signal:* Using a wider bandwidth translates into receiving more undesired signals from other services (e.g. broadcast and radar signals). So, issues such as image rejection, reciprocal mixing have to be considered.
- *Nonlinearities in analogue receiver components:* Distortion and intermodulation create additional signals under overload conditions, which can affect the demodulation process.
- *Reciprocal mixing:* When undesired signals mix with the oscillator noise, additional noise is introduced into the receiver, resulting in an additional noise figure.
- *Receiver performance:* The performance of the receiver will be limited by all the previous listed elements.

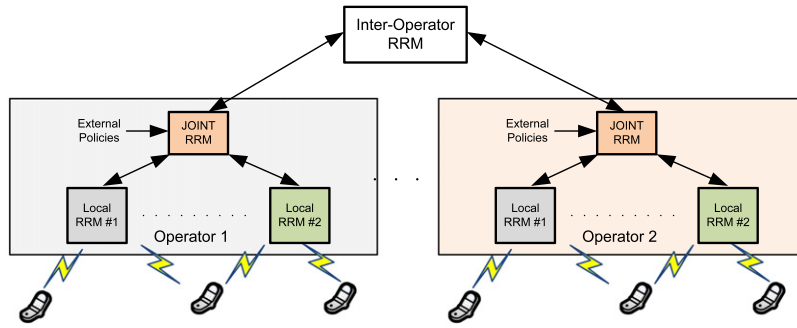


Fig. 12. Inter-operator RRM.

- *Maximum input signal*: The receiver has to have a sufficient dynamic range to avoid overload conditions.
- *Sampling frequency*: Sampling the entire spectrum from the lowest to highest frequency would represent an extremely high sampling frequency.
- *ADC dynamic range and output data rate*: With the models described in [16], a resolution of 21–24 bits is needed with dynamic range of 120–130 dB. Combining this requirement with the previous one translates into processing rates far beyond what is currently feasible. This also translates into high power consumption which could not be used in UE.

These elements, among others, will determine the design requirements for the RF components, ADCs, and the signal processing to be done in LTE-Advanced devices. According to [16], the existing technologies cannot address all the limitations and requirements previously listed for the design of a wideband transceiver, and this suggests that the only feasible technical solution is the one shown in Fig. 7. Nevertheless, due to the attractiveness in terms of potential complexity, number of elements, and power consumption reduction of wideband receivers, some approaches have been explored for their design.

For example, in [25], the use of bandpass sampling [26] is proposed for receiving signals from multiple bands without the need of a full transceiver for each band. The advantage of this technique is that the sampling frequency is proportional to the signal bandwidth and not to the RF carrier. Their focus is to calculate a single parameter, the sampling frequency, in order to process all bands. However, this calculation is subject to constraints that could increase the sampling frequency considerably. Also, it requires the ADC to be able to accommodate the RF carrier, even if the sampling frequency is lower. To overcome these constraints, [27] proposes the use of a common intermediate frequency stage with a common oscillator and common bandpass filter, reducing the number of required elements after LNA to half by sharing components, and allowing adjustable receiver bandwidth. However, in both of the previous approaches, only the aggregation of two spectrum bands has been studied.

A more comprehensive study in the design of multiple single-band transceivers in which the “union point” is as close as possible to the antenna is still required. In addition, new approaches for designing wideband transceivers (for more than two spectrum bands) that could be implemented with current technologies, or at least lower the

requirements for the transceiver components, must be studied. In this way, the evolution needed in current technologies in order to satisfy the requirements could be lowered. The design of elements such as wideband antenna, LNA, and RF components must also be investigated, taking into account the requirements of LTE-Advanced.

As we have described, the level of complexity, power consumption, and size required to achieve the highest carrier aggregation modes is high. Therefore, enabling high-end carrier aggregation modes may be unfeasible for mobile phones. However, LTE-Advanced is not only targeting mobile phones, but also laptops/netbooks and other types of customer-premises equipment (CPE). These devices do not have the same restrictions as mobile phones, which makes them more suitable for high-end carrier aggregation modes, as described in [14].

3.3.2. Increased FFT size

LTE utilizes up to 20 MHz bandwidth, for which it requires a 2048-point FFT [28]. In the case of LTE-Advanced, a bandwidth of 100 MHz requires an FFT of increased size. If we follow the trend in LTE of FFT size versus bandwidth, for 100 MHz, an FFT size of 10 240 would be needed. This will directly affect the memory size, and the base-band processing power requirement.

3.3.3. Resource management

The option of using more than one spectrum band (either dedicated or shared) is immediately followed by the decision of how many bands and which bands should be used in order to satisfy the different constraints and requirements (delay, jitter, rate, interference, power consumption, mobility, reliability, subscription plan, coverage—path loss, fading, Doppler effect, etc.). As explored in [29], the lower-frequency bands are better suited for longer-range, higher-mobility and lower-capacity systems, while higher-frequency bands are better suited for shorter-range, lower-mobility, and higher-capacity systems. This decision should also take into account the capabilities of the UE: multiple band support, minimum and maximum distance between component carriers, and minimum and maximum number of frequency bands that can aggregate. For example, [30] takes into account the number of CCs in which each UE can be scheduled in order to improve the performance of a proportional fair scheduling algorithm.

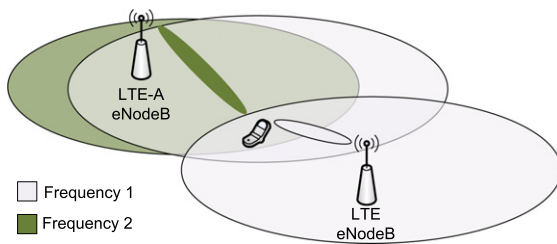


Fig. 13. LTE and LTE-Advanced carrier aggregation scenario.

Service providers will choose different spectrum and network sharing schemes according to their objectives and agreements. Hence, efficient RRM strategies for each scheme are required, flexible enough to support evolution from each scheme to another. The efficiency and flexibility of the RRM will be a key point in the success of spectrum sharing for LTE and LTE-Advanced.

At the radio access network level, the existing processes must be re-examined. The processes of admission control, congestion control, cell selection and re-selection, handover, and scheduling (of users and data across bands) have to be re-examined and adapted to take into account the multi-band nature of LTE-Advanced. For example, consider a scenario where a group of the component carriers in use by the UE is no longer available. A new set of component carriers must be assigned to the UE in order to continue providing the services that the UE required. This situation could trigger any of the processes mentioned before.

Another possible scenario is the one depicted in Fig. 13. The LTE-Advanced UE is within the transmission range of an LTE-Advanced eNB and an LTE eNB. The UE has the flexibility of using the spectrum band of the LTE eNB and the extra bands provided through the LTE-Advanced eNB. In this way, the “base band” (utilized for LTE UEs within the LTE-Advanced eNB coverage) can be prioritized for LTE UEs. This scenario of coordinated transmission from multiple eNBs is possible and enhanced through the MIMO and CoMP schemes available in LTE-Advanced, which will be discussed in the following sections. In this scenario, the radio resource management (RRM) processes and algorithms can be enhanced to achieve the highest resource utilization possible.

Some solutions have already been proposed for the adaptation of the processes mentioned before. In [31], the idea of a multi-band scheduler is explored in a scenario where spectrum sharing is utilized and a second scenario where single-band relays are utilized to extend coverage. The multi-band scheduler acts as a new layer in the protocol stack, controlling independent schedulers for each band. It also supports user context transfer from one band to another when the first band is no longer available. Regarding the implementation of a multi-band scheduler, [32] explores the user allocation over two frequency bands based on an HSDPA network and a suboptimal solution. However, user distribution, mobility, QoS requirements, multi-radio UE, and multi-operator scenarios are left as future work. In terms of performance, [33] analyzed the performance of LTE-Advanced spectrum aggregation over two frequency bands by considering two

different types of scheduler, and three different traffic models (full buffer, finite buffer, and burst traffic). However, the scheduling only solves the resource allocation up to a capacity limit; when the demand is increased, queues will eventually start to overflow, and admission control, congestion control, and handover functionality are required.

3.3.4. Retransmission control

LTE uses a combination of ARQ (at the RLC layer) and hybrid ARQ (at the MAC layer) in order to achieve the low error probability required to achieve 100 Mbps. Both methods complement each other to avoid excessive overhead while achieving high throughput, specially taking into account the relation between the error probability and throughput in TCP.

In LTE-Advanced, data rates of 100 Mbps are expected in scenarios of high mobility and 1 Gbps in scenarios of low mobility. Also, shorter delays are expected in LTE-Advanced. In order to achieve these high data rates and small delay, the interaction of ARQ and hybrid ARQ must be revisited to examine their current maximum performance and analyze any adaptations required to achieve the expected data rates and delay targets.

Some approaches to improve the ARQ/hybrid-ARQ interaction have been proposed. In [21], a shorter transmission time interval (TTI) is proposed where the hybrid-ARQ control information is transmitted each TTI, while the rest of the control information is transmitted each two or three TTIs, in order to reduce the transmission delay. In [34], a global outer ARQ in a combination of hybrid ARQ for each component carrier is proposed to reduce the switching delay when the UE needs to switch from one component carrier to another. In addition, allowing the transfer of HARQ information related to one component carrier to another when this type of switching is required is proposed. However, deeper understanding and analysis of the performance achievable through carrier aggregation with the current ARQ/hybrid-ARQ mechanism must be achieved in order to propose new improved mechanisms.

3.3.5. Other aspects

Radio parameters, such as the number of carriers that are needed as guard bands between contiguous component carriers, must be optimized to achieve high utilization of the spectrum without degrading the performance. In [35], an initial investigation of the minimum spectrum distance (carrier guard band) between component carriers in contiguous spectrum bands was done.

Even though 3GPP's initial deployment scenarios consider the use of up to five component carriers and up to three spectrum bands, it is reasonable to expect that more scenarios will be required and investigated.

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 beamforming, 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.

4.1. General description

The enhanced MIMO concept is conceived as an adaptive multi-mode framework where the demand of higher data rates and wider coverage is accommodated by selecting the appropriate MIMO scheme according to the current system requirement. The adaptation strategy is chosen based on all the different channel measurements that are gathered at the base station through a low rate feedback mechanism. Additionally, LTE-Advanced will allow several of the above-mentioned MIMO technologies to be combined in what is known as extended or advanced precoding. Fig. 14 shows the idea behind this concept.

Fig. 15 illustrates the main three operating modes. Further, each of them targets one of the improvements pursued by LTE-Advanced.

- *Single-User MIMO (SU-MIMO)*: transmit diversity and spatial multiplexing techniques can be selected for

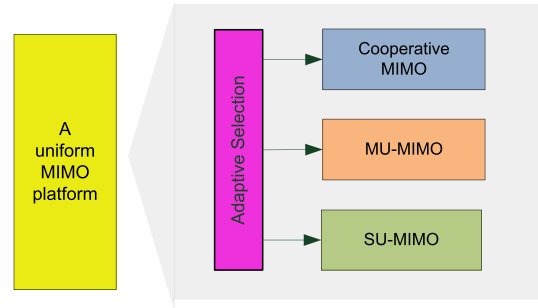


Fig. 14. MIMO adaptive switching scheme.

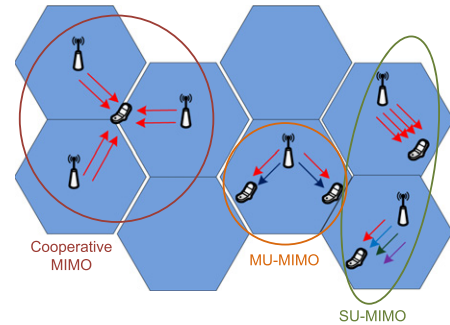


Fig. 15. LTE-Advanced main MIMO modes.

transmission in combination with beamforming. This new feature together with a higher-order MIMO (i.e. an increased number of antenna ports) make possible a substantial increase in the peak user data rates.

- *Multi-User MIMO (MU-MIMO)*: great emphasis is placed in MU-MIMO since it offers the best complexity–performance trade-off. The flexibility of SDMA is increased by allowing a different number of streams to reach each user in order to increase the cell average data rate. SU-MIMO and MU-MIMO constitute what is called single-site MIMO.
- *Cooperative MIMO*: cell-edge user throughput is boosted by enabling techniques that use coordination in transmission and reception of signals among different base stations, which also helps reducing inter-cell interference. These techniques, known as Cooperative Multi-point (CoMP) transmission and reception, are another set of key technologies, and they will be covered in Section 5.

4.2. Single-site MIMO

Single-site MIMO refers to any MIMO communication that takes place between a single eNB and one or multiple UEs, i.e., SU-MIMO and MU-MIMO. If a single user is served, the additional spatial dimensions introduced with MIMO in a wireless communication system can be used in three different possible ways: transmit and receive diversity to improve the reliability of the transmission, spatial multiplexing to boost the data rate, or beamforming to increase the coverage through more directive antenna patterns. The spatial scheme or MIMO method should be chosen on a frame-by-frame basis in such a way as to adapt

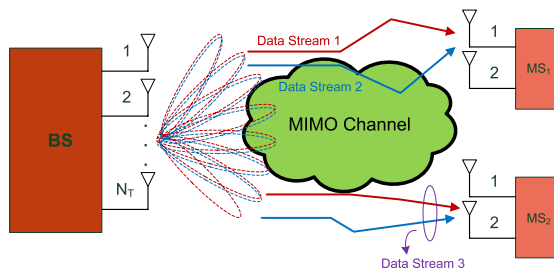


Fig. 16. Advanced precoding concept.

continuously to the spatial properties of the channel with high spectral efficiency.

The single-site MIMO design currently under investigation for LTE-Advanced considers a substantial increase in the number of transmission layers in both the uplink and the downlink to achieve higher peak rates. However, this measure entails two drawbacks. Firstly, the gains due to additional diversity with such high-order configurations become much smaller. Secondly, the spatial multiplexing of a large number of transmission layers to a single user may only be feasible if the radio conditions (i.e. SINRs) are extremely favorable, which is unlikely to be found outside very small cells, indoor scenarios or the proximities of an eNB.

A more relevant technique aimed at increasing the wide range of the data rates (i.e. coverage) is beamforming. New technologies considered for LTE-Advanced include improved support for beamforming as a tool to increase the SINR at the receiver and employ some kind of spatial multiplexing or diversity within the beam. An excessive overhead may result if, as done in LTE, codebook-based beamforming with cell-specific reference signals is employed with a large number of antennas. Therefore, extended UE-specific reference signals need to be considered for LTE-Advanced.

4.2.1. Advanced precoding

Under the concept of advanced precoding, a novel combination of single-user beamforming with spatial multiplexing and spatial diversity as well as multi-user beamforming is meant. Fig. 16 depicts an example of this technology where two beamformed users are served with multiplexing and diversity, respectively. As has been pointed out before, the sole idea of increasing the number of transmission layers or the diversity order does not produce enough performance gain to compensate the complexity increase. Besides, a more relevant target rather than further increasing the peak rates is to improve the range of the data rates and that is the reason why beamforming is the base element of these new techniques.

Single-user or multi-user beamforming can be combined with spatial multiplexing and diversity in order to simultaneously improve the range of the transmission and either obtain higher data rates (multiplexing) or a higher reliability (diversity). These diverse techniques share the requirement of multiple antenna elements but differ in the antenna element spacing necessary for the different schemes to work.

On the one hand, beamforming is able to provide high directional gain and reduce the interference from other directions provided that the MIMO channels are highly correlated. This implies that, under the beamforming mode of operation, the antenna spacing must be small. A common distance used for these purposes is a half wavelength. On the other hand, both spatial diversity (e.g. STBC) and spatial multiplexing techniques (e.g. V-BLAST) require the antenna spacing to be large enough (usually of several wavelengths) that the correlation among the MIMO channels is low and the distribution of their corresponding fades can be considered as independent. Only in that way is the former technique able to combat channel fading, and the latter achieves a linear capacity growth with the number of antennas. Possible solutions for the antenna spacing problem have been published in the last few years. Some of the proposed ideas in the literature are the following.

- *Smart antenna arrays* [36]: the base stations are equipped with more than one antenna array separated by several wavelengths while the antenna elements within the arrays are separated only by a half wavelength; mobile stations are supposed to be equipped with multiple antennas as well. This scheme simultaneously provides the high-correlation and low-correlation scenarios necessary for the different techniques. Both the spectrum efficiency and the BER performance are significantly improved. However, this solution presents the disadvantage of needing a large number of antennas at the base station.
- *Antenna grouping* [37]: beamforming weight vectors are calculated at the receiver and sent back to the transmitter. The performance will not deteriorate with highly correlated channels since those are grouped and beamforming is applied on them while spatial multiplexing is applied among the different groups, which tend to be less correlated.
- *Antenna cross-polarization* [38]: an antenna is said to be cross-polarized if it can transmit electromagnetic waves with orthogonal polarization modes. Two spatially separated antennas can be replaced by a cross-polarized single antenna element emulating two MIMO channels. It was shown that in the presence of high spatial fading correlation this scheme can yield an improved multiplexing gain. Therefore, multiple antennas should be spaced only a half wavelength apart and beamforming can be also applied. Cross-polarization is currently the solution that is being utilized in the LTE-Advanced standardization process.

LTE Release 9 already incorporates a single-user dual-layer beamforming functionality that extends the single-user beamforming of LTE to support spatial multiplexing. It is also based on UE-specific reference signals and it supports fast rank adaptation (i.e., the number of data streams that are to be sent at the same time may vary from one time slot to another) without the need for higher layer signaling. These new enhanced features and capabilities should be backward compatible with LTE Release 8 and forward compatible with LTE Release 10 (LTE-Advanced). Advanced precoding is the natural extension of this feature to MU-MIMO and is currently under discussion.

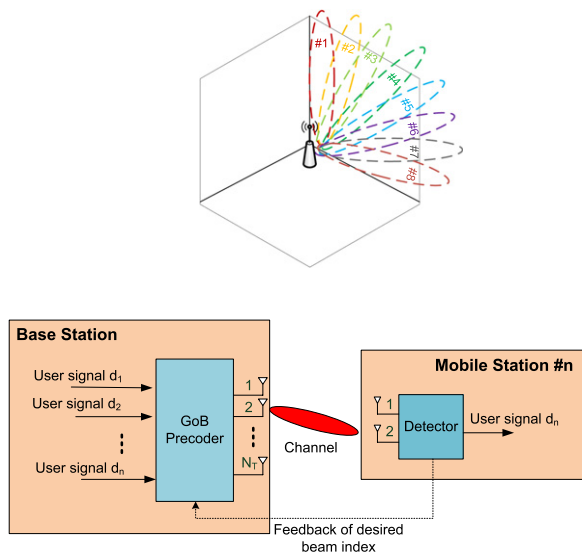


Fig. 17. Grid of beams approach: spatial beams (top) and concept illustration (bottom).

4.3. Downlink MIMO transmission

The characteristics of the downlink single-site MIMO transmission are summarized in this section. The number of antennas in both transmission and reception is increased: a 4×4 MIMO antenna configuration would become the baseline while a maximum configuration of 8×8 MIMO could be set to achieve high peak rates. Operation in both open-loop and closed-loop modes is possible in combination with diversity and spatial multiplexing, i.e. feedback information may or may not be sent back by the UE depending on the radio conditions and the UE mobility. Closed-loop transmit diversity is a new feature of LTE-Advanced intended for scenarios with low mobility and bad channel quality.

In order to minimize intra-cell interference, MU-MIMO will be based on one or two of the following approaches: a set of fixed beams, a user-specific beam technique, or a combination of both. Solutions under consideration for the two cases are briefly described in the following, although this is still an open issue.

Grid-of-Beams (GoB) is a concept widely accepted for the fixed-beam approach [39] and is depicted in Fig. 17. A limited set of possible precoding vectors is associated one-to-one with the set of beams so that radio resources in time and frequency are shared among different users without severe interference. The system can operate in both open-loop and closed-loop modes by using UE feedback in the former case and deriving the selected beam from the uplink in the latter one. This scheme is suitable for high mobility and requires pilots dedicated to each beam to determine the one with the highest received power.

User-specific beamforming is an approach that does not employ predefined precoder sets in order to provide the base station with more freedom to control or nearly null intra-cell interference. Instead, the base station may freely adjust downlink transmission weights depending on the

channel conditions. These techniques are known as non-codebook-based techniques. The idea of LTE-Advanced is to extend the single-user dedicated beamforming concept of LTE to multiple users (i.e. SDMA) while supporting spatial multiplexing, and transmit diversity at the same time. The most common precoding technique for this case is zero-forcing (ZF), a suboptimal strategy that can easily be implemented in practice by choosing the weight vectors as the pseudo-inverse of the composite channel matrix of the users to avoid interference among user streams [40, 41]. Dirty Paper Coding (DPC) [42] is another multi-user precoding strategy based on interference pre-subtraction that achieves optimal performance in the downlink but suffers from high computational burden when the number of users is large. Precoding based on maximization of signal-to-leakage ratio [43] is another candidate approach to design the beamforming vectors that does not impose a restriction on the number of available transmit antennas and so is Block Diagonalization (BD) [44]. Any of these techniques could be used to implement user-specific beamforming.

These kind of non-codebook-based precoding schemes require the terminal to make an estimate of the overall beamformed channel, as LTE already established. This is enabled through the inclusion of UE-specific reference signals that are equally precoded before transmission as the user data so that the terminal is capable of estimating the overall beamformed channel. Additionally, the number of transmit antennas used for non-codebook transmission is not constrained by the number of available cell-specific reference signals which must not interfere with each other.

LTE-Advanced needs to specify new reference signals in addition to the common reference signals (CRS) defined in Release 8 of LTE. Besides in-band channel estimation, other measurements need to be considered in order to enable adaptive multi-antenna transmission. Two additional reference signals have been specified by 3GPP. They are depicted in Fig. 18 and explained in the following.

- Channel state information reference signal (CSI-RS): this is used for channel sounding, i.e. estimation of the channel quality in different frequencies to those assigned to the specific UE. The signals are located in a sparse grid and require low overhead.
- UE-specific demodulation reference signal (DM-RS): this reference signal is precoded in the same way as the data when non-codebook-based precoding is applied. The grid pattern should be extended from the dual stream beamforming mode defined in Release 9 where Code Division Multiplexing (CDM) between the RS of two layers is utilized.

4.4. Uplink MIMO transmission

The LTE-Advanced uplink should provide significant improvements over LTE Release 8 in cell-edge, cell average, and peak data rates. The favorable characteristics of Single-Carrier Frequency Division Multiplex Access (SC-FDMA) of LTE Release 8 have reassured LTE-Advanced to keep the same access method, which basically consists of an additional DFT precoding phase preceding the

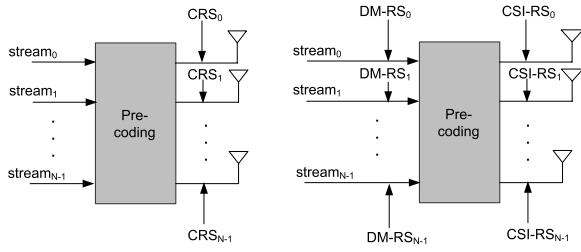


Fig. 18. CRS-based versus DM/CSI-based precoding.

conventional OFDMA. However, the inclusion of SU-MIMO in combination with a higher-order MIMO is seen as one of the key techniques to achieve significant technology advancement. The baseline MIMO configuration for LTE-Advanced is changed to 2×2 MIMO and a maximum configuration of 4×4 MIMO should be available, enabling a spatial multiplexing of up to four layers. This feature allows a large increase in the peak spectrum efficiency, getting to achieve 15 bits/s/Hz with 64-QAM [6].

Codebook-based precoding plays an essential role in the uplink. Two main alternatives have been under discussion in 3GPP: wideband (WB) precoding and frequency selective (FS) precoding. The former scheme applies the same precoding vector on the whole frequency band while the latter may select a different precoder on each resource block. After multiple discussions, it has been agreed that WB precoding is more suitable since FS does not provide any gain over WB for an equal amount of feedback [45]. Codebooks are designed so that the cubic metric (CM), a parameter defined as the cubic power of the signal of interest compared to a reference signal, is kept low. The CM is used for describing practical amplifier design. This way, the peak-to-average power ratio (PAPR) is more emphasized in the uplink and the favorable SC-FDMA properties are maintained [46]. Dynamic rank adaptation [47] is also introduced in Release 10 to obtain further performance improvements.

Link Adaptation will be supported in addition to some advanced receiver implementation such as Successive Interference Cancellation (SIC). Optional layer shifting (LS) in combination with HARQ-ACK spatial bundling [46] has also been proposed. In order to introduce additional spatial diversity gain a transmit antenna switching (TAS) scheme may be introduced where code symbols belonging to the same stream are transmitted on different antennas on a slot-by-slot basis. The required channel quality feedback for multiple streams is therefore reduced since all the spread data streams pass through similar channel conditions. Fig. 19 shows a sample transmitter with a TAS for

two streams and four transmit antennas. Further, instead of associating one HARQ process per layer, two layers could share a single HARQ process by generating a single ACK for both layers, which would be true only when both transport blocks have been decoded properly.

Different transmit diversity schemes supporting SU-MIMO are being studied for the uplink. The challenge is to find suitable transmission schemes for all uplink channels maintaining backwards compatibility and low CM properties. Both open-loop and closed-loop schemes have been proposed. Open-loop schemes differentiate between the Physical Uplink Control Channel (PUCCH) and the Physical Uplink Shared Channel (PUSCH) since it seems unfeasible to find an optimal scheme for both channels. Many contributions have centered their attention on this topic [48–52]. For PUCCH, Orthogonal Resource Diversity (ORT) or Precoder Switching Diversity (PVD) have been proposed, while Space–Time Block Coding (STBC) or Space–Frequency Block Coding (SFBC) are candidate schemes for PUSCH. Further, an alternative slow closed-loop precoding exploiting spatial correlation among transmit antennas has been proposed in [52].

As mentioned above, in the development of these new technologies the backwards compatibility needs to be taken into account. Support for legacy devices must be granted at least on part of the component carriers. Therefore, an additional complexity arises from the need to keep multiple solutions and the achievable gains have to be compared against this extra complexity.

4.5. Research challenges

There exist a number of research challenges related to single-site MIMO that are currently being investigated. New techniques enabling the above features should be developed and at the same time compatibility with the current standard and previous versions of it to ensure backward compatibility must be taken into account.

4.5.1. Physical size limitation at the UE

The main challenge regarding the support for four antennas at the UE is related to the physical space limitations. As is well known, a reduced spatial separation between the antennas of the same array can significantly decrease the achievable MIMO gain, and this fact becomes a problem when trying to accommodate a large number of antennas with adequate spacing in a handset device. Furthermore, if four to eight antennas are working in the same handset, the power consumption might be too high to be absorbed by a single power unit. Solutions to this problem have been proposed in the literature. Among them we highlight the following two approaches.

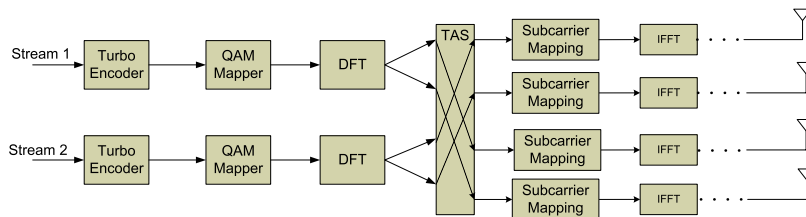


Fig. 19. TAS transmitter for two streams and four transmit antennas.

- *Virtual MIMO communications* [53]: virtual MIMO techniques among UEs are a promising approach that could be applied in both the uplink and the downlink. If the UE needs to communicate with an eNB, it could look for UEs in its vicinity to share the data with, and transmit the data in one slot as if the multiple antennas were located on the same MIMO device. An analog approach would be followed for the downlink: knowing the UEs in the surroundings of the targeted terminal, the base station could deliver the data to all of them as if they were a single device. The main issue regarding this technique is to design a reliable and efficient inter-UE link (IL) taking into consideration the special features of both the uplink and the downlink. Relaying strategies, IL spatial re-use, radio access technologies, or location information of the UEs at the eNBs are examples of issues that would need to be studied.
- *Antenna selection* [54]: the mutual antenna coupling at the UE due to close spacing can be also combated with antenna selection schemes. These schemes may range from hard detection, such as hybrid selection method where only some of the antennas are active, to soft detection methods, which apply a certain transformation to the received signals across all the antennas in the RF domain. Studied soft selection methods include so-called *FFT-based selection* and *phase-shift-based selection*. Results show that soft selection methods outperform hard selection methods when the spacing is larger or equal to one half wavelengths. Moreover, a better performance in terms of spectral efficiency can be achieved if a few more antennas than necessary are placed and a phase-shift-based selection is applied.

4.5.2. Feedback design

The uplink feedback channel is a bottleneck for the system performance in an FDD system. Many of the new features included in LTE-Advanced require an increased quantity of channel information, and very efficient feedback schemes are needed in terms of lower resource usage and finer granularity of the CSI knowledge at the eNB.

In the context of single-site MIMO, the feedback scheme must be defined taking into account that the use of up to eight transmit antennas require an accurate channel information which, at the same time, must maintain a decent amount of overhead. MU-MIMO is greatly affected by the feedback design since, in practice, inter-user interference cannot be nulled out perfectly. Terminals need to be aware of this interference when reporting the channel quality indicator (CQI), but this is not always an easy task. Regarding the uplink, efficient channel state as well as precoding information feedback for closed-loop operation need also be well designed. In this case, TDD may have a slight advantage over FDD due to the channel reciprocity.

The introduction of UE-specific beamforming poses new challenges to optimize the feedback design as well. Since there are no predefined codebooks, the feedback should not be restricted to an index pointing to a precoding matrix. Instead, methods to reliably and efficiently transmit the channel information should be investigated. Here, the compression method and source coding of the SINR

value play a major role and they should be designed in such a way that an adaptive frequency resolution over the bandwidth is allowed. Techniques that have been investigated include the Wavelet Transform [55], where the UE adaptively provides high CQI resolution (i.e. a larger number of bits) on good resource blocks and low resolution (i.e. a smaller number of bits) on bad resource blocks, and Hierarchical Feedback, probably the most relevant approach in this field. With this technique, the channel quantization is based on hierarchical codebooks that take advantage of the channel slow fading, as the CSI is refined successively over several feedback periods. They can be represented as hierarchical trees [56] supporting multiple tree types.

All these feedback issues bring about the debate whether more complex channel reporting methods are necessary for LTE-Advanced. LTE Release 8 acquires CSI by *implicit* reporting consisting of CQI, PMI (Precoding Matrix Indicator) and RI (Rank Indicator). The three indicators point to a recommended modulation and coding scheme, precoding matrix and number of transmitted streams, respectively. *Explicit* reporting, however, attempts to quantify more precisely the characteristics of the propagation channel such as the covariance matrix, complex channel impulse response, or eigenbeams. Moreover, schemes combining both types of reporting have also been proposed. In [57], an efficient feedback scheme that combines ‘short-term’ information (a quantized function of instantaneous channel) and ‘long-term’ information (channel covariance matrix) is used for the design of the scheduler and beamformer to further improve performance.

4.5.3. Enhanced codebook-based transmission

In codebook-based precoding the transmit precoders are chosen from predefined sets based on the feedback received from the terminals. It is a GoB concept since the antenna arrays are uniformly linear, and combined with precoding they form directional beams. The support for up to eight transmit antennas has a great impact in the codebook design for closed-loop operation. The size of the codebook is large, so the terminal will need to determine the preferred precoding matrix index (PMI) among a large number of them, and the required calculation and processing will be very large. Therefore, there is an important need for optimized codebooks to reduce the computational burden and both intra-cell and inter-cell interference.

Two relevant codebook-based approaches to further reduce the inter-cell and intra-cell interference are known as “best companion” and “worst companion” [58,59]. The approaches are based on the idea that the UE will report the best beam index for its serving cell plus the so-called best-companion (or worst-companion) index (BCI and WCI), i.e. the codebook index of a potential co-scheduled interferer which maximizes (minimizes) the SINR at the receiver output. Likewise, CQIs for the case that BCIs (WCIs) are not used will be reported as well. Based on this information, a user pairing based on BCI can be performed by the eNB to reduce intra-cell interference. Beam coordination can also help to reduce inter-cell interference by using a centralized scheduling that accounts for the fact that no interference from reported WCIs will occur.

5. Cooperative multipoint transmission and reception for 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 beamforming/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 precoding, 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.

5.1. The CoMP architecture

Coordination among eNBs is a very promising technique to reduce inter-cell interference in the network in both the downlink and the uplink. CoMP is applied in the downlink by performing a coordinated transmission from the base

station, whereas interference in the uplink can be reduced by means of a coordinated reception in eNBs. Most of the CoMP approaches share the requirement of needing some scheduling information regarding the users at the different base stations that must be shared among them. This means that very-low-latency links are required so that information can be exchanged between coordinated nodes in the order of milliseconds.

Two kinds of architecture can be distinguished with respect to the way this information is made available at the different transmission points as described in [60]: centralized and distributed CoMP. Both types of architecture can be combined with any of the different CoMP transmission schemes that will be presented in Section 5.2, although the degree of complexity to implement them may vary from one scheme to the other.

5.1.1. Centralized architecture

In a centralized approach, a central entity is needed in order to gather the channel information from all the UEs in the area covered by the coordinating eNBs. This entity is also in charge of performing user scheduling and signal processing operations such as precoding. Furthermore, tight time synchronization among eNBs is needed and user data need to be available at all collaborating nodes. On the downlink of FDD systems the UE needs to estimate the channel and derive channel coherent or non-coherent indicators (CSI/CQI) to feed back to the eNB. In TDD systems, the channel information can be obtained by using channel reciprocity.

Fig. 20 depicts the centralized framework for coordination among different base stations. In the case of FDD operation, terminals must first estimate the channel related to the set of cooperating eNBs. The information is fed back to a single cell, known as the anchor cell, which acts as the serving cell of the UE when coordination is being employed. Once the information is gathered, each eNB forwards it to the central entity that is in charge of deciding the scheduling and the transmission parameters, and this new information is sent back to the eNBs.

The main challenges of this architecture are related to the new associated communication links between the central entity and the eNBs. They must support very-low-latency data transmissions and in addition communication protocols for this information exchange must be designed.

5.1.2. Distributed architecture

A distributed architecture is another solution to perform coordination that alleviates the requirements of a centralized approach. Based on the assumption that schedulers in all eNBs are identical and channel information regarding the whole coordinating set can be available to all cooperating nodes, inter-eNB communication links are no longer necessary to perform cooperation. Thus, this architecture has the great advantage of minimizing the infrastructure and signaling protocol cost associated with these links and the central processing unit, so conventional systems need not undergo major changes. Furthermore, the radio feedback to several nodes could be achieved without additional overhead.

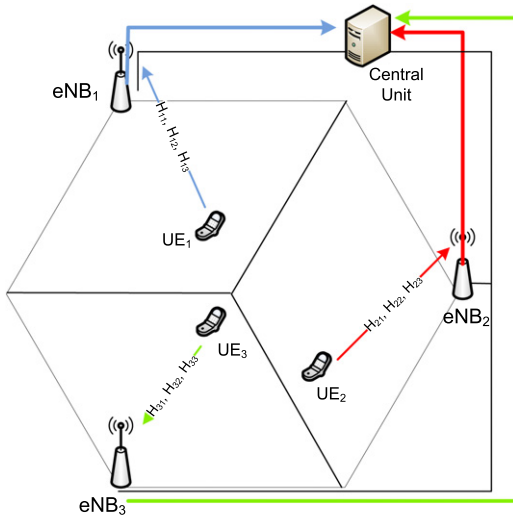


Fig. 20. Centralized CoMP approach.

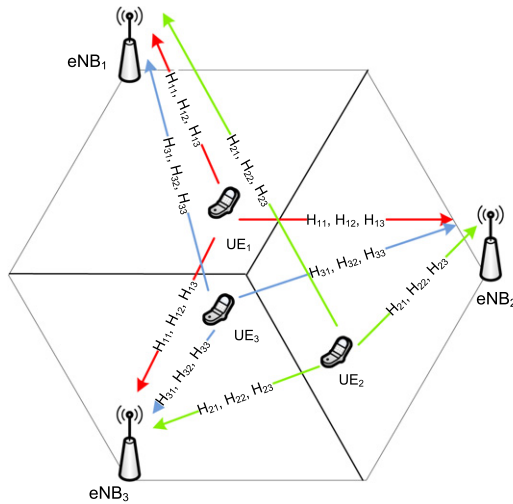


Fig. 21. Distributed CoMP approach.

The procedure that needs to be followed in a distributed CoMP environment can be described as follows. The UE estimates the channel from all the coordinating eNBs in the very same way as in the centralized approach. The estimates are then sent back to all cooperating eNBs and the scheduling is independently performed in each of them, as Fig. 21 shows. Since the schedulers are identically designed, the same input parameters produce the same output decisions and therefore the same UEs are selected in the entire eNB cluster. Similarly, transmission parameters are jointly selected according to a common design in the different nodes.

This scheme presents some drawbacks. First, if different eNBs do not perform cooperation via a wired backhaul, the performance of the CoMP algorithms is less efficient. Furthermore, an obstacle associated with distributed transmission is the handling of errors on the different feedback links. The same UE reports its channel conditions to all the eNBs in the set but the wireless links to the different nodes

might be very different and the impact of these errors on the system performance cannot be neglected. In [61], this impact is analyzed, and enhancements to the robustness of this approach are proposed. They propose both to decrease the probability of a malfunction and to recover from it.

5.1.3. Mixed architectures

There are also some promising approaches that lie between the former extreme cases and can combine advantages of both schemes. 3GPP is thinking of an approach that suppresses the central unit but maintains the communication links among the different eNBs. The decisions are jointly made by the connected eNBs transmitting almost simultaneously due to the high speed of the backhaul link. Another technique decouples the scheduling and precoding process [62], the former being carried out at the central entity while the latter is locally designed at each eNB. This approach, called collaborative MIMO, reduces the amount of information that has to be exchanged among the different nodes.

5.2. The CoMP schemes

In this section, we outline the different possible CoMP schemes that are envisioned in LTE-Advanced for both the downlink and the uplink. Independently of whether the architecture is a distributed or a centralized one, different approaches with different levels of coordination exist. Their requirements in terms of measurements, signaling, and backhaul are different, where as usual the highest performance achieving schemes require the highest system complexity.

CoMP techniques are being studied for both the downlink and the uplink transmission paths. In the downlink, two main CoMP transmission techniques are envisioned: cooperative scheduling/beamforming and joint processing. Their main difference lies in the fact that in the former scheme it is only one eNB that transmits data to the UE, although different eNBs may share control information. In the latter scheme, many eNBs transmit data simultaneously to the same UE. In the uplink, however, only a coordinated scheduling approach is envisioned.

In general, the cost of the CoMP mode is found only beneficial to the cell-edge users where the perceived Signal-to-Interference-and-Noise Ratio (SINR) is low. This is because more system resources are allocated to a single user during its operation. However, first simulation results suggest that CoMP can be used to increase both the average cell throughput and the cell-edge user throughput [63].

5.2.1. Downlink

(a) *Coordinated scheduling/beamforming.* Coordinated scheduling/beamforming (CS/CB) is characterized by the fact that each UE is served by a single cell known as the “anchor cell”. However, precoding at each base station to achieve beamforming may be coordinated to improve the sum throughput and reduce interference. Fig. 22 depicts an architectural example of this transmission scheme.

The feedback design should be enhanced to give support for this transmission strategy. The scheduler at each

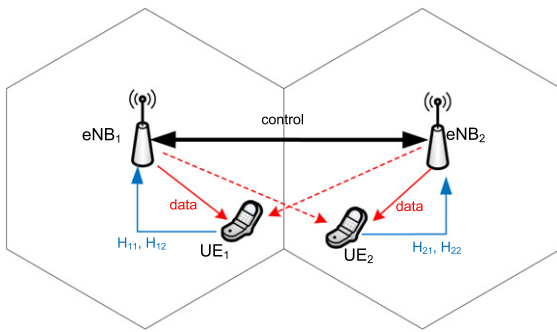


Fig. 22. Coordinated scheduling/beamforming approach.

eNB makes its decisions independently but additional information about other user's channel conditions is necessary in order to perform a more optimal scheduling and beamforming. In the example of Fig. 22, the CS/CB procedure would entail the following operations.

- Two eNBs have determined a candidate set of UEs to be attached to both eNBs on a semi-static basis. For coordinated precoding and UE pairing, eNBs then request the candidate UEs to feed back channel information for CoMP mode operation.
- The UE must estimate the downlink channel quality of both the anchor cell and the interfering eNB. At this point, different reference signals for link adaptation measurements and demodulation purposes should be used. Common reference signals (CRS) specific at each cell present the problem of ensuring orthogonality for each of the coordinating eNBs, especially given the fact that the set of participating points in CoMP may be different for each individual UE. Overhead is also a concern since UEs close to the eNB may not benefit from CoMP. UE-specific reference signals, called demodulation reference signals (DM-RS) in LTE-Advanced, overcome this problem and also enable precoding flexibility by not constraining it with a codebook. However, for link adaptation purposes, CRS measurements could be more tolerable to channel estimation errors so cell-specific reference signals for channel state information (CSI-RS), in addition to DM-RS, help the scheme to properly work.
- The UE feeds back its channel information together with the interfering channel to its anchor eNB. The same operation is performed with the second UE.
- Precoding matrices based on throughput maximization and fairness constraints and final UE selection/pairing are obtained by each of the base stations and the transmission is performed accordingly. The UEs may use the above-mentioned reference signals to perform demodulation and link adaptation.

The generalization of this procedure to a more realistic scenario with a larger number of base stations and terminals is quite straightforward, although the accurate measurements in multiple UEs, the feedback, and the information exchange among eNBs still present some challenges. Nevertheless, simulations so far have demonstrated that CS/CB with improved feedback can deliver significant gain to cell-edge users [64].

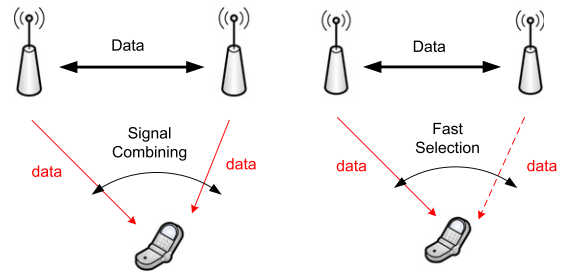


Fig. 23. Joint processing techniques: joint transmission (left) and dynamic cell selection (right).

(b) *Joint processing*. In the category of joint processing (JP), data intended for a particular UE are jointly transmitted from multiple eNBs to improve the received signal quality and cancel interference. The information theory paradigm to be exploited is the following: if antennas are uncorrelated, the number of independent communication channels is the same as the product of transmitting and receiving antennas. Different site location means inherent low correlation; hence, even though this approximation gives an upper bound for the system capacity, a high potential gain may be achievable.

Two different methods are being studied for the JP scheme: joint transmission and dynamic cell selection. Although data are indeed transmitted from several sites, the former scheme does it simultaneously while the latter uses a fast cell selection approach and only one of them transmits data at a time. This advanced pair of techniques is particularly beneficial for cell-edge throughput and is anticipated to be the dominant application of CoMP. Fig. 23 shows a simplified scheme of both techniques. In both cases user data need to be shared among base stations so a very fast link interconnecting them is required, although the complexity of the signal processing is higher in the joint transmission scheme.

The *joint transmission* scheme primarily considers that the transmission points correspond to different cell sites and a cluster of base stations must jointly decide on the transmission scheme of a signal to the UE. Precoding in this context must be applied using DM-RS among the coordinating cells. There are several design considerations that need to be studied in order to take the most advantage of this technique. Two relevant ones are the serving set determination and the coherent versus non-coherent transmission approach.

- **Serving set determination:** the determination of the serving eNBs (also called eNB cluster) can be performed in different ways. Firstly, the eNBs forming the CoMP cluster can be determined either by the network, the UE [65], or adaptively between the UE and network [66]. Secondly, the cluster could be formed by a fixed set of serving cells or by a flexible set. These two different candidate approaches are described in the following. If the serving set is a fixed one, the cells within the cluster will always serve the target UE simultaneously. An approach to implement this idea could be to employ different frequency zones for users performing CoMP, i.e. users at the cell-edge. The procedure would be then simple: the UE is determined to be served with

CoMP mode or not depending on its SINR value before the scheme is applied. If the decision is positive, the UE will be scheduled to a preconfigured frequency zone jointly scheduled with other CoMP UEs. At that moment, all the cells within the cluster will serve the UE simultaneously.

The problem with the above-described approach is that forcing all the cells within the cluster to serve a single UE may lead to a waste of resources since the signal strength from some of the cluster's eNBs might be very weak. An example is a cluster of three eNBs where the signal strength coming from eNBs 1 and 2 is much stronger than the one coming from 3. In other words, $H_{11} \approx H_{21} \gg H_{31}$. In this situation, the size and elements of the CoMP cluster could be changed, but flexible scheduling of the actual transmitting cells within a specified cluster would be much easier to implement. Additionally, the cluster setup might have been statically or semi-statically established and a change in its configuration could affect the other UEs. The third base station would improve its resource utilization by serving another UE closer to its position. Although interference to UE 1 would appear, it would not cause much throughput degradation due to its remoteness.

- Coherent and non-coherent transmission: in terms of ways to transmit and combine the signals, joint transmission can be classified as coherent and non-coherent transmission techniques. In coherent transmission, the network obtains channel state information (CSI) from all the cooperating cell sites. The phase of the transmitted signal can be adjusted to the CSI in such a way that the receiver is able to combine them at symbol level coherently. While combining is an implementation issue, it affects the signaling support design for the CoMP downlink. This allows for an additional multi-cell array gain besides the single-cell and multi-cell precoding gains. Two possible implementations of coherent transmission could be a different phase correction applied to each cell or a global precoding matrix based on all the CSI between cooperating cell sites and the intended UE where each cell uses part of the global matrix as precoder.

On the other hand, for non-coherent transmission the network does not have information concerning the relationship of the channels among the cooperating cells. Under this situation, the received signals arriving at the UE cannot be coherently combined. This is due to the fact that cell-edge users calculate channel quality indicators (CQIs) and report them to their serving cells without providing thus channel phase information. This kind of scheme has been widely used for single-user MIMO to simplify the system overhead and backhaul capacity, although the gains are not as big as with the coherent approach. Examples of implementations of this technique include SFBC, Cyclic Delay Diversity (CDD) [67], or multi-user eigenmode transmission (MET) scheduling [34]. Non-coherent combining can be performed at soft-bit level after demodulation, analogously to HARQ combining.

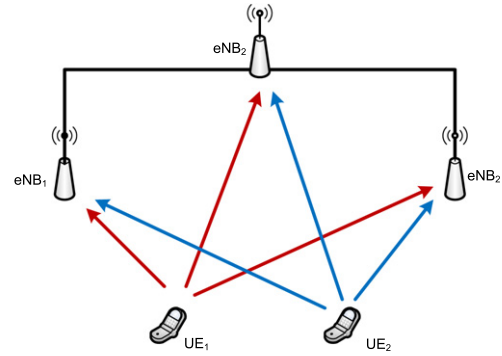


Fig. 24. Uplink CoMP scheme.

On the other hand, the *dynamic cell selection* approach is a joint processing scheme where the transmission to the intended UE only takes place from one point at a time. This point must be drawn from the CoMP cooperating set serving the same UE. The switching can be produced at most on a subframe-by-subframe basis, thus allowing a dynamic change in the transmission point that is transparent to the UE. The related radio resource management, packet scheduling, and common channels are tasks always performed by the serving cell. The fact that no more than one eNB transmits at the same time implies that there is no need for the eNBs to have a tight phase synchronization. Hence, dynamic cell selection can be implemented with relaxed RF performance requirements, what makes it an appropriate technique for HeNB networks.

5.2.2. Uplink

In the uplink the CoMP scheme, aimed at increasing the cell-edge user throughput, implies the reception of the signal transmitted by UEs at multiple and geographically separated points, as Fig. 24 shows. These points are nothing but the set of coordinating eNBs assigned to each UE. Generally speaking, the terminal does not need to be aware of the nodes that are receiving its signal and what processing is carried out at these reception points. This is all an implementation issue, so CoMP reception is expected to have limited impact on the specifications, and no major change in the radio interference should be required. Nonetheless, scheduling decisions can be coordinated among cells, and some specification impact may be brought from this fact.

There are different schemes that can be used at multiple reception points to combine the received signals. Maximum Ratio Combining (MRC), Minimum Mean Square Error Combining (MMSEC), and Interference Rejection Combining (IRC) are examples of techniques that extract the transmitted information from the received signal.

Despite the above-mentioned considerations, it has been noticed that there are some issues which may impact the system performance and should be further investigated. In particular, the delay spread issue may limit the benefits of CoMP since the signal could arrive at different cells at dispersive time instants separated by a larger interval than the normal cyclic prefix length, and this would cause performance degradation [68]. Basically there are two proposed approaches to combat this problem [69].

- Flexible cyclic prefix: the delay spread problem can be solved by using an extended cyclic prefix that would get rid of it. However, this solution also implies a high overhead for the whole system that needs to be avoided if high cell average throughput is also desired. UEs that cause a large delay spread may be then scheduled in the TTIs with extended cyclic prefix so that it can be served by more than one cell; on the other hand, the rest of the UEs can be scheduled in the TTIs with normal cyclic prefix and no unnecessary throughput has to be sacrificed.
- New timing advance (TA) adjustment: this method aims at reducing the arriving time spread in CoMP cells by adjusting the TA of the cell with minimum transmission time delay (i.e. the closest cell) in the active CoMP set so that the signal will not arrive at this cell's receiver earlier than expected.

The delay spread is a topic that should be effectively solved with either one or both of the above approaches. In any of the cases, uplink timing estimation at multiple receiving cells is an open issue that needs to be further investigated and enhanced.

5.3. Research challenges

Cooperative multipoint transmission and reception comprises a promising spectrum of techniques that still need to be further investigated. First simulations have shown great potential and very promising results but there are many issues that still remain open. Probably the most relevant issue that still needs to be addressed is a thorough evaluation of the practical performance versus complexity trade-off since the feasibility of CoMP technology within LTE-Advanced is still not clear. In fact, 3GPP has recently decided that only coordination between the sectors of a single site will be included in LTE Release 10 [70].

Some of the challenges have been already pointed out along the description of the techniques. Here, a summary of the most challenging issues is provided.

5.3.1. Channel estimation and feedback

An important concern regarding cooperative transmission is the support for multi-cell channel estimation that must be provided at the UE. Since propagation losses vary between cells and consequently the power of the reference signal to be measured, channel estimation at the UE becomes more challenging.

A need also arises for enhanced feedback in FDD systems with minimal impact on the signaling overhead to avoid both reducing the uplink capacity and increasing the UE battery consumption. Feedback signalling is also the key to a fast and flexible adaptation from single-site to multiple-site MIMO in varying radio environments and different network scenarios. The parameters which may need to be acquired include coherent or non-coherent channel information between the UE and eNBs antennas as well as preferred precoding matrix indices and received power from each of the coordinated points. In any case, JP is more sensitive to feedback errors than CS/CB, and it becomes difficult to ensure constructive addition of signals from different cells at the receiver.

The requirements on TDD systems are somewhat different from those for FDD. Since the channel reciprocity property is used, the main problem is to understand how the coherence time of the channel and the accuracy of the channel estimation affect the different techniques. Additionally, the quantization and feedback of the channel information over the backhaul also needs to be independently studied, as the problem definition is different from the FDD feedback.

5.3.2. Backhaul aspects

As mentioned throughout this paper, a large amount of data exchange between eNBs must be carried out over the backhaul with the minimum possible latency. This calls for very-high-speed communications links and efficient communication protocols. The technologies and media available for backhauling will have a strong impact on the available rates and latencies so they have to be carefully selected according to their cost/performance trade-off.

In addition, it is important to distinguish if the cooperation is performed between sectors of the same eNB, requiring no bandwidth backhauling, or between different sites. Regarding the amount of data to be transmitted, the cooperation can be carried out only in the control plane (CS/CB) or in the control and user plane (JP). The JP schemes are the most challenging ones since channel information, scheduling decisions, and precoding weights must be exchanged over the backhaul. Besides, user data must be available at each transmission point.

There exist different solutions in the literature that have been proposed for alleviating backhaul requirements. Serving only subsets of UEs with joint transmission [71] or partitioning a cellular network into small subsystems where these schemes can be applied locally [72] are some examples. However, a clear configuration and coordination policy for the serving sets are still to be decided.

5.3.3. Reference signal design

The main challenge regarding the design of reference signals is to obtain the precise channel state information that is required for CoMP among the cooperating eNBs. This imposes requirements on the pilot design to enable such estimation with sufficient quality. The idea introduced in LTE-Advanced is to transmit relatively low-density CSI-RS in some selected subframes with a certain periodicity (e.g. 10 ms) such that the degradation of the legacy LTE terminals unable to make use of these resources is not too high. A different option is to set the requirements on additional signal processing methods to separate the pilots from different cells.

The reference signal design must be also studied for the uplink. A joint channel estimation must be performed at each antenna head of the eNBs for all the users being served. This may not be an easy task if the users are situated at different distances from the same eNB. The received signal levels of uplink transmissions users would vary significantly from one to another user, making the joint channel estimation across some of them a difficult work. A solution for this problem defines virtual pilot sequences [73], taking the path loss into account. This enables mobile terminals to distinguish stronger interference channels with an increasing length of the correlation window utilized for the estimation process.

5.3.4. Cyclic prefix/OFDM parameters

As it was mentioned in Section 5.2.2, the delay spread issue can be affected by the processing delay of coordinated transmission. Typically, OFDM parameters such as the cyclic prefix length or the duration of the frame are based on the radio environment characteristics such as average or worst-case delay and Doppler spreads but this framework forces the design of the OFDM parameters to be reconsidered. Proposed solutions include a flexible cyclic prefix and new timing advance adjustment.

Other aspects

The list of remaining challenges for CoMP is long. There are also other aspects that need further research to make the most out of CoMP while maintaining the complexity level reasonable. The necessary conditions that both the UE and the eNB need to fulfill in order to be eligible for cooperative mode transmission must be studied. Further, algorithms ensuring tight base station synchronization or distributed power allocation schemes need to be designed. Standardization issues cannot be forgotten either, although 3GPP has been working intensively on them. These issues include, for example, signaling protocols and the backwards compatibility of the new standard with LTE.

6. Relays

Relaying is another of the elements that is introduced in LTE-Advanced to improve the performance of LTE, in terms of coverage and throughput. According to 3GPP [13], the use of relays will allow the following improvements.

- Provide coverage in new areas.
- Temporary network deployment.
- Cell-edge throughput.
- Coverage of high data rate.
- Group mobility.

These improvements can be grouped as “coverage extension” and “throughput enhancement”. In addition to the previous improvements, the use of relays brings the following advantages.

- Cost reduction: The cost of a relay, by itself, should be less than the cost of an eNB, assuming that the complexity of a relay is less than the complexity of an eNB. Due to the lack of a wired backhaul, the deployment cost and time should also be reduced, compared to an eNB.
- Power consumption reduction: The single-hop distance between the eNB and the UE is divided into two distances: the distance from the eNB to the relay, and the distance from the relay to the UE. If the relay is located and used in the appropriate locations, the required TX power (by the eNB, relay, and UE) can be reduced. The power consumption reduction can be simply due to the reduction of the path loss, while further reductions can be achieved through enhanced relaying schemes and interference control. This power consumption reduction also translates into reduced operational costs.

In Fig. 25, the basic scheme in which relays are planned to be deployed in LTE-Advanced is depicted. The UE will connect to the relay node (RN) via interface Uu, while the

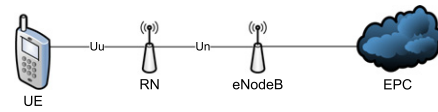


Fig. 25. Relay basic scheme.

relay connects to a donor cell of a donor eNB utilizing a new interface called Un.

The communication between the RN and the eNB can occur in two ways: inband or outband. In inband, the communication link uses the same band that the eNB uses to communicate with UEs within the donor cell, while in outband a different band is used.

3GPP has specified that LTE-Advanced will at least support “Type 1” and “Type 1a” RNs (other alternatives are under study [74]). Each one is defined as follows.

- **Type 1**
 - It controls cells, appearing as a new cell to the UEs. Each of its cells have their own Physical ID, synchronization channels, reference symbols, etc.
 - In single-cell operation, scheduling information, HARQ feedback, and control channels are exchanged directly between the UEs and RNs.
 - It appears as a Release 8 eNB to Release 8 UEs, for backward compatibility.
 - It may appear differently to LTE-Advanced UEs, to allow further performance enhancements.
- **Type 1a:** Has the same characteristics of Type 1, but operates outband.

In terms of the resource partitioning for the RN–eNB link for inband relay, 3GPP specifies the support of (at least) the following.

- Time division multiplexing for downlink (eNB to RN, RN to UE) and uplink (UE to RN and RN to eNB).
- Multiplexing of backhaul link in FDD: eNB to RN transmissions occur in the DL frequency band and RN to eNB transmissions occur in the UL frequency band.
- Multiplexing of backhaul link in TDD: eNB to RN transmissions occur in DL subframes of the eNB and RN, and RN to eNB transmissions occur in UL subframes of the eNB and RN.

To facilitate the resource assignment for the backhaul, 3GPP considers the addition of new control and data channels for the RN–eNB link. The new physical control channel (R-PDCCH) dynamically or semi-persistently assigns resources for the new downlink physical channel (R-PDSCH) and uplink physical channel (R-PUSCH) backhaul data.

In WiMAX, the use of relays has already been included and standardized through 802.16j. On the other hand, in LTE-Advanced it is still a general concept, whose main ideas we have just described. This allows a high degree of flexibility in terms of the type of RNs, types of deployment, number of functions performed by the RN, and protocol definitions.

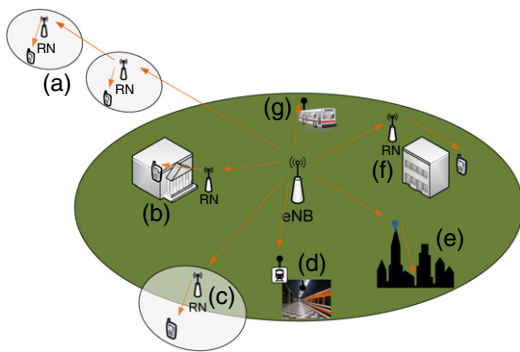


Fig. 26. Relay deployment scenarios.

6.1. Scenarios

The basic scenario for the use of relays is depicted in Fig. 25. This scenario can be expanded by taking into account how the relays can help to achieve the objectives previously mentioned. Fig. 26 shows an expanded scenario.

In case (a), multi-hop relay communication is used to provide coverage to isolated areas that otherwise would not be under coverage. In (b), the RN is used to improve the signal received by UEs that are within a building (or any other indoor location) in order to enhance the throughput achievable by these UEs. In (c), an RN is located near the cell-edge in order to extend the coverage or improve the throughput at the cell-edge. In (d), an RN is located in order to extend the coverage or improve the throughput at underground areas (e.g. trains). In (e), coverage and/or throughput can be improved at valleys located within buildings. In (f), similar to (e), areas that lack coverage due to shadowing (e.g. because of large buildings) can be covered through RNs. In (g), a mobile RN is used to improve throughput. In each of the previous cases, the type of RN that is going to be used may vary according to the specific requirements of each case.

6.2. Types

The definition of a “type” of relay, according to 3GPP, is done by combining a set of characteristics that a relay should have. The most common characteristics used to classify relays are their duplexing scheme, layers, and level of integration into the RAN. On top of these classifications, relays can contain “add-ons” such as enhanced-MIMO capabilities, cooperation capabilities, etc. The following section provides an overview of the classifications of relays.

6.2.1. Layers

Relays can be classified according to the layers in which their main functionality is performed.

- A Layer 1 (L1) relay is also called a repeater. It takes the received signal, amplifies it and forwards it to the next hop, which may be another RN or UE. As its name implies, it works at the L1 of the protocol stack and implements (part of) the PHY layer. However, L1 relays amplify not only the desired signal but also noise

and interference. Their advantage is that they can do the forwarding almost immediately, which translates into a small delay that appears as more multipath to the UE. If some intelligence is added to the L1 relay it could utilize power control or self-cancellation to reduce interference [75].

- A Layer 2 (L2) relay is also called decode and forward relay. It works up to the Medium Access Control (MAC) and Radio Link Control (RLC) layers, which enables the relay to perform radio resource management (RRM) functions, i.e. distributed/decentralized RRM. Due to the extra functions performed by an L2 relay, a more significant delay is introduced compared to an L1 relay.
- A Layer 3 (L3) or higher-layer relay can be thought of as a wireless eNB that uses a wireless link for backhaul instead of a wired and expensive link. In this case the wireless backhaul link would require high efficiency and the signaling overhead will be higher, compared to the L1 and L2 relays.

6.3. Duplexing schemes

A relay can use TDD or FDD, with variations, to communicate with its donor eNB and its UEs. While TDD is inherently half-duplex in the case of a pair of communicating nodes, a relay node communicates with two types of node: eNB and UE. This characteristic of relay communications enables them to use simultaneously, in TDD, the DL/UL frame of the eNB–RN link with the DL/UL of the eNB–UE link. On the other hand, the use of FDD is inherently full-duplex in the case of a pair of communicating nodes. However, since the relay node communicates with an eNB and several UEs, efficient schemes to utilize the frequency resources should still be analyzed.

A simple example for the TDD case is shown in Fig. 27(a): in the first time slot the eNB–RN DL transmission is done, in the second time slot the RN–UE DL transmission is done, in the third time slot the UL UE–RN transmission is done, and in the fourth transmission the RN–eNB UL transmission is done. As just described, at each time slot at most one element is transmitting/receiving.

A better utilization can be achieved if at each time slot more than one element is transmitting/receiving. For example, DL eNB–RN and DL eNB–UE in the first time slot, UL UE–eNB and UL RN–eNB in the second time slot. In this case, the RN can transmit and receive at the same time, but to different nodes. However, this requires from the RN the capability of suppressing inter-antenna interference through the suppression of interference or isolation of the TX and RX components in each link [76]. Another possibility would be DL eNB–RN and UL UE–RN in the first time slot, UL eNB–RN and DL UE–RN in the second time slot. In this case, the RN either transmits to the eNB and the UEs or receives from the RN and UEs. A natural extension of the previous TDD cases involves transmitting and receiving to the eNB and UEs simultaneously, but this requires full-duplex radios with their inherent complexity and challenges.

In case of FDD, a basic scheme will work as shown in Fig. 27(b). The DL and UL transmission between the RN and eNB will occur in the same time slot but at different

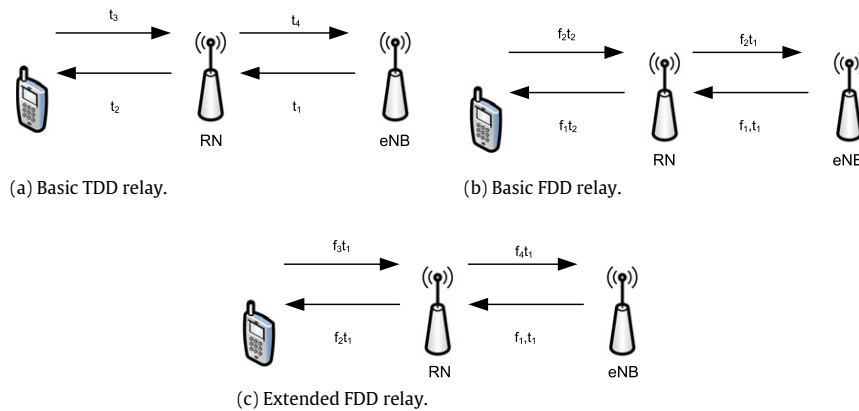


Fig. 27. Relay duplexing schemes.

frequencies, and the same will occur for RN–UE case. However, the UE–RN and RN–eNB transmissions occur at different times.

By extending the basic FDD approach, a general scheme can be designed as shown in Fig. 27(c), where each link uses different orthogonal frequencies. Even though this scheme could provide the highest level of throughput, it also requires the highest number of resources available for the relay scheme, since four groups of orthogonal frequencies are used.

The previous descriptions illustrate the flexibility in the design of the relay scheme based on the duplexing scheme. These examples are not an exhaustive list of all the possible variations of FDD and TDD, but a brief overview of possible options.

6.3.1. Integration into RAN

A relay can integrate into the RAN and appear to the UEs and eNB in different ways.

- **Transparent versus non-transparent (UE perspective):** UEs that are being served with the aid of a transparent RN (L1, L2, or L3) will not be aware that they are communicating with an RN instead of (or in addition to) an eNB. This is the best alternative when backward compatibility is required, as in LTE-Advanced. On the other hand, UEs being served with the aid of a non-transparent RN will be aware of such a situation potentially using this knowledge to optimize the communication with the RN and eNB.
- **Transparent versus non-transparent (eNB perspective):** A transparent RN will appear as any other UE to the eNB, and will be served as any other UE by the eNB. A non-transparent RN will appear as a special type of node, an “RN”, to the eNB, allowing the definition and optimization of the communication link between the eNB and the RN.
- **Controlling own cells versus extending donor cell:** An RN (L2 or L3) can control its own cells, transmitting its own Physical Cell ID, synchronization channels, reference symbols, HARQ, etc. On the other hand, an RN can simply reuse the elements previously listed of the donor cell and use it for serving UEs within its range.

- **Inband versus outband:** In the inband case, the backhaul link between the RN and eNB uses the same frequency band that the donor eNB uses in the donor cell. In the outband case, this backhaul link will use another frequency band or any other type of wireless link. A combination of inband and outband will allow several interfaces for the backhaul link, which allows provisioning load balancing and high availability.

6.3.2. Add-ons

Beyond the classifications listed, the use of RNs can be further improved by using the same techniques thought for eNBs: enhanced MIMO, cooperation, and carrier aggregation techniques. The description of these elements and the challenges associated with each one can be found in previous sections.

Each of the techniques discussed in the section of enhanced MIMO can be applied to the eNB–RN link and to the UE–RN link, according to the type of RN that is being used and the scenario in which it is used, where a “type” is a combination of one of the classifications previously listed.

Carrier aggregation could also be applied at the RN for the eNB–RN link and to the UE–RN link, where static, dynamic, or semi-static frequency bands could be scheduled for each link according to the scenario.

In terms of cooperation, the RNs provide an extra degree of flexibility since three types of cooperation can occur: cooperation between RNs, cooperation between RNs and eNBs, and cooperation between RNs (among themselves) and also with eNBs. For the first case, the information required to achieve cooperation among RNs can be exchanged through a virtual X2 interface among the RNs, such as a direct communication between RNs, or by exchanging information through the X2 interface between their donor eNBs. For the second case, information can be exchanged between the RNs and eNBs to cooperate and apply the techniques described in Section 5.

Fig. 28 shows two possible basic cooperation scenarios with RNs. In case (a), one of the RNs receives data from the eNB and then it communicates with a second (group of) RNs to perform a cooperative transmission to the UE. In case (b), the eNB sends the data that is to be transmitted to the UE to the RNs and a cooperative transmission among the eNB and the two RNs is performed towards the UE. Another possible scenario would include

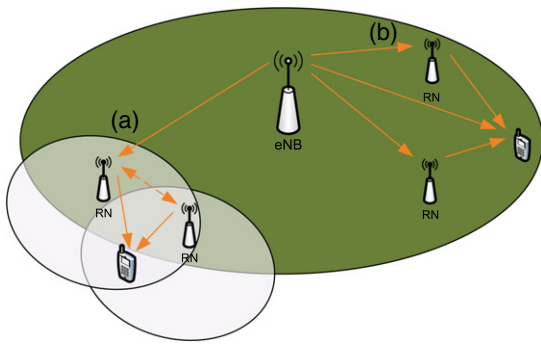


Fig. 28. Cooperation schemes for relay networks.

a combination of (a) and (b); the eNB will establish a cooperative transmission towards the UE with the RNs while at the same time the RNs will communicate among themselves to achieve cooperation.

Even though the cooperation scheme has been described for a single cell and two hops, more complex scenarios in which more than two hops occur and more than a single cell is taken into account can also be analyzed. In the case of more than one cell, an RN could have more than one donor eNB which adds a new degree of freedom for the cooperation mechanisms.

However, as the number of RNs, their complexity, and features required for a specific scenario increase, their cost will also increase, which goes against the main idea of using RNs: a low-cost alternative to improve performance and coverage. Hence, a balance between the number of RNs, their features, and their cost is one of the key points for a wide successful deployment of RNs.

6.4. Topologies

The most basic topology for the deployment of RNs consists of a single RN served by a single donor eNB and serving a group of UEs. If the RN is located at the cell-edge it could be used to extend the coverage of the network or improve the cell-edge throughput, as shown in case (c) of Fig. 26. If it is located within the cell coverage, the RN could improve the coverage in areas where the eNB is not providing adequate coverage or no coverage at all; this corresponds to cases (b)–(f) of Fig. 26. The next basic topology of RNs would consist of a single path of RNs where each one can communicate with two other RAN elements (another RN or an eNB), this topology corresponds to case (a) of Fig. 26. If in the previous topologies we replace each single RN with a group of RNs we can obtain cases (a) and (b) of Fig. 28. As previously analyzed, each topology can be mapped to different deployment scenarios. One of the challenges consists in identifying which topologies and which types of RN are more suitable in order to achieve the objectives in the most common deployment scenarios.

6.5. Research challenges

The previous section showed the high level of flexibility that the use of RNs introduces into the RAN. Even though extensive research has been done in terms of analyzing the

achievable gains through the use of RNs in different mobile multi-hop relay network scenarios, integrating relays into a system such as LTE involves several constraints and functionality that must be taken into account.

6.5.1. Architecture

The introduction of RNs into the RAN is already considered in LTE-Advanced, by indicating that at least “type 1” and “type 1a” relays should be supported, as described at the beginning of this section.

Based on the description of the functionalities that relays should provide in LTE-Advanced, some ideas on the type of relays that should be used can be inferred. On the Uu interface (Fig. 25) all AS control plane (RRC) and user plane (PDCP, RLC, MAC) protocols are terminated in the RN, which suggests the use of L2 or L3 relays. The use of RNs should also be backward compatible with Release 8 UEs, which suggests that RNs should support transparent (from the UE point of view) mode, allowing a non-transparent mode for LTE-Advanced UEs. However, the advantage of using a non-transparent RN still has to be shown, i.e. having UEs that are aware of transmission coming from an RN instead of an eNB must prove to increase efficiency without adding excessive complexity/cost to the UE and RAN. This could be the case for cooperative transmission of RNs and eNBs, where the UE awareness could reduce the complexity of the scheme.

The characteristics of the eNB–RN link and the awareness of eNB of RNs should also be taken into account. First, on the Un interface between RNs and eNB, the user plane is based on standardized protocols (PDCP, RLC, MAC) while the control plane uses RRC (for the RN in its role as UE). Second, at least at an early stage, most RNs will be fixed instead of mobile. Third, the addition of a dedicated “relay control channel” and “relay data channel” for the Un interface suggests the use of non-transparent (from the eNB point of view) RNs. These three characteristics (standard user and control plane protocols, fixed RNs, eNB awareness of RNs) can be used to optimize the protocols in the eNB–RN link, in order to reduce their overhead and improve their performance.

Beyond the characteristics (“type 1” and “type 1a”) initially suggested by 3GPP for RNs, there exists the possibility of creating other “types”, based on a combination of the features described in Section 6.2. However, their performance in different topologies, as shown in Section 6.4, and scenarios, as shown in Section 6.1, needs to be studied not only from a theoretical point of view but also from a compatibility (with LTE-Advanced) and backward compatibility with a Release 8 UE point of view.

The evaluation of the economic and theoretic aspects of relay-enhanced networks, and real deployment performance has already started for some relay “types” and scenarios. In [77], a techno-economic analysis of a generic cellular-relay networks according to the fairness goals of the operator is done. It is found that relays are best suited for providing coverage for guaranteed data rates, rather than to boost the data rate in specific locations. [78] provides an analysis of the effect of generic L2 relays on coverage for LTE-Advanced. Their proposed evaluation framework relates the transmission power of the RN, the

ratio between the number of eNBs and RNs, and the performance of the system. [79] analyzes the performance of L2 relays taking into account distributed SFBC for two-antenna relays, while [80] analyzes timing asynchronism in L1 cooperating relays with distributed STBC. [81] analyzes the throughput of cooperative and dynamic resource relaying at a system level. The results obtained in these papers have shown that the addition of cooperation and enhanced MIMO techniques can significantly increase the performance of a relay-enhanced network, but at the same time the use of such techniques should adapt to the specific deployment scenarios. [82] provides measurements on the performance of an L2 relay in an indoor full-frequency reuse environment, showing that relays may be a viable solution for indoor environments. [83] performs coverage and capacity analysis of relay performance based on a 3D models of a city, providing a more realistic view of the application of relays and achievable improvements in a cellular network.

6.5.2. Functionality

As described before, RRC, PDCP, RLC, and MAC are terminated at the RN for the Uu interface. Identifying up to what level each of these protocols will depend on information provided by the eNBs or the core network needs to be defined, as well as the methods in which such information is obtained. Also, the amount of resources available in the backhaul link will affect the way each of these protocols behave. For example, in the case of admission control two cases could occur.

- The RN is completely controlled by the eNB. Based on the amount of resources that an RN is assigned (and its capabilities), the RN is able to communicate with its own UEs. If the amount of resources needed to serve the UEs is more than the amount of resources the RN has available, then some UEs may not be served.
- The RN “negotiates” with the eNB. Based on the amount of resources that an RN needs to communicate with its UEs, according to the required QoS, an RN will negotiate with the eNB the amount of resources that it needs. In this case, the eNB can assign all (or part) of the resources that the RN requested, based on network policies or any other criteria.

Handover procedures will also be affected. Simple aspects in the handover procedure that need to be analyzed in the presence of relays are depicted in Fig. 29.

In Fig. 29, the following types of handover could occur (assuming the UE is being served initially by RN_1).

- From RN_1 to eNB_1: UE moves from the RN_1 cell to be served directly by the eNodeB_1.
- From RN_1 to RN_2: UE moves from the RN_1 cell to be served by RN_2, that is also served by the same donor cell.
- From RN_1 to RN_3: UE moves from the RN_1 cell to be served by RN_3, that is served by a different donor cell.
- From RN_1 to eNB_2: UE moves from the RN_1 cell to be served by another eNodeB on another cell.

In addition to these basic handover procedures, more complex ones also need to be studied, such as when MIMO techniques, carrier aggregation, and CoMP are used.

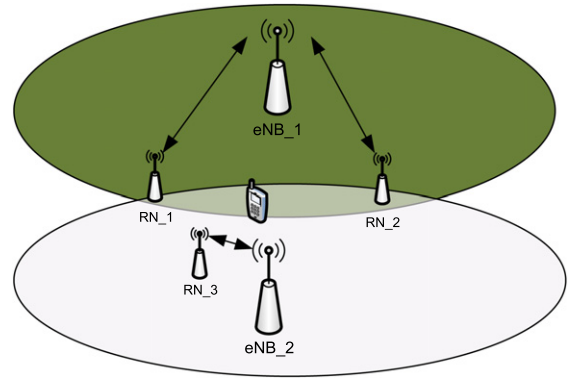


Fig. 29. Handover with RNs.

6.5.3. Location and type of relay

The location of an RN will directly affect the performance improvement that it can provide to the network. The optimal location will be determined not only by the scenario in which the RN will be deployed, but also by other factors, such as the following.

- Coverage provided by other RNs and eNBs.
- RN “type” and “add-ons” (MIMO, carrier aggregation, CoMP).
- Type of cooperation between RNs.

As has been described in previous section, the full set of characteristics that an RN has is open to several variations. However, which variations are more suitable to different scenarios in order to provide high efficiency, in terms of performance and cost, deployment options should be studied.

6.5.4. Resource management

There are two RRM main areas related to the use of RNs: RRM performed by the donor eNB and RRM done by the RN. In the first case, the eNB is not only in charge of doing RRM for its own UEs but also for the RNs that it is serving. The eNB, being aware of the presence of RNs, must make a balance between scheduling resources for its UE and RNs not only to guarantee the QoS requirements but also fairness, while taking into account interference and any other constraints and policies. In the second case, the RN is in charged of performing similar RRM as the one done by a typical eNB, with the additional constraint that it has a limited set of resources to communicate with the core network due to the wireless RN–eNB backhaul link.

In the case of interference management at the level of eNBs, LTE has already proposed some techniques to achieve it by exchanging information between eNBs through the X2 interface. Similar techniques could also be applied for interference management between relay nodes, taking into account the lack of a direct X2 interface between RNs and eNBs.

Due to the possibility of achieving cooperation among eNBs and RNs, as depicted in Fig. 28, RNs will also require the exchange of channel state information regarding RN–RN links and RN–eNB links. Also, depending on the cooperation scenario, a certain level of integration and support of the RN by the eNB would be required.

6.5.5. Routing

Due to their expected lower cost, more than one RN could be deployed to satisfy a requirement (improved coverage or throughput) in a specific area. This immediately raises the question on how to route the information through this network of RNs, while satisfying QoS, fairness, and interference requirements and constraints. At the same time, the use of more than one RN in an area opens the possibility of other features such as load balancing and fault tolerance. The basic alternatives go around doing centralized or distributed routing decisions, with their inherent optimality and scalability trade-off. As with other topics related to RNs, they have been studied from a theoretical point of view, but need to be integrated into the LTE-Advanced network with its requirements, constraints and architecture.

6.5.6. User equipment as relay

The possibility of using UEs as RNs is not one of the main approaches followed by LTE-Advanced to improve coverage and performance. However, this capability can be of high importance in emergency situations where the availability of eNBs and fixed RNs infrastructure is reduced. This scenario is characterized as being not frequent, and no a priori information of the time in which it will be required is known. In such cases, using other UEs as relays could allow a flexible solution, but poses new challenges. Battery consumption would be one of the main problems. Also efficient procedures for searching UEs in emergency situations, routing, and selection of the most appropriate UE relay would be needed [76].

In general, the main research challenge of a relay-enhanced network is to achieve the introduction of RNs into the network while still meeting the performance targets (average and peak throughput within and at the cell-edge, and delay) and providing improvements in the network.

7. Conclusions

LTE-Advanced, the backward-compatible enhancement of LTE Release 8, will be fully specified in 3GPP Release 10. 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 Release 10, 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 femtocells, self-organizing networks, and energy management systems will drive the evolution of current and future mobile wireless networks.

Acknowledgements

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