Carrier Aggregation - Improved Downlink Scheduling in LTE-Advanced Networks Review on LTE-A networks and Carrier Aggregation

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***Abstract*— Use of wireless communication is increasing day by day at exponential rate. Number of data users and wireless devices are increasing effectively. Hence, network providers are demanded to provide higher data rates. Evolution of LTE-Advance networks has developed a bright hope in this context. Continuous work is being done to find the ways to meet the requirements of IMT-Advance like data rate of 1Gbps. To achieve such a high data rate, high channel capacity and proper utilization of spectrum is required. Many techniques have been introduced to improve the performance of LTE-A networks like MIMO, Layer 3 relay, Heterogeneous networks, network coding, COMP, Carrier Aggregation etc. Out of these, Carrier Aggregation (CA) is most notable as it solves the problem of limited bandwidth by combining components carriers. In this paper, we have discussed about LTE-Advance networks their features and then, a review on carrier aggregation is presented.**

***Keywords* — LTE-A, Carrier Aggregation, Component Carrier, Quality Of Service, IMT-Advance, OFDM, Scheduling.**

I. INTRODUCTION

Third generation partnership project (3GPP) launched LTE as 4G communication systems and as successor of UMTS which was finally standardized in the release 9. Nevertheless, these versions provided high improvement over 3G systems, however, these were not capable of fulfilling all the requirements of IMT-Advance specified by 3GPP like data rate of 100 Mbps in mobility. Hence, 3GPP continues to work on advancement of LTE system and launched its highly improved release 10 which was called LTE-advance (LTE-A). LTE-A fulfills the requirements of 3GPP. It has also been specified by 3GPP that LTE-A can also meet the specifications of IMT-A like data rate of 1Gbps (non-mobility). Employment of various techniques in LTE-A has improved the performance of system to significant level but now, it seems impossible to further improve the quality of service (QOS) of LTE 4G systems due to the fact that bandwidth of system is limited. The only way to achieve such a high data rate is to increase the channel bandwidth. The problem of limited channel bandwidth is solved by standardization of a key technique in 3GPP as part of release 10 which is named as Carrier Aggregation (CA). In this paper, a brief review is given about LTE-advance systems CA technique.

II. LONG TERM EVOLUTION (LTE) – REVIEW

4th generation mobile system (4G) is an emerging technology in the field of communication. Basically, 4G is an improvement and integration of various existing technologies including GSM, GPRS, CDMA, W-CDMA, IMT-2000, Wireless LANs and Bluetooth etc. [1]. ITU has provided two standards to meet 4G IMT-Advanced requirements, these are LTE-Advanced (LTE-A) given by 3GPP and WirelessMAN-Advanced (WiMAX-Advanced) given by IEEE. IMT-Advanced is closer to 4g requirements as compared to IMT 2000. WiMax is based on wireless MAN technology. WiMAX is a wireless broadband technology that supports high speeds like WiFi to wide areas. It relies on the IEEE 802.16. WiMAX works in similar manner as WiFi but at faster speeds over larger distances [2]. The current 4G systems that are used widely by service providers are Evolved High Speed Packet Access (HSPA+), WiMAX and LTE. The latter two systems are pure packet based networks without the traditional circuit based capabilities. These networks provide voice services via VoIP (Voice over Internet Protocol) [1]. 3GPP launched LTE in its Release 8 as the successor of Universal Mobile Telecommunications System (UMTS) in November 2004. The LTE standard has been finalized with Release 9 of 3GPP as its final version, however, improvements provided by LTE are not sufficient. Hence, 3GPP continues to work on further advancements of LTE. The improved versions of LTE like LTE Release 10 and beyond, which are under development, are called LTE-Advance. LTE-Advance is able to fulfill the given requirements. Here, not only the throughput has been dramatically increased but also latency greatly decreased as compared to early mobile packet services. LTE network architecture is based on packet switching services and hence it offers a seamless internet protocol IP between User Equipment (UE) and Packet Data Network (PDN) without any interference or disturbance to users even in moving state. This is called all IP protocol [3]. The all IP protocol is the evolution by the 3GPP system to fulfill the increasing demands for high data rate. This type of protocol system provides a convenient access system for various networks along with provisions for guarantee of user satisfaction, system latency and low cost. The requirements specified by 3GPP for LTE are summarized below:

- High data rate of 100Mbps in the downlink(DL) and 50 Mbps in the uplink(UL) [4].
- Improvements in Spectrum efficiency and scalable bandwidth.
- Easy and simple interfacing with existing 3GPP and non-3GPP systems.
- Cost effective migration towards LTE.
- Reduced CAPital EXpenditure (CAPEX) and Simple architecture that allows a lower OPerational EXpenditure (OPEX).

A. LTE Architecture

Architecture of LTE consists of User Equipment (UE), evolution of the radio access network Evolved-UTRAN (**E-UTRAN**) and a Non Radio Access counterpart knows as System Architecture Evolution (**SAE**), which comprises the Evolved Packet Core (EPC) [6]. The relationship between the UE, E-UTRAN and the EPC is shown in Figure 1. A broader view is shown in figure 2.

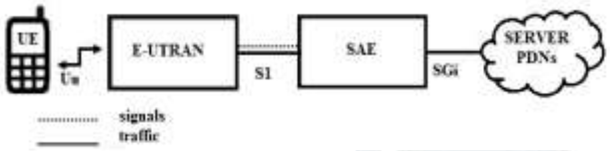


Figure 1: LTE Architecture components [5].

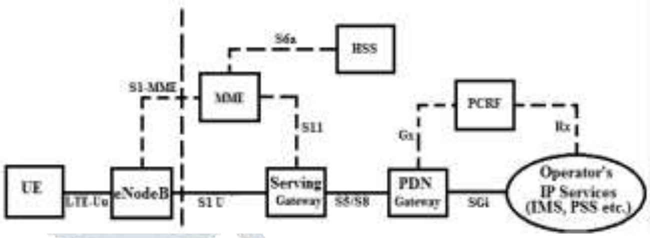


Figure 2: The EPC architecture Interfaces [6]

Various components of LTE architecture are explained below:

(1) The User Equipment (UE): UE represents mobile equipment which could either be cellular phone, a laptop or any other device that can be used for wireless communication. It consists of a mobile terminal (MT) to transmit and receive signals, a Terminal Equipment (TE) to terminate the data streams and UICC also called SIM that run an application called as USIM which is used by SIM part of UE to store information of user like phone number, home network identity and security keys [7].

(2) Evolved-UTRAN (E-UTRAN): E-UTRAN handles the radio communication between UE and EPC. It is also referred as LTE access network. It performs radio related functions within the network like Radio resource management, Header compression, Security, Positioning and EPC connectivity. It consists of base stations called eNodeBs that control the activities of UE and EPC and are interconnected through an interface known as X2 and are connected to EPC via S1 interface. eNodeB coordinates the sending and receiving of radio packets between UE and EPC using the analog and digital signal processing functions in its interface. It also handles various UE low level operations like handover. Figure 3 gives the fundamental structure of the access network of LTE E-UTRAN. Various connections in E-UTRAN are done using following interfaces:

(i) X2 interface: It is used in connection between eNodeBs, and also performs handover preparations and eNodeBs' neighbourhoods maintenance. The E-UTRAN can be considered as a mesh of eNodeBs basically connected via X2 interfaces. This interface can be used for interference management aiming at improvement in inter-cell interference [8].

(ii) S1-MME interface: It acts as the reference control node protocol between MME and E-UTRAN.

(iii) S1-U interface: It acts as the connecting interface between E-UTRAN and responsible S-GW.

(3) The Evolved Packet Core (EPC): EPC is responsible for overall control of the UE and establishes the bearers. It is also known as Core Network (CN). It consists of three logical nodes named P-GW, S-GW and MME. Also, it has some supporting nodes like HSS, PCRF etc. Figure 4 shows the structure of EPC and its connection with RAN (E-UTRAN).

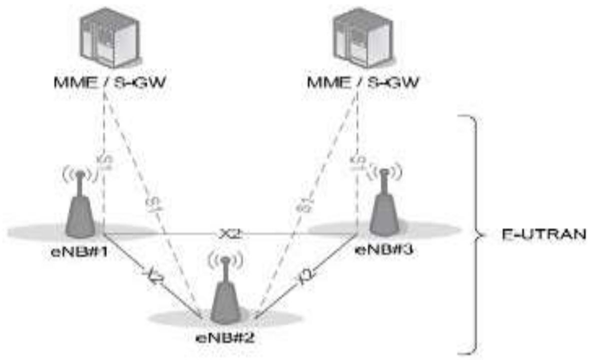


Figure 3: E-UTRAN architecture [9]

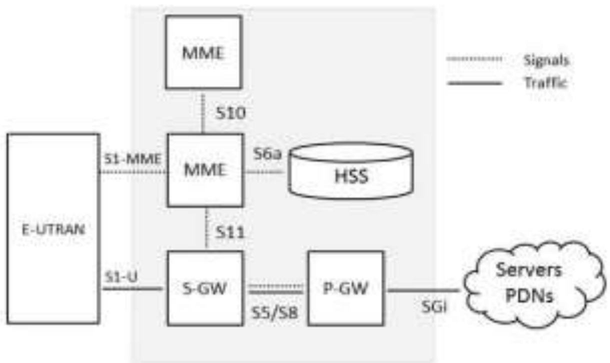


Figure 4: EPC Connection

(4) The Evolved Packet Core (EPC): EPC is responsible for overall control of the UE and establishes the bearers. It is also known as Core Network (CN). It consists of three logical nodes named P-GW, S-GW and MME. Also, it has some supporting nodes like HSS, PCRF etc. Figure 4 shows the structure of EPC and its connection with RAN (E-UTRAN).

Various EPC nodes are described below:

(i) **PDN Gateway (P-GW):** P-GW helps to communicate with outside world using SGi interface. It provides IP connections to UEs and allocates IP addresses to them. It helps EPC to perform the required QOS by IP filtering for individual traffics on the basis of report of PCRF on downlink side. P-GW serves as bedrock for other non-3GPP technologies to co-exist with LTE.

(ii) **Serving Gateway (S-GW):** S-GW behaves as a router between LTE RAN and PDN gateway (P-GW) by forwarding data between them. It plays its role as mobile anchor between EPC & LTE RAN and inter-connectivity with other 3GPP GSM and UMTS. It also keeps information about the volume of data sent or received in and data charges at the visiting network. Information stored by the S-GW is used by MME to re-establish an idle UE during UE reestablishment at the downlink side. When UEs' bearers refer to the IP packet, it defines the Quality of Service (QOS) between the User Equipment (UE) and the Gateway (GW). It makes resource allocation on the basis of requests from the MME, P-GW and/or PCRF.

(iii) **Mobility Management Entity (MME):** MME is the main control node in EPC. It controls signalling between UE and EPC by controlling Non-Access Stratum (NAS) protocol which is a high-level operation between the UE and the EPC. It is also responsible for idle state, security and EPS bearer control. It manages the subscription profile and service connectivity. User location can be tracked using MME in form of security and various paging procedure.

(iv) **Home Subscriber Support (HSS):** HSS acts as the central database server for the LTE that contains information for the home users like information related to identity and subscription. Function of HSS is same as HLR plays in the 3G technologies.

(v) **Policy and Charging Rules Function (PCRF):** Mainly three vital functions are performed by PCRF - policing, decision making for the EPC and control of the flow-based charging functionalities. It is also responsible for the control of QOS of UE and it reports for the same to P-GW and S-GW.

(vi) **E-SMLC:** The E-SMLC manages all the coordination and resource scheduling that is needed for UEs' locations in connection with the E-UTRAN. The final location is estimated on the basis of calculated values from the E-SMLC and it estimates for the UE speed and accuracy level.

B. Multiple Access Techniques Used In LTE Network

LTE networks offer multiple access transmission mainly based on Frequency Domain multiplexing. LTE network uses Orthogonal Frequency Division Multiple Access (OFDMA) for downlink transmission and Single Carrier Frequency Division Multiple Access (SC-FDMA) for uplink transmission.

(1) OFDMA: LTE networks use OFDMA technique in downlink transmission section to access broadband wireless system in 4G. This technique combines TDMA and FDMA and allocates fraction if system bandwidth to each user in each specific time slot. It guarantees better spectral efficiencies and better resource scheduling based on frequency responses and channel time.

OFDMA uses smaller frequency bands dedicated to sub-carriers. These are transmitted at low power, unlike full transmission of whole frequency band. The whole spectrum is divided into series of uniform narrowband subcarriers orthogonal to each other. Each sub-carrier is spaced at 15 KHz. Figure 5 and 6 show a comparison between FDM and OFDM [10].

Figure 5: Frequency Division Multiplexing [10]

Figure 6: Orthogonal Frequency Division Multiplexing [10]

(2) SC-FDMA: LTE uses SC-FDMA for multiple transmissions at uplink side. This technique combines advantages of OFDM with multi path resistance for uplink transmission. One basic advantage of SC-FDMA is power management in UE during uplink transmission. OFDMA has advantage over SC-FDMA of better utilization of the available narrow band, on the other hand, SC-FDMA is less sensitive to the channel frequency-selective fading than OFDMA. This is due to its ability to spread each modulated symbol across the total channel bandwidth. Other advantage of SC-FDMA is its low PAPR.

C. LTE Frame Structure and Resource Block

The LTE frame structure contains 10 sub-frames of 1ms each in time domain. There are two slots of 0.5 ms for each sub-frame and each slot contains seven OFDM symbols as shown in figure 7. In LTE, resources are arranged in 2-dimensional Resource blocks (RBs). One RB contains 12 subcarriers and 7 OFDM symbols forming 84 resource elements. Hence, one RB occupies one time slot and a bandwidth of 180 MHz. RBs are assigned to user dynamically on the basis of available resources and channel state. Figure 8 shows an illustration of a resource element..

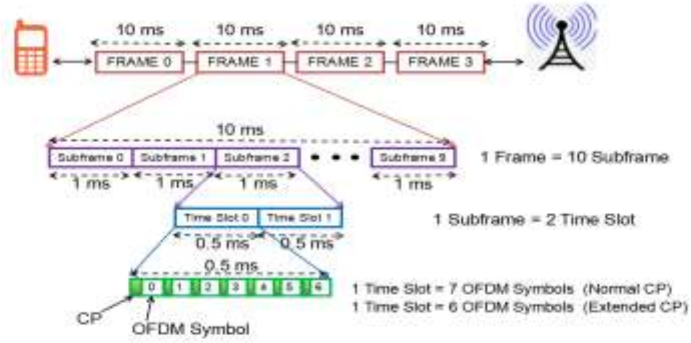


Figure 7: Typical LTE Frame Structure

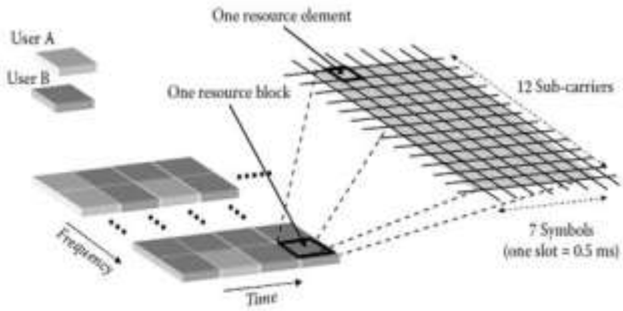


Figure 8: LTE resource element illustration.

D. LTE QOS Parameters

Quality of Service (QOS) was not available in 2G and 3G networks but LTE as all IP network, defines QOS to not only guarantee the quality of a service but it also supports different level services for other bit-rate sensitive applications. LTE has adopted a class-based QOS model called QOS Class Identifier (QCI) to ensure bearer traffic. The QOS parameters include QCI, ARP, GBR, MBR and AMBR. ARP is only used by admission control entity to decide whether a bearer establishment/ modification request can be accepted or not. In case of resource limitations, ARP together with PCI and PVI will decide which bearer to release. After bearer is established, scheduling in eNodeB is fully controlled by other parameters. QCI is a scalar that is used as a reference to a set of node-specific parameters such as Resource Type (RT), Priority (PL), Packet Delay Budget (PDB) and Packet Error Loss Rate (PELR), which control bearer level packet forwarding treatment. The MBR and GBR defined for GBR bearers must be set equal at thisstage. To non-GBR bearer, the AMBR includes APN AMBR and UE-AMBR. These AMBR values are defined separately for uplink and downlink, but we will not distinguish these four AMBR values in later sections [11].

(1) Bearer Types: a bearer is a virtual connection between the UE and the P-GW that determines the network configuration used to carry a set of user traffic. A bearer, commonly known as an EPS bearer, consists of three parts, the radio bearer between the UE and the eNB, the S1 bearer between the eNB and the S-GW, and the S5/S8 bearer between the S-GW and the P-GW. Upon UE connection for the first time, the LTE network assigns a default bearer along with an IP address to the UE. Default bearer cannot provide any QOS, only best effort is there. Hence, LTE network establishes additional bearers when higher QOS than best effort is needed to carry the user traffic. These are called dedicated bearers [12].

(i) **Granted Bit Rate (GBR) :** A GBR bearer sets a definite minimum bit-rate values to the traffic. Thus, packet flows through GBR bearer is shielded from congestion caused packet loss, causing it suitable for real-time services[14]. bearer for the transport of the IP packet flows with high priority (e.g. VoIP packets); it requires dedicated resources for the duration of the transmission and high data rate, delay and low error rates.[13]

(ii) **Non-Granted Bit Rate (Non-GBR) :** Non-GBR bearer offers no MBR guarantee. EPS bearer is also classified into default bearer and dedicated bearer. Default bearer is an automatically set-up non-GBR bearer once a UE is registered in an EPC. This bearer provides always-on connectivity to the outside PDN such as Internet[14]. GBR bearer cannot guarantee the availability of the resources allocated during the entire transmission, so it is established for applications that do not require particularly high bit rate[13].

(iii) **Default bearer:** bearer established during the UE attach procedure to the mobile network; it provides basic connectivity and it is suitable for transport of Best Effort traffic [13].

(iv) **Dedicated bearer:** bearer established after the default bearer if the IP packet requires specific QOS parameters and therefore a specific QOS treatment.[13]

(2) Bearer Parameters: QCI (Quality of Service Class Identifier) is a scalar used to manage functions (scheduling, queue management), relating to the forwarding of packets on a network. Each QCI is characterized by priority level, packet delay budget and acceptable packet loss rate. The set of standardized QCIs are shown in Table 1. Each bearer has an associated QCI Value [13]. It is highly important in LTE because it defines the packet forward treatment at each node, like scheduling weight, admission control priority, queuing threshold etc. **ARP (Allocation Retention Priority)** parameter is used for the management of priority in access procedures in case of cell congestion. Allocation and retention priority method is used to decide whether new bearer modification or establishment request should be accepted considering the current resource situation[13]. This supports to determine relative priority of a bearer over other bearers in case of congestion. **Maximum bit rate** parameter is used to specify the maximum bit rate supported by a bearer [13].

E. LTE Downlink Scheduling

An LTE network contains base stations called eNodeB and some user equipment (UEs) with a gateway. Network operator performs a basic packet scheduling in UE and eNodeB for uplink and downlink. The scheduling problem is to determine the allocation of RBs to a subset of UEs in order to maximize some objective function, for example, overall system throughput or other fairness-sensitive metrics. To reduce complexity, most schedulers operate in two phases: TDPS followed by FDPS. The

TDPS creates a SCS which is a list of users which may be allocated resources in the current scheduling period and the FDPS determines the actual allocation of RBs to users in the SCS. There are no scheduling specifications defined by 3GPP and it is left on service provider. Packet scheduling is basically a function of LTE Radio Resource Management (RRM). Main functionality of packet scheduling is to decide users that would transmit their data on the air interface. At eNodeB, packet scheduler allocates RBs to various active UEs. The design of packet scheduler must satisfy the QOS requirements, maximize the system capacity and provide a good fairness while allocating the available RBs. The diagram of a simplified packet scheduler is shown in figure 9.

QCI	**Resource Type**	**Priority**	**Packet Delay Budget (ms)**	**Packet Error Loss Rate**	**Example Services**
1	GBR	2	100	10^{-2}	Conversational Voice
2	GBR	4	150	10^{-3}	Conversational Voice (Live Streaming
3	GBR	3	50	10^{-3}	Real Time Gaming
4	GBR	5	300	10^{-6}	Non-conversational Video (Buffered Streaming)
5	Non-GBR	1	100	10^{-6}	IMS Signalling
6	Non-GBR	6	300	10^{-6}	Video (Buffered Streaming) ,TCP- Based Services (e.g. www, e-mail, chat, FTP, P2P file sharing, Progressive Video etc.)
7	Non-GBR	7	100	10^{-3}	Voice, Video (Live Streaming), Interactive Gaming.
8	Non-GBR	8	300	10^{-6}	Video (Buffered Streaming) ,TCP- Based Services (e.g. www, e-mail, chat, FTP, P2P file sharing, Progressive Video etc.)
9	Non-GBR	9	300	10^{-6}	Video (Buffered Streaming) ,TCP- Based Services (e.g. www, e-mail, chat, FTP, P2P file sharing, Progressive Video etc.)

Table 1: Standardized QCI characteristics [18]

Physical Downlink Control Channel (PDCCH) is the most important physical channel as the assignments for downlink resources and uplink grants are carried by this. The RBs are distributed to different UEs according to metric based on which the scheduler has been designed. For example, the *k-th* RBs will be allocated to *i-th* UE, if this UE has the biggest instantaneous metric among all other UEs. General requirements of a good scheduler are [15]:

(i) **Efficient link utilization**: Scheduler must take the advantages of multiuser diversity so as to utilize the channel efficiently.
(ii) **Delay bound**: Scheduler must guarantee delay bounds for individual flows in order to support delay-sensitive applications.
(iii) **Fairness**: To avoid flows with QOS overprovision certain level of fairness is required in the system.
(iv) **Implementation complexity**: Less complex algorithm require in high speed networks for scheduling decisions.
(v) **Isolation**: The algorithm should isolate a session from the ill effects of misbehaving sessions. The QOS guarantees for a session should be maintained even in the presences of sessions whose demands are in excess of their reserved values.
(vi) **Delay/bandwidth decoupling**: Delay is tightly coupled to the reserved rate in most of the schedulers, i.e., a higher reserved rate provides a lower delay.
(vii) **Scalability**: The algorithm should operate efficiently as the number of sessions sharing the channel increases. Moreover, the scheduler must be flexible enough to work well in different scenarios.

III. CARRIER AGGREGATION TECHNIQUE

LTE-A offers quite higher data rates than even its initial releases. However, the spectrum usage efficiency has been improved, but, this alone cannot provide the required data rates that are specified for 4G LTE Advanced. Spectral efficiency of LTE cannot be improved much beyond its current performance limit to meet the requirement of 1Gbps set by IMT-Advanced. Therefore, the only way to achieve such a high data rate is to increase the channel bandwidth. The method proposed for this is termed as carrier aggregation (CA). Carrier Aggregation is a widely used tool to provide bandwidth extension for high data rate transmission in LTE-advanced networks. It enables UE and Network to use more than one carrier frequencies by combining multiple carriers in same or different frequency bands. With this, resource allocation module has more flexibility in radio resource scheduling to users. Carrier aggregation (CA) is one of the most notable key features of LTE-Advanced which has been standardized in 3GPP as part of LTE Release 10. It allows scalable expansion of effective bandwidth provided to a user by proper utilization of radio resources across multiple carriers. These carriers may be of different bandwidths, and may be in the same or different bands to provide maximum flexibility in utilizing the limited radio spectrum available to operators. In the carrier aggregation, up to 5 component carriers can be aggregated. The term “component carrier” (CC) refers to any of the bandwidths defined in LTE.

A. Types of CA techniques

The creation of wider bandwidths has three options. **Intra-band contiguous CA** provides a contiguous bandwidth wider than 20MHz (Figure 10(a)). Here the carriers are adjacent to each other. The aggregated channel is considered as a single enlarged channel by user terminal. **Intra-band non-contiguous CA** combines multiple CCs belonging to the same band but in a non-contiguous manner (Figure 10(b)). This scheme can be used in conditions where spectrum allocation is discontinuous within a single band. **Inter-band non-contiguous CA** (Figure 10(c)) is the most general mode where multiple CCs belong to different bands.

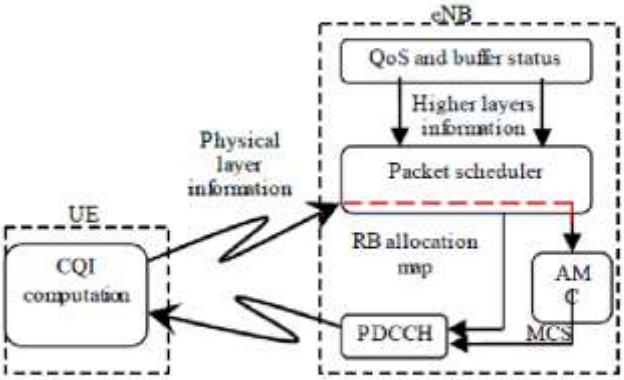


Figure 9: Simplified model of LTE packet Scheduler [16].

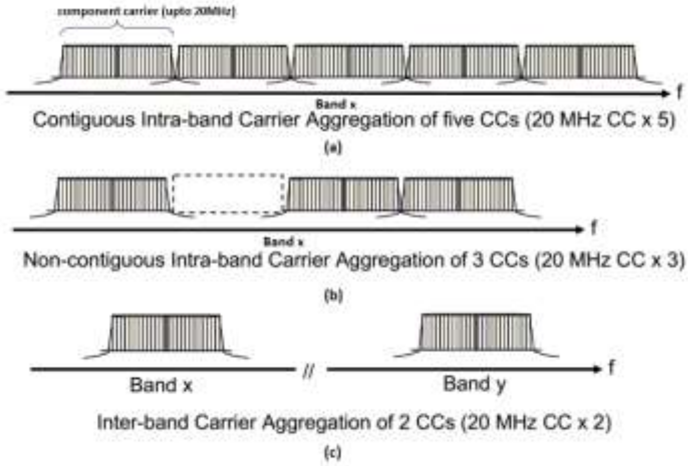


Figure 10: Types of carrier aggregation [17]

B. Carrier aggregation scheduling

A Carrier aggregation scheme must be capable to schedule the data across the component carriers in same or different band and also to inform the UE about DCI of different carriers. This information may be implicit or explicit depending on whether cross carrier scheduling is used or not. An association is created between a downlink component carrier and an uplink component carrier. When uplink grants are sent, UE will know that which uplink component carrier is to be applied. When cross carrier scheduling is active, PDSCH at downlink or PUSCH at uplink is transmitted on an associate component carrier other than the PDCCH. The carrier indicator in the PDCCH provides the information about the component carrier used for the PDSCH. To facilitate this, component carriers are numbered. There are twp type of CCs- Primary and secondary. Primary CC is given number zero in all cases and various secondary CCs are assigned with a unique number through RRC signalling specified by UE. This means that even if the UE, base station or eNodeB may have different understandings of the CC numbering, transmission on the primary component carrier can be scheduled.

C. Carrier Aggregation Deployment

There are four possible CA Scenarios for real LTE-Advanced deployment given below :

(1) Overlapped coverage: In this, Multiple CCs are aggregated over contiguous bandwidth and their areas are co-located as shown in figure 11.

(2) Different Coverage: In this, areas of multiple CCs are co-located but CCs have different coverage in cells due to different path loss as shown in figure 12.

(3) Cell Edge Beamforming: In this, CCs cover cell edges of different CC cells to increase cell edge throughput as shown in figure 13.

(4) RRH Integration: In this, macro coverage is provided with lower CC and coverage at hotspots with RRH (Remote Radio Heads) as shown in figure 14.

Figure 11: Overlapped coverage

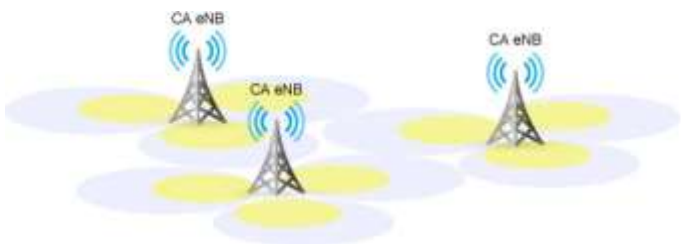


Figure 12: Different coverage

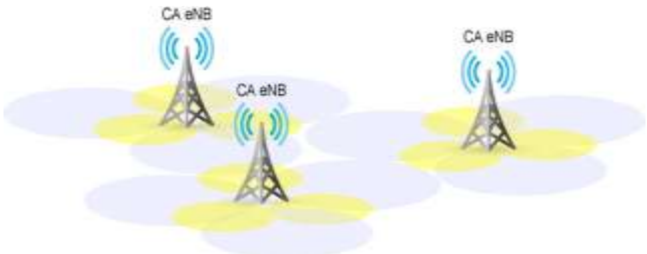


Figure 13: cell edge beamforming

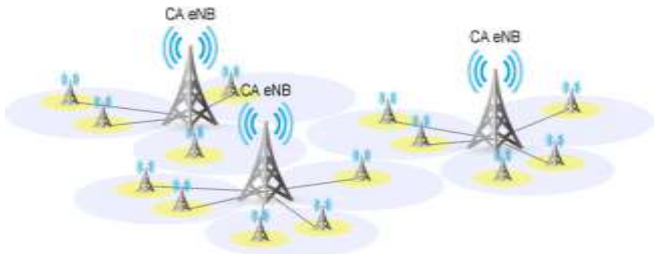
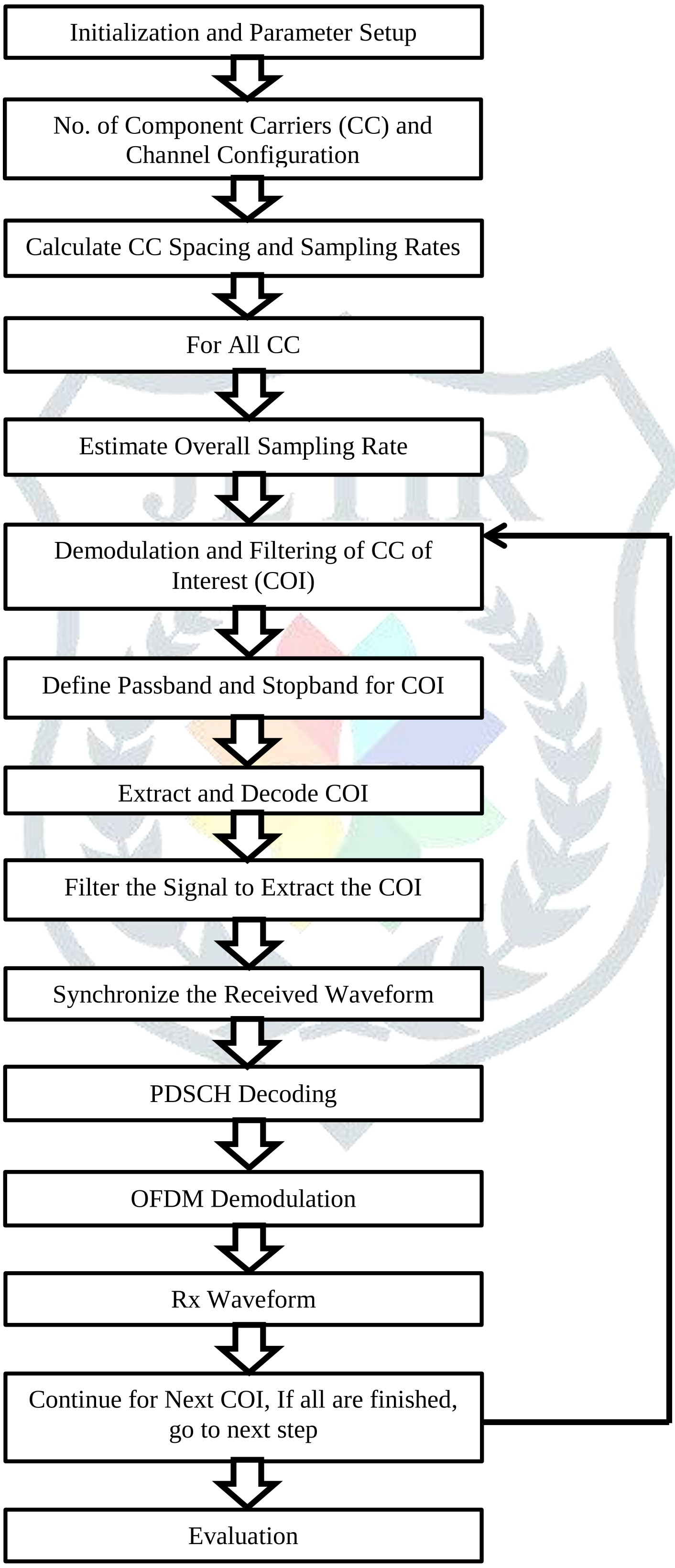


Figure 14: RRH integration

IV. EXAMPLE OF A CARRIER AGGREGATION SCHEME

Many scheduling schemes based on carrier aggregation have been introduced to improve the performance of 4G networks with a dedicated target of achieving requirements specified by IMT-Advance. Each scheme has its own merits and demerits. Here, we have introduced a CA scheme for downlink scheduling in LTE-A networks which specifically improves the throughput, average delay, average sojourn time and spectrum utilization, however, this scheme is slighter complicated to implement than commonly used CA schemes nowadays. Flow chart for this carrier aggregation scheme is given below:



V. CONCLUSION

With the rapid increase in number of wireless devices, we need highly efficient technologies for LTE-4G systems so that high demand of data rate and resource allocation can be fulfilled. Carrier aggregation is a good option for this purpose as it removes the basic restriction in LTE performance i.e. limited bandwidth. It manipulates the carriers to get required scheduling bandwidth by combining them and ultimately increases the channel capacity and spectrum utilization. This technique is superior to other scheduling techniques used. This technique has been deployed to produce bandwidth of 40MHz by combining two or three carriers and it is believed that algorithms will be developed in near future to get the high bandwidth of 100 MHz. Advanced carrier aggregation is used in Airtel 4G systems.

VI. ACKNOWLEDGMENT

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Abbreviations:

PDSCH :Physical Downlink Shared Channel
PUSCH :Physical Uplink Shared Channel
DCI :Downlink Control Information
RRC :Radio Resource Control
UTRAN : UMTS Terrestrial Radio Access Network
UICC : Universal Integrated Circuit Card
USIM : Universal Subscriber Identity Module

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