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LTE-Advanced – Interference Management in OFDMA Based Cellular Network: An Overview

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Abstract: From 1G in late 80s to 5G in 2019, revolutionary changes have been emerged in the telecom sector. Higher data rate, spectral efficiency and performance are the focusing areas. Radio spectrum is vital to cellular network and one of the most expensive and scared resource. It needs to be utilized efficiently and requires high level of manageability. An effective Frequency Reuse or Frequency Planning scheme ensures an efficient utilization of radio spectrum provides higher data rate increases coverage area expands network capacity and thus overall performance. Any increase by applying Frequency Reuse scheme may also lead to interference which significantly decreases the network performance. The paper overviews the requirements, standards and different kinds of interference and their management in LTE-Advance cellular network which more or less are the fundamental of 5G technology.

Keywords: Radio Spectrum, LTE-Advanced, Frequency Reuse, Interference Management, 5G.

I. INTRODUCTION

Due to immense increase in the number of mobile devices like smart-phones and other mobile and internet related gadgets for improved user experience, there is always a need of high bandwidth and capacity wireless network to serve them [1]. Enormous amount of devices and their demand of connectivity with high speed data on the go are the upcoming challenges for the cellular industry. The cellular industry is combating with this challenge. It is expected that in near future a significant increase in the number of mobiles, internet users and IOT (Internet of Things) enabled devices with a demand of response rate at the blink of an eye.

A cellular standard termed as Long-Term Evaluation or LTE which was standardized in release 8 by 3GPP (3rd Generation Partnership Project) [2] came in 2008 to achieve capacity and performance of the cellular network by keeping in view the future challenges of cellular industry. 3GPP introduced LTE as 4G mobile communication technology which is based on the Orthogonal Frequency Division Multiple Access (OFDMA) technology [3]. In release 10, Long-Term Evaluation – Advanced (LTE-Advanced or LTE-A) was standardized to achieve even higher speed and performance of mobile network [4]. For the achievement of key goals of LTE-A like high data rate, maximum bandwidth and advancement in spectral efficiency, OFDMA was introduced for the downlink air interfaces [5]. OFDMA system is capable enough to provide a scalable bandwidth and higher spectral efficiency and offers a high capacity bandwidth in limited available spectrum. OFDMA adopts number of techniques to enhance the overall system performance.

The allocated spectrum band to the mobile companies is limited and high cost therefore, the bandwidth divided into sub-bands and allocated to a cell and then re-used in another cell but in different clusters to mitigate performance related challenges [6]. The LTE-A OFDMA based cellular network has the ability to mitigate the spectral limitations by applying an effective Frequency Reuse (FR) technique. FR enables the cellular companies to reuse same set of frequencies at spatially separated locations after certain distance to increase network performance, efficiency and throughput. It also allows an increase in the network coverage area and simultaneously handling a huge traffic volume at certain point of time or peak time. Each Base Station (BS) is allocated a unique group of radio channels also called frequencies to be used for a particular geographical region and that group of cells which are using a complete set of frequencies is called cluster. BS in the adjacent cells are allocated group of radio channels which are completely different in scheme than the other neighboring cells [7].

In this study we tried to explore LTE-A with the perspective to explore advance research opportunities for the evolution of 5G. An important aspect of massive peak data rates i.e. 20Gbps in 5G can be achieved with the availability of wider spectrum and extremely efficient utilization of frequencies and before moving on towards 5G technology and in-depth understanding of underlying 4G spectrum sharing is required. LTE-A uses MIMO (Multi-input Multi-Output) -OFDM whereas 5G uses Massive MIMO [8] and Scalable OFDM [9] as well as advanced spectrum sharing technology which makes spectrum utilization further efficient. Full realizable economic effect across the globe will be visible by 2035 that is estimated around $12 trillion worth of goods and services [10]. Since 5G spectrum in millimeter wave frequency range has lower reachability and range, updated cell and FR planning is required for rollout.

ROADMAP: Our study focuses on OFDMA based LTE-A cellular network. We mainly covered the requirements and standards of LTE-A network and further discussed Co-Channel Interference (CCI) and Adjacent-Channel Interference (ACI). The paper is organized as follows: Section II discusses the LTE-Advanced requirements. Standards are discussed in Section III. Section IV covers Interference Management and the paper is concluded in the last section.

II. LTE-ADVANCED REQUIREMENTS

LTE-A in comparison with 4G technology, is experiencing a huge number of customers and devices to serve where users are expecting high speed internet connection for HD media streaming, better call quality, less battery consumption and adoptability for large number and variety of IOT devices. 3GPP keep on working with new standards and they are being added in every new release. LTE was introduced in release 8 in 2008 and later LTE-Advance standardized in release 10 and was released in early 2012, with many advanced features that distinguish this technology from LTE. Efforts were put-in to develop a cellular system that is spectral and bandwidth efficient, with an increase in data throughput, flexibility in spectrum allocation and better coverage on cell's edges. Table 1 illustrates the LTE-A technical requirements.

TABLE I. LTE-ADVANCED REQUIREMENTS

Technical Item	Requirements
Downlink (DL) peak data rate	1 GBPS - Maximum performance at <= 15 km/hr mobility
Uplink (UL) peak data rate	0.5 GBPS - Maximum performance at <= 15 km/hr mobility
Scalable Bandwidth	Scalable up to 20-100 MHz
Transmission Bandwidth	100 MHz DL and 40 MHz UL
Planned user latency	10 ms
Planned control latency	50 – 100 ms
Mobility	Optimum performance: <= 15 km/hr High performance: up to 120 km/hr Sustain connection quality up to 350 km/hr
Capacity	Up to 600 active users per cell
Coverage	5 km cell area using micro cells
Multiple Access scheme	OFDMA
Compatibility	Backward compatibility with 3GPP legacy system

III. LTE-ADVANCED STANDARDS

In today's communication era, satisfying high data rates demand within the limited resources has become a core issue [11]. For the improvement of user experience, data rate, efficient utilization of spectrum and to meet LTE-A requirements defined in release 10 and onward, several aspects were considered while standardizing LTE-A and mainly they are: Carrier Aggregation (CA), Multiple-Input Multiple-Output (MIMO), Inter-Cell Interference Coordination (ICIC), Coordinated Multipoint (CoMP) transmission for downlink, Licensed Assisted Access (LAA) and Radio Resource Management (RRM).

A. *Bandwidth Widening*

Bandwidth widening technology or CA introduced in release 10 which allows to combine multiple carriers simultaneously for higher data rate to a dedicated single user [12]. CA helps; to maximize peak data rate, to manage consistent and better Quality of Service (QoS) by balancing the load across the cell and enable interference management with intelligent allocation of resources by applying scheduler in RRM. The key concept of CA is to transmit data on two different bands simultaneously and CA is particularly important when assigning more bandwidth to User Equipment (UE) which eventually results in high data rate while spectrum is limited. In release 10, up to 5 carrier components can be aggregated each with 1.4, 3, 5, 10, 15 or 20 MHz [13] which allows an aggregated bandwidth of 100 MHz.

CA is a technique for de-fragmentation of spectrum and works for both Frequency-Division Duplex (FDD) and Time-Division Duplex (TDD) schemes and is done on contiguous and non-contiguous carrier components. CA is categorized into two main types: Contiguous Aggregation, Non-Contiguous Aggregation [14] as illustrated in Figure1.

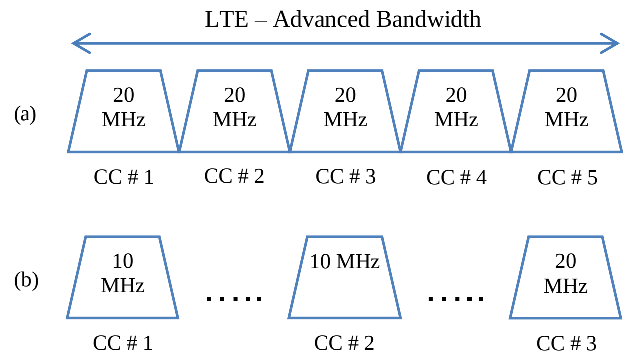

Figure 1 – Carrier Aggregation types;

a) Contiguous aggregation of five carrier components of equal bandwidth; b) Non-contiguous aggregation of three carrier components of different bandwidths

B. *Multiple-Input Multiple-Output (MIMO)*

MIMO is a special type of multiplexing used to increase data transfer by transmitting two or more different data streams on two or more different antennas simultaneously [15].

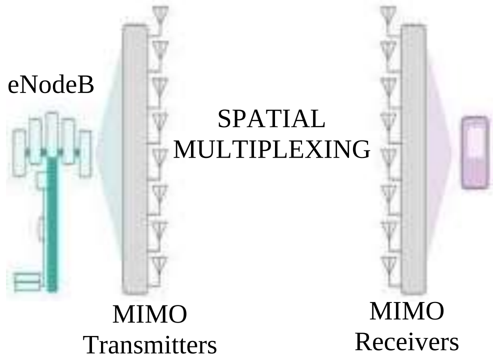

Figure 2 – 8x8 MIMO Formation

MIMO is a smart Multi-Antenna technology that enables the use of multiple antennas at transmitter's and receiver's ends and vitally important to achieve high data rate. LTE-A supports advance multi-antenna schemes like Beam-Forming [16], transmission diversity and spectral multiplexing [17]. Figure 2 illustrates an 8x8 MIMO formation.

In MIMO technology, data transmits through multiple antennas on the same path, therefore, there are less chances of data loss. In release 8, the maximum number of spatially multiplexed transmission signals was four and in release 10 the maximum number of layers in the downlink were extended to eight and support was initiated for a maximum of four MIMO layers in the uplink [4].

C. *Inter-Cell Interference Coordination (ICIC)*

FR schemes used in LTE network planning are optimized using ICIC method [18]. FR schemes are very effective to maximize the output from a limited available spectrum. However, reusing the same frequency channels on adjacent cells creates ACI particularly on the cell edges which drastically reduce the network performance. ACI is a big setback for overall network performance and it arises when transmission occurs on the same frequency bands in the adjacent cells simultaneously [19]. ACI decreases Signal-to-Interference Noise Ratio (SINR) specifically for the users located on the cell edges and relatively far away from their connected BS. In LTE-A, a transmitter side scheme ICIC has been introduced for interference avoidance. ICIC presents a practically feasible solution by applying restrictions on RRM operations with improved and favorable channel conditions for the users that are severely affected due to the ACI which eventually result in attaining high spectral efficiency [20].

D. *Coordinated Multipoint (CoMP)*

CoMP along with CA is the most important component in LTE-A which considerably increases the capacity and performance of the cellular network. In legacy cellular networks, one UE can only be served by a one particular BS to which that is connected and any other reception of signal from other BS(s) causes strong interference particularly when the user is in the cell edge area. Sometime the UE was about to move into another cell area and expecting handoff operation and in this state the UE communicates with two BS at the same time and experiences very low data rate. This scenario becomes worst if UE is moving fast in the cell edge area.

CoMP technology is similar as a distributed MIMO in distributed nodes located on different location. Nodes are equipped with multiple antennas and capable to communicate or transmit and receive information from UEs. CoMP was considered as a solution for increased system capacity and throughput particularly on the cell edges where UEs encounter sever ACI due to applying conventional FR schemes. MIMO and CoMP schemes are effective to produce outputs from RRM processes and algorithms to achieve maximum possible resource utilization.

E. *Licensed Assisted Access (LAA)*

In 3GPP release 13, the standardization of LAA was initiated in two phases; Study Item (SI) phase and Working Item (WI) phase. The objective of SI phase was the feasibility study of LTE-A to enable LAA operation in the unlicensed spectrum while fulfilling the regulatory requirements. The SI concluded that LAA proposal is feasible and can fairly coexist with Wi-Fi and LAA networks, provided an appropriate channel access scheme is adopted such as listen-before-talk (LBT) [21]. A key objective of the project was to ensure a fair coexistence between LTE-A LAA and Wi-Fi [22].

LAA is an unlicensed 5 GHz band which offers in combination with available spectrum to increase performance, efficiency and speed of internet on mobile devices. LAA is implemented by applying CA with LTE-A licensed band and unlicensed 5 GHz band to provide higher data rate and better user experience. The proposed architecture is able to increase the overall throughput around 70% as compare to Wi-Fi use but still there is room for improvement [23]. The combination of licensed and unlicensed technologies is a key milestone towards the road to 5G technology where users would experience high data rate and outstanding QoS.

F. *Radio Resource Management (RRM)*

RRM is a system level management to control; CCI, radio resources and other transmission related techniques in wireless communication systems. RRM deals with multi-users and multi-cells related issues and consists of processes and algorithms for regulating system parameters like transmit power, resources allocation to users, beamforming through MIMO, DL and UL data rates, handover operation and error handling scheme etc. The primary objective of RRM is to observe, evaluate and allocate system resources to maximize the overall output through limited spectrum and available infrastructure as efficiently as possible [24].

IV. INTERFERENCE MANAGEMENT

LTE-A provides significantly higher throughput and quite efficient in spectral utilization as compared to any legacy cellular system. One technique that has been adopted in the modern cellular network to mitigate the limitation of spectral availability is FR. FR is a technique to reuse same set of available frequencies again and again within an operational area to overcome the limitation of spectral availability. Each BS in the network is assigned a group of radio channels to be used for a particular geographical region that is called cell and a group of cells which are using a complete set of assigned frequencies is called cluster. BS in the adjacent cells are allocated group of channels which are completely different in frequency from the neighboring cells [7].

There are different types of FR schemes which have been practically implemented and producing satisfactory results. However, any FR scheme which is practically possible to implement is always dominated by the interference. In cellular network, interference is the term which is used to describe the factors which affect the signals of the transmitter and lead to the overall performance of the system [25].

LTE-A standards ensure that the network must be capable enough to minimize all type of interferences. There are two main types of interferences encountered by a cellular network that are required to be addressed to maintain the QoS of the system. The two types are: CCI and ACI. Same Frequency channels allocated to multiple cells that are spatially separated cause CCI. ACI is caused due to the signals that are adjacent in frequency. Any kind of interference reduces the SINR which ultimately reduces the QoS and overall network performance [26]. Users who are particularly located on the cell edges suffer the most as they are in the range of two BSs at the same time.

There are some other type of interferences which also deteriorate the QoS and overall network performance. These types include scattering, reflection, fading, multi-path and Doppler effects. These interference effects cater for by simple signal processing techniques at receiver end and don't require as much planning as required by CCI and ACI.

A. *Co-Channel Interference Management*

CCI cannot be overcome by increasing the transmit power just like reducing the thermal noise as it will increase power on all co-channels cells and net impact will be more interference. Interference management is heavily dependent on the cells and clusters planning.

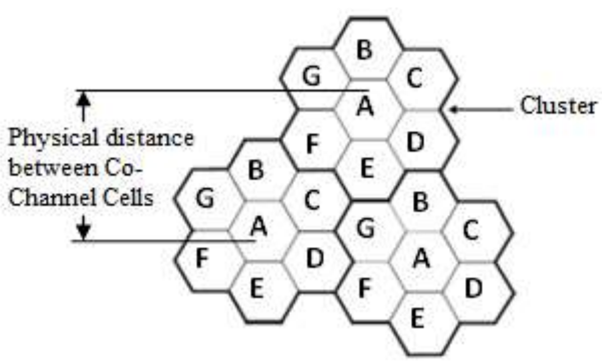

Figure 3 – Cluster of Cells

The distance between two cells using same set of frequencies must be sufficient enough to keep CCI into an acceptable threshold level. The cells in a cluster using the same set of frequencies are illustrated in Figure 3 and are outlined in bold. Each cluster consists of a typical size of 7 *(N)* cells, hence called 7 cells cluster. Two cells assigned the same set of frequencies in specific coverage areas or cells are called Co-Channel Cells. To determine a cluster size for FR, following formula is used:

$N = i^2+ij+j^2$ *(where i and j are non-negative integers).*

From geometry of grid of hexagons, there are two steps involved in the formation of cluster. 1: move *i* cell along center of any hexagon direction and 2: turn 60 degree anti-clockwise and move *j* cells as shown in Figure 4.

CCI is the key challenge while implementing FR schemes and is the major limiting factor for performance evaluation of the system. CCI is categorized as one of the major obstacle when talk about increase in the system capacity, higher data and QoS. Capacity of a mobile network is directly proportional to the CCI. The only way-forwarded to keep CCI into an acceptable range is to maintain a minimum distance to keep co-channel cells spatially separated.

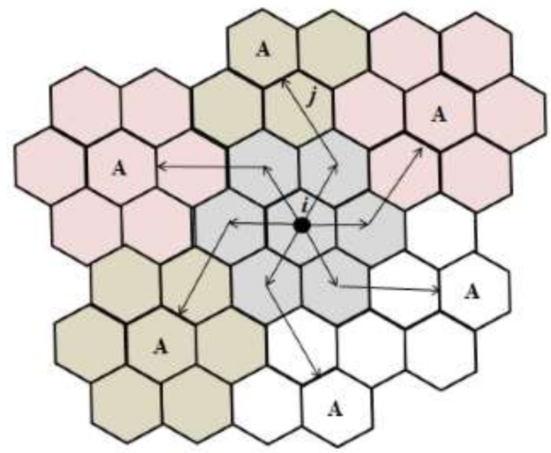

Figure 4 – 7 Cells Cluster Formation

A cellular network for which subjective tests indicate that sufficient voice quality is provided when S/I (Signal to Interference) ratio is greater than or equal to 18 dB. In Figure 5, it is illustrated a worst case CCI in which a UE (X) is located on the edge of the cell in a seven-cell cluster (N = 7). The UE location is D (Distance) – R (Radius) from two nearest co-channel interfering cells and D + R from other two relatively away cells and D from the remaining two cells, and all cells are using same set of frequencies and are from first tier.

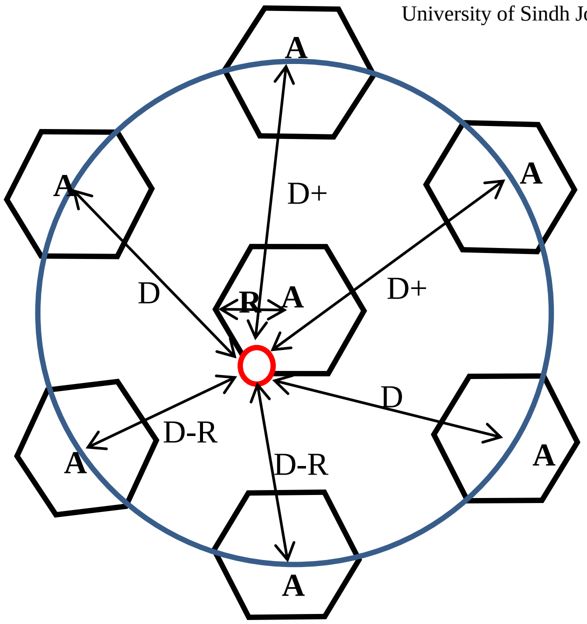

Figure 5 – Co-Channel Interference (First Tier)

For the worst case scenario, where n=4 (path loss exponent in urban area) the S/I ratio as:

$$\frac{S}{I} = \frac{R^{-n}}{2(D-R)^{-n} + 2(D+R)^{-n} + 2D^{-n}} \qquad (1)$$

Equation 1 can also be rewritten in terms of co-channel reuse ratio q (which is already known) as:

$$\frac{S}{I} = \frac{1}{2(q-1)^{-n} + 2(q+1)^{-n} + 2q^{-n}} \qquad (2)$$

Where:

q= 4.58 for seven-cell reuse pattern (N=7).

Substituting q in Equation 2 we get S/I = 53.24 or 17.26 dB. The seven-cell cluster yields S/I ratio slightly less than 18 dB which is necessary to maintain the required voice call quality and overall network stability.

To attain a minimum required 18 dB, cluster size (N) is required to move to the next cluster size from the Table 2 which is 9 therefore, q= 5.20 for nine-cell reuse pattern (N=9) and that would yield S/I = 95.09 or 19.78 dB.

A significant decrease can be observed in capacity as spectrum utilization would be 1/9 for each cell previously which was 1/7 in seven-cell cluster. When the cells' size is identical in a network and BS transmitting same power, CCI becomes independent of transmitting power and can only be controlled by the function of radius *(R)* of the cell and distance *(D)* between two co-channel cells. By increasing D/R ratio, the spatial distance between the cells increases and any interference reduces. Co-channel reuse ratio *(Q)* is dependent on cluster size *(N)*.

TABLE II. CO-CHANNEL REUSE RATIO - CLUSTER SIZE (N)

Cluster Formation	Cluster Size (N) $N = i^2+ij+j^2$	Co-Channel Reuse Ratio (Q) $Q = \frac{D}{R} = \sqrt{3N}$
$i = 1,\ j = 1$	3	3
$i = 1,\ j = 2$	7	4.58
$i = 0,\ j = 3$	9	5.20
$i = 2,\ j = 2$	12	6

As shown in Table 2, a small value of Co-Channel Reuse Radio (Q) provides and larger capacity, since the cluster size (N) is small and any large value of Q improves in the transmission quality due to the reduced level of CCI.

B. *Adjacent-Channel Interference Management*

ACI results from signals that are adjacent in frequency of the desired signals. The simplest and basic method to avoid ACI is use filtering at receiver end. Since, filter designs also have limitations and cannot exceed above certain threshold level, therefore further channel assignment scheme is required. One way could be addition of guard bands of frequency between adjacent channels but that is highly inefficient utilization of the spectrum. Therefore, it has not been discussed in this paper.

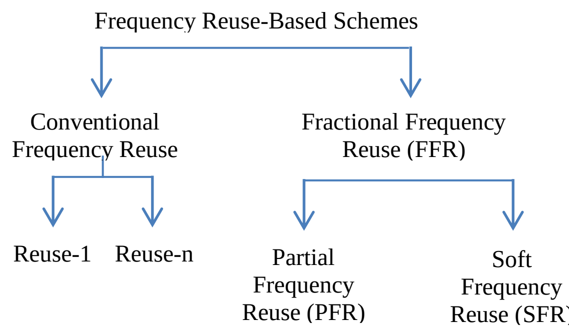

Figure 6 – Frequency Reuse Based ACI Avoidance Schemes

Other more efficient ways of channel assignment based FR schemes to avoid ACI are; 1: Conventional FR and 2: Fractional Frequency Reuse (FFR) both flavors come with some of their sub categories shown in Figure 6.

1) *Reuse-1*

A Reuse-1 scheme is the simplest approach in which all cells in a cluster use complete spectral channels assigned to a cellular network with equal power and all Resource Block (RB) are available for allocation to the users. Reuse-1 scheme is ideal for attaining peak data rates but high ACI is also observed on cell edges.

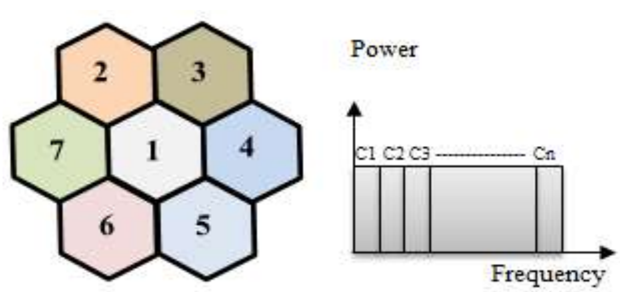

Figure 7 – Reuse-1 Scheme

Figure 7 illustrates Reuse-1 scheme in which all cells are transmitting complete available sub-carriers in same and full capacity. *C1, C2* and *C3* are sub-carriers assigned to cells. Entire bandwidth is utilized and reused in multiple cells. Reuse-1 approach is known for higher network capacity, data rate and spectrum efficiency [27]. But, on the other hand, this scheme also creates a considerable ACI especially for the users on the edges of the cells and, reduces over all QoS by reducing SINR.

2) Reuse-n

Reuse-n scheme provides improved interference avoidance by not deploying and same sub-carrier in the adjacent cells. Frequencies are reused at spatially-locations to avoid or maintain minimal ICI level. In this scheme, all available sub-carriers are divided into *n* and each cell is allocated specific non-interfering sub-carrier.

This scheme is useful to minimize any ACI between the cells. Figure 8 describes a complete spectrum divided into 3 (*n*) groups A, B and C and each group is allocated with same sub-carrier *C1, C2* and *C3*. *n* is called FR factor and can be written as $n = i^2+ij+j^2$, for $i, j \in$ N.

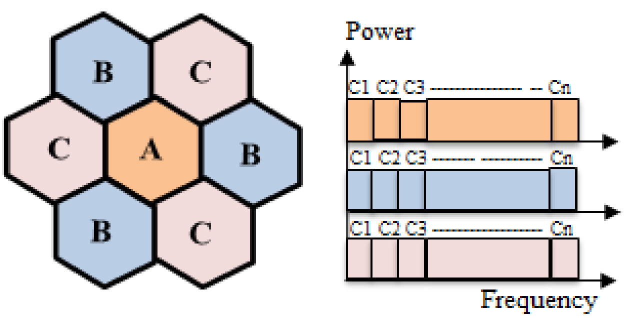

Figure 8 – Reuse-n Scheme

By increasing FR factor, ACI can further be reduced. However, interference avoidance comes at the expense of bandwidth [28].

3) Fractional Frequency Reuse (FFR)

A s discussed in the previous section, Reuse-n scheme is good enough to reduce ACI but it is not bandwidth efficient [29][30]. In FFR scheme where whole available spectrum is divided in two parts: one with FR factor 1 or Reuse-1 and the other one as Reuse-n where cluster size (N) is 7 and FR factor (n) is 3 [31].

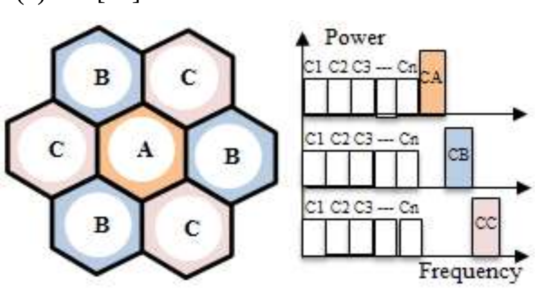

Figure 9 – Fractional Frequency Reuse – Full Isolation (FFR-FI)

In this scheme, Reuse-1 part is deployed in the center of the cell region which is in a form of circle and Reuse-3 part deploys on the edges of the cell as described in Figure 9. *C1, C2* and *C3* are sub-carriers assigned to inner cells and *CA, CB* and *CC* are assigned to cell edges. As a result of dividing available spectrum into inner and out regions of the cells, users inside the circle don't share spectrum with the users on the edges of the cell, therefore, this scheme minimizes the any ACI between cells [32]. This scheme is good enough to mitigate ACI but UEs on the cell edges are not able to utilize full spectrum and this is a major drawback of this scheme. This scheme also reduces the throughput of the network while implementing on cell edges.

4) Partial Fractional Frequency Reuse (PFFR)

PFFR is relatively new FR scheme which has the ability to nullify any interference in OFDMA network and gaining considerable attention. In FFR complete spectrum is utilized in the cell-center and on the cell edges [33]. Available spectrum is divided into two parts; Inner and outer. The inner part of the available spectrum is allocated, with a reduced power, to the users who are closely located in the cell-center near the BS. The allocation of spectrum in cell is done on Reuse-n FR scheme basis and completely used by the all BSs.

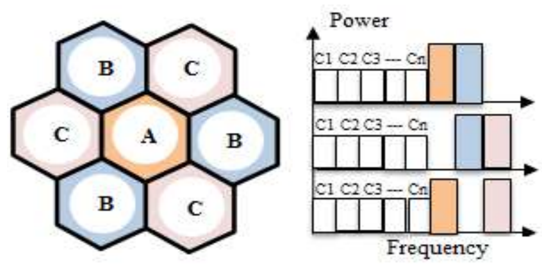

Figure 10 – Partial Frequency Reuse (PFR) One Interference Only (Worst Case)

For the users who are located on cell edges are allocated with the outer part of the spectrum with high power. The PFFR can encounter only one worst case scenario where the only outer channels can cause any ACI on the cell edge. The chances of such interference are 1/3 as channels are not allocated in sequence [29]. Figure 10 illustrates PFFR implementation on cell-center and cell edges.

5) Soft Fractional Frequency Reuse (SFFR)

This scheme derived key idea from FFR to apply Reuse-1 scheme in cell-center and Reuse-3 scheme on the edges with higher power. This scheme reduces CCI at the considerable level without losing the efficiency of spectrum. Figure 11 illustrates SFFR implementation. SFFR splits available spectrum into two parts i.e. cell-center or inner band or cell-out or outer band. Users inside the cell are group into two classes. Those who are in the circle or closer to the BS are grouped as inner users and those who are at the edges of the circle are grouped as out users.

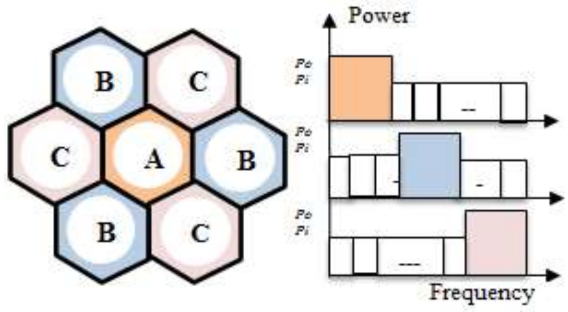

Figure 11 – Soft Fractional Frequency Reuse (SFFR)

As shown in the Figure 11, full spectrum is available inside the cell circle and only a limited portion is available

on the cell edges. BS transmits higher power to the cell edges and low power to the cell circle [34]. The cell edge users are restricted to use only the outer band and cell-center users have the exclusive access to the inner band but they also have the access to the outer band with low priority.

VI. Conclusion

This study presents a review on LTE-A cellular system based on OFDMA technology. Several aspects were considered while standardizing LTE-A like: Carrier Aggregation (CA), Multiple-Input Multiple-Output (MIMO), Inter-Cell Interference Coordination (ICIC), Coordinated Multipoint (CoMP) transmission for downlink, Licensed Assisted Access (LAA) and Radio Resource Management (RRM) and by applying said components LTE-A has become capable enough to mitigate CCI and ACI. Beside LTE-A components discussed earlier, implementing FR requires a very deep level of understanding to manage interferences. In this study, we have also reviewed five types of FR schemes i.e. Reuse-1, Reuse-n, Fractional Frequency Reuse, Partial Fractional Frequency Reuse and Soft Fractional Frequency Reuse with the reference to their reuse patterns to keep any interference within an acceptable level. Frequency planning is a fundamental part of cellular network design and it's a tradeoff between overall cost of the network and effective planning.

This study will form the basis to explore advance research opportunities for evolution of in upcoming 5G technology. The most important aspect of massive data rates (peak rates of 20Gbps) possible for 5G is the availability of wider spectrum and extremely efficient utilization of frequency channels. Before moving on towards research areas of 5G, deep understanding of underlying 4G spectrum sharing is required. LTE-A uses MIMO-OFDM whereas 5G uses Massive MIMO and Scalable OFDM as well as advanced spectrum sharing technology which makes spectrum utilization further efficient. Full realizable economic effect across the globe will be visible by 2035 that is estimated around $12 trillion. Since 5G spectrum in millimeter wave frequency range has lower reachability and range, updated cell and FR planning is required for rollout. This paper provides basis for researchers to deeply understand OFDM based spectrum utilization and FR schemes which can be used to implement in 5G based network rollout planning.

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