



Survey paper on frequency reuse schemes for enhanced 5G spectrum management

Aji Jacob Onu¹, B O Omijeh², I Uchendu³

¹ Centre for Information and Telecommunication Engineering, University of Port Harcourt, Rivers State, Nigeria

² Professor, Department of Electrical/Electronic Engineering, University of Port Harcourt, Rivers State, Nigeria

³ Department of Electrical/Electronic Engineering, University of Port Harcourt, Rivers State, Nigeria

Abstract

The growing demand for wireless communication services has resulted in a growth in the number of connected devices and data-intensive applications, putting enormous strain on the available radio frequency spectrum. The development of efficient spectrum management strategies is critical for addressing the difficulties of spectrum scarcity and interference in modern wireless networks. This survey article provides an in-depth examination of the state-of-the-art in frequency reuse methods, with a focus on novel approaches that improve spectrum management. The study's primary goal is to identify and evaluate alternative frequency reuse approaches offered to optimize spectrum utilization, decrease interference, and improve overall network performance. Subsequently, the survey delves into recent advancements and emerging frequency reuse schemes that address the limitations of traditional methods. These include adaptive frequency reuse, cognitive radio-based approaches, and software-defined networking techniques, among others. Each scheme is examined in terms of its key principles, benefits, and potential drawbacks. The evaluation encompasses key performance metrics such as throughput, spectral efficiency, interference mitigation, and overall system capacity. Furthermore, the paper discusses the challenges and open research areas in the field of frequency reuse and spectrum management. Promising directions for future research are identified, considering the evolving landscape of wireless communication technologies and emerging applications.

Keywords: Frequency reuse, congestion, interference, telecommunication network, 5G

Introduction

Hand-held wireless devices have become an indispensable part of our daily lives. The growing need for smartphones and tablets for applications such as live video meetings, group messaging, online gaming, and on-demand video streaming, as soon as, leads to a rapidly increase requirement for radio spectrum. Despite the increase in spectrum availability, which has evolved, the utilization of frequency in terms of resource management is very important in the deployment of telecommunications equipment and services. The efficient use of the available frequency will enhance user experience, and increase throughput and signal efficiency (Khandekar *et al*, 2010) ^[1]. With the current progress beyond the Fifth Generation (5G) communication systems, standards are required to support the coexistence of heterogeneous networks that provide effective wireless coverage to mobile subscribers and other wireless appliances in both indoor and outdoor environments when compared to other Generations of telecommunication technologies (from 1G to 4G) (Xu, *et al*, 2021) ^[2]. Because 5G operates at high frequency, which limits the distance it can cover, the denser space within a geographical area becomes congested thereby requiring efficient utilization of the available frequency resources to continue to improve service delivery by reducing interference and congestion. Hence, this calls for significant improvement in spectrum efficiency to support the increased number of users that will be using the same spectrum resource (Ahmad, *et al* 2020) ^[3]. In the process, the spectrum resource will then be reused more frequently, which will result in higher inter-cell interference. The need

for frequent usage of the frequency resource leads to frequency reuse. Frequency reuse is the method or scheme that requires the use of the same frequency band within a network in the geographical area in such a way that cells with the same frequency bands are placed far apart while cells with different frequency bands are placed adjacent back to back. Frequency reuse optimizes spectrum usage; enhances channel capacity, and reduces interference (Ahmad, *et al* 2020) ^[3]. The scheme for recycling or reassigning the frequency channels throughout the coverage area is referred to as a reuse plan (Asaka, 2021) ^[4]. The distance between cells in the same cluster using the same frequency channel is called reuse distance. The principal objective of the frequency reuse scheme is to ensure adequate channel isolation to reduce channel interference while maintaining a high channel capacity (Song, *et al* 2021) ^[39].

In this work, a detailed survey of the various approaches used in frequency reuse is examined to identify areas of improvement for the 5G communication system. This will provide more insight into the challenges of the current systems and directions for future frequency reuse techniques. The paper is structured as follows:

In Section II, a brief background of network layout showing the implementation of frequency reuse is presented. In section III, key performance indicators essential for analyzing each frequency reuse technique are presented as figures of Merit. In section IV, detailed analyses and critiques of each of the frequency reuse technique and their limitation for use in 5G systems are presented. We have emerging technology in section V and list of directions for

future work necessary for implementing an efficient frequency reuse scheme for 5G systems is presented in section VI, and the paper is concluded in section VII

Background to frequency reuse scheme

A crucial idea in contemporary telecommunications is frequency reuse, which enables many users to effectively share the limited radio frequency spectrum. Reusing the same frequency bands across several geographic areas is the notion underlying frequency reuse, if they are sufficiently apart to prevent interference as shown in figure 1 below. The idea of frequency reuse first came into being during the early stages of wireless communication, when the industry's expansion was seriously hampered by the limited supply of spectrum. Early wireless technologies were only capable of small distances and worked in a single frequency band (Bakare *et al* 2022) [6]. This restricted the number of users that could access the network at once and made it challenging to increase the network's range. Researchers came up with the notion of segmenting the frequency spectrum into various frequency bands or channels to solve this issue. They were able to expand the number of concurrent users who could use the network by doing this. Due to the possibility of several users transmitting on the same frequency band, this however also brought about the issue of interference, which reduced the quality of the signal and made it challenging to discern between different messages (Kufakunesu *et al* 2020) [7]. To overcome this challenge, Researchers developed the concept of frequency reuse, which involves dividing the network coverage area into smaller cells each using the same frequency band. Each cell is assigned a unique set of channels, which are carefully selected to minimize interference between adjacent cells. By reusing the same frequency band across different cells, the overall capacity of the network can be improved, allowing more users to access the network simultaneously (Sangaiah *et al*, 2022) [8]. In today's wireless communication systems, such as cellular networks, satellite communication systems, and Wi-Fi networks, frequency reuse is a basic idea. The tradeoff between the number of users or subscribers that is to be reached, the available frequency spectrum, and the desired quality of service (QoS) is carefully taken into account throughout the design stage of these systems. Frequency reuse has enabled the wireless industry to support billions of users globally while also enabling new applications and services that were previously unattainable by maximizing the use of the available spectrum (Song *et al*, 2021) [5].

Consider a cellular system

Total duplex channels = S

Cluster size = N cells

Number of channels in each cell: $k = S/N$ (1)

Capacity in a cluster: $C = kN = S$ (2)

If a cluster is replicated M times

Total capacity: $C = MkN = MS$ (3)

The capacity is increased by M.

In order to connect without gaps between adjacent cells

$N = i^2 + ij + j^2$ (4)

Where i and j are non-negative integers.

To find the nearest co-channel neighbor of particular cell, move i cells along any chain or hexagon. Then turn 60 degrees counterclockwise and move j cells (Sen, 2020) [10]

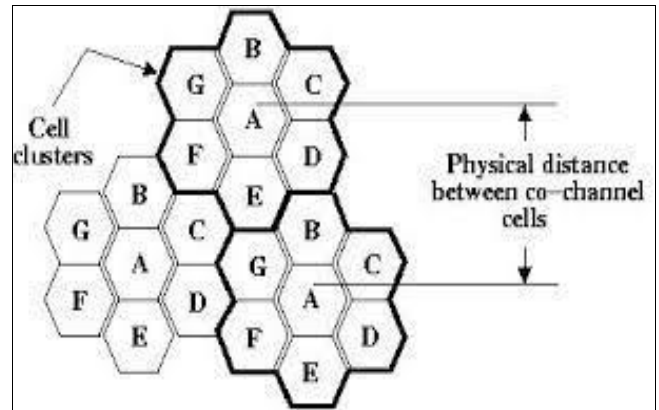


Fig 1: Frequency Reuse showing distance between cells (Datta Shingate 2018).

Figures of merit

The performance of frequency reuse can be evaluated using various figures of merit, including the following:

Signal-to-Interference-plus-Noise Ratio (SINR)

This measures the quality of the received signal relative to the level of interference and noise from other cells that use the same frequency band. A higher SINR indicates a higher quality of service representing fewer dropped calls lost data packets or interference. Interference is the major limiting factor in the performance of cellular radio systems (Gadre *et al*, 2020) [11]. Sources of interference include another mobile in the same cell, a call in progress in a neighboring cell, other base stations operating in the same frequency band, or any noncellular system that inadvertently leaks energy into the cellular frequency band. Interference on voice channels causes cross-talk, where the subscriber hears interference in the background due to an undesired transmission. On control channels, interference leads to missed and blocked calls due to errors in the digital signaling. Interference is more severe in urban areas, due to the greater RF noise floor and the large number of base stations and mobiles. Interference has been recognized as a major bottleneck in increasing capacity and is often responsible for dropped calls (Nnebe *et al* 2021) [12]. The two major types of system-generated cellular interference are co-channel interference and adjacent channel interference. Even though interfering signals are often generated within the cellular system, they are difficult to control in practice (due to random propagation effects). Even more difficult to control is interference due to out-of-band users, which arises without warning due to front-end overload of subscriber equipment or intermittent intermodulation products. In practice, the transmitters from competing cellular carriers are often a significant source of out-of-band interference, since competitors often locate their base stations near one another to provide comparable coverage to customers.

The SINR is affected by the distance between cells, the transmit power of each cell, and the modulation scheme used. The idea of SINR makes an effort to portray these features. In particular, for a receiver located at some point x in space (usually, on the plane), (Baccelli & Błaszczyszyn, 2010) [13] then its corresponding SINR is given by:

$$SINR(x) = \frac{P}{I+N} \tag{1}$$

The propagation (P) model leads to a model for the SINR (Haenggi, 2012) ^[14] considering a collection of N base stations located at points x_1 to x_n in the plane or 3D space.

Types of interference

Co-Channel Interference (CCI)

This occurs when cells that use the same frequency band overlap with each other and cause interference. The level of CCI depends on the distance between cells, the transmit power of each cell, and the modulation scheme used. A lower level of CCI is desirable, as it can improve the overall capacity of the network. Unlike thermal noise which can be overcome by increasing the signal-to-noise ratio (SNR), co-channel interference cannot be combated by simply increasing the carrier power of a transmitter (Carvajal *et al*, 2020) ^[15]. This is because an increase in carrier transmit power increases the interference to neighboring co-channel cells. To reduce co-channel interference, co-channel cells must be physically separated by a minimum distance to provide sufficient isolation due to propagation.

Signal to interference ratio (SIR, or S/I) for a mobile receiver is given by:

$$\frac{S}{I} = SIR = \frac{S}{\sum_{i=1}^{i_0} I} \tag{2}$$

S = desired signal power from designated base station

I_i = interference power caused by the i th interfering co-channel cell base station

i_0 = number of interfering co-channel cells

When the size of each cell is approximately the same and the base stations transmit the same power, the co-channel interference ratio is independent of the transmitted power and becomes a function of the radius of the cell (R) and the distance between centers of the nearest co-channel cells (D). By increasing the ratio of D/R, the spatial separation between co-channel cells relative to the coverage distance of a cell is increased (Kihero, *et al* 2021) ^[16]. Thus, interference is reduced from improved isolation of RF energy from the co-channel cell. The parameter Q, called the co-channel reuse ratio, is related to the cluster size.

Co-channel reuse ratio (Q)

$$Q = \frac{D}{R} \tag{3}$$

R = radius of the cell

D = distance between centers of nearest co channel cells

For hexagonal geometry, Co-channel Interference

$$Q = \frac{D}{R} = \sqrt{3N} \tag{4}$$

For any given antenna (base station) the power at a distance d is given by

$$P_r(d) = P_r(d^0) \left\{ \frac{d}{d^0} \right\} \text{ or } P_r(d)(dBm) = P_r d^0(dBm) - 10n \log \left\{ \frac{d}{d^0} \right\} \tag{5}$$

$P_r(d_0)$ = power receiver at a close-in reference point in the far field region of the antenna

d_0 = distance from the transmitting antenna to the reference point

n = path loss exponent (between 2-4 in urban cellular systems)

When different base stations transmit the same power, the SIR becomes:

$$\frac{S}{I} = SIR = \frac{R^{-n}}{\sum_{i=1}^{i_0} (D_i)^{-n}} \tag{6}$$

i_0 = number of first tier interfering co-channel cells

R = radius of the cell

D_i = distance of the i th interferer from the mobile.

Adjacent-Channel Interference (ACI)

This occurs when cells that use adjacent frequency bands interfere with each other. The level of ACI depends on the separation between frequency bands, the transmit power of each cell, and the modulation scheme used. It is the interference created by the signal that has the same frequency as the desired signal. Imperfect receiver side filters cause adjacent signals to mix with the genuine pass band (Janis, 2013). If the adjacent channel signal intensity increases, it will be difficult for the base station to distinguish between the true mobile signal and the strong mobile signal.

A lower level of ACI is desirable, as it can also improve the overall quality of service.

The following are the causes of adjacent channel interference:

1. Because several channels speaking on similar frequencies are close to each other.
2. A nearby channel emits insignificant power.

The following factors can help reduce Adjacent Channel Interference:

1. Filtering properly
2. Channel assignments must be made with caution
3. By controlling the space between two neighboring cells, which should always be the same.

Congestion

This measures the amount of traffic carried by each cell in the network. A higher cell load can lead to congestion and decreased quality of service, while a lower cell load may indicate underutilization of the available spectrum. Congestion in mobile networks can be caused by various factors, such as an increase in the number of subscribers, the use of data-intensive applications, or insufficient infrastructure investment (Rony *et al* 2021) ^[18]. LTE networks use various congestion control mechanisms, such as packet marking, queue management, and rate limiting, to ensure that network resources are allocated efficiently and fairly among users. Network designers aim to balance the cell load to ensure that the network operates efficiently without any bottlenecks. In mobile communications, congestion is a network condition when a node or link is carrying so much data that it could degrade network service quality, leading to queuing delay, frame or data packet loss, and the barring of new connections. Response time slows with decreased network performance in a congested network (Haile *et al* 2021) ^[19]. One formula that is often used to measure congestion in mobile networks is the Erlang formula, which calculates the number of channels or circuits required to handle a given amount of traffic at a certain level of service quality. The Erlang formula is used in network

planning and capacity management to estimate the number of channels or circuits needed to handle a certain amount of traffic and to ensure that the network can meet the required level of service quality without experiencing congestion (Danbatta & Dan-Isa, 2021) [20].

The formula provides the Grade of Service (GoS) which is the probability (Pb) that a new call arriving to the resources group is rejected because all resources (servers, lines, circuits) are busy: B (E, m) where E is the total offered traffic in erlang, offered to m identical parallel resources (servers, communication channels, traffic lanes).

$$P_b = (B, m) = \frac{\frac{E^m}{m!}}{\sum_{i=0}^m \frac{E^i}{i!}} \tag{7}$$

Pb = is the probability of blocking
 m = is the number of identical parallel resources such as servers, telephone lines and other elements.
 Offered traffic (in erlangs, E) is related to the call arrival rate, λ, and the average call-holding time (the average time of a phone call), h, by:

$$E = \lambda h \tag{8}$$

h and λ must be represented in the same time units.

Practical traffic measurement is often based on continuous observations over a number of days or weeks, with instantaneous traffic recorded at regular, short intervals (such as every few seconds). These measurements are then combined to yield a single result, most frequently busy-hour traffic (in erlangs). This is the average number of concurrent calls over a specified one-hour period of the day, chosen to yield the best results. (This is referred to as time-consistent busy-hour traffic). Another option is to compute a busy-hour traffic value for each day (which may correspond to somewhat different periods each day) and average these numbers. This usually results in a somewhat higher value than the time-consistent busy-hour figure (Pimpinella, *et al* 2022) [21].

To determine the Grade of Service of a specific group of circuits or routes, a series of assumptions based on the network losing calls when all circuits in a group were busy were used. These are the assumptions:

- All network traffic is pure-chance traffic, which means that all call arrivals and terminations are separate random events.
- There is statistical equilibrium, which means that the average number of calls remains constant.
- Network availability, that is every outlet from a switch is accessible from every input
- Any call that experiences congestion is dropped immediately.

Erlang established the Erlang-B formula, which describes the likelihood of congestion in a circuit group, based on these assumptions. The likelihood of congestion determines the Grade of Service received (Bohloulzadeh & Rajaei, 2020) [22].

Frequency reuse factor (FRF)

This is a measure of how many times a given frequency band can be reused within a particular geographic area. A

higher Frequency Reuse Factor means that more cells can be packed into a given area, which can increase the overall capacity of the network. However, increasing the Frequency Reuse Factor also increases the likelihood of co-channel interference (CCI) between cells.

Frequency reuse in cellular networks describes the usage of the same frequency band in other cells to expand the network's capacity. The number of cells that can utilize the same frequency band in a specific area is determined by the reuse factor as shown in Figure 3 below. For example, a reuse factor of 1 means that each cell uses a unique frequency band, while a reuse factor of 3 means that a given frequency band is reused every three cells. The capacity of the network may rise with a higher reuse factor, but interference between cells that use the same frequency band may also increase (Aljjakli, & Abdullah 2020) [23]. The reuse factor affects the quantity of frequency reuse. The design and optimization of dynamic frequency reuse systems depend greatly on the choice of reuse factor. The reuse factor, denoted by N,

$$N = D / R$$

Where D is the distance between adjacent cells and R is the radius of each cell.

In other words, based on the distance between neighboring cells and the size of each cell, the reuse factor is the maximum number of cells in a given region that can be assigned the same frequency band. More cells can use the same frequency band when the reuse factor is higher, which can boost network capacity but also increase cell-to-cell interference (Alshantti, 2021) [24].

Only a few cluster sizes and cell arrangements are feasible because each hexagonal cell has six equidistant neighbors and the line connecting the centers of each cell and each of its neighbors is separated by multiples of 60 degrees. The geometry of hexagons is such that the number of cells per cluster, N, can only have values that satisfy the following conditions:

$$N = i^2 + ij + j^2 \tag{3.9}$$

Where i and j are non-negative integers as shown in table 1 below.

Table1: Possible outcome of Reuse Factor

		j												
N		0	1	2	3	4	5	6	7	8	9	10	11	12
i	0	0	1	4	9	16	25	36	49	64	81	100	121	144
	1		3	7	13	21	31	43	57	73	91	111	133	157
	2			12	19	28	39	52	67	84	103	124	147	172
	3				27	37	49	63	79	97	117	139	163	189
	4					48	61	76	93	112	133	156	181	208
	5						75	91	109	129	151	175	201	229
	6							108	127	148	171	196	223	252
	7								147	169	193	219	247	277
	8									192	217	244	273	304
	9										243	271	301	333
	10											300	331	364
	11												363	397
12													432	

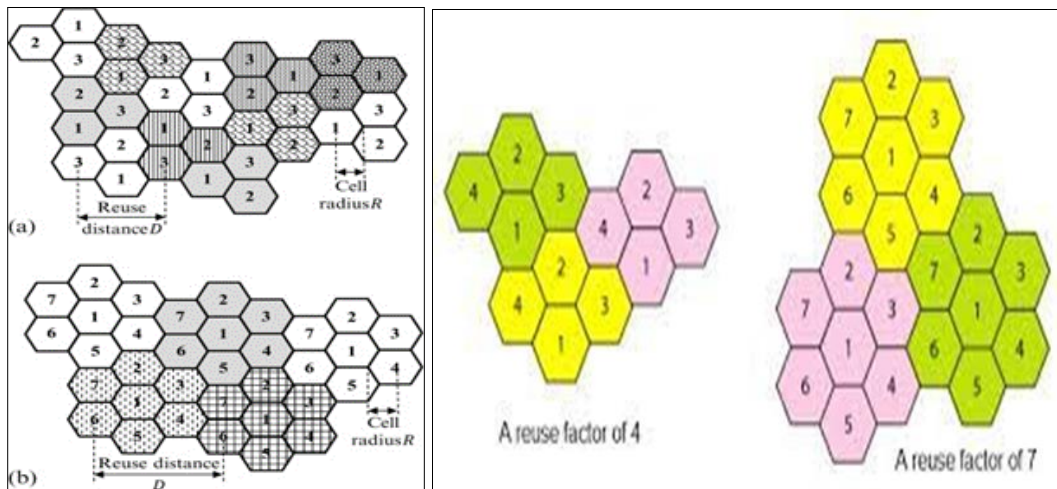


Fig 2: Reuse Factors of 3,4 and 7.

Spectral efficiency

This can be defined as the sum of the maximum average data rates per unit bandwidth per unit area supported by a cell's base station. Expressions for this efficiency as a function of the reuse distance for the worst and best case interference configurations are derived (Mukherjee *et al* 2021) [25]. Spectral efficiency is typically referred to as bits per second per hertz (bps/Hz).

$$\text{Spectral efficiency} = \frac{(\text{Capacity in bps})}{(\text{bandwidth in Khz})} \tag{9}$$

The amount of data transported over a given spectrum or bandwidth with the fewest transmission faults is referred to as spectrum efficiency. The spectrum efficiency of a cellular network, also known as bandwidth efficiency or spectral efficiency is the maximum number of bits of data that may be transmitted to a certain number of users per second while maintaining an acceptable quality of service. The number of people accessing the network concurrently influences spectral efficiency in wireless communications speeds (Tanwar *et al* 2022) [26].

The data transfer rate is determined by the bandwidth of the transmission device as well as the strength of the sent signal or signal-to-noise power ratio. Improved signal-to-noise ratio improves spectral efficiency and channel capacity. Simply said, more data must be transferred over the spectrum in order for it to be used efficiently (Ji *et al* 2020) [27].

Throughput

The actual amount of data that is successfully transferred or received across the communication link is known as throughput. A number of technical factors, like as delay, packet loss, jitter, and more can cause throughput, which is displayed as kbps, Mbps, or Gbps to differ from bandwidth (Taha, & Ali, 2023) [28]. Many variables, including channel width, guard interval time, symbol length time, number of bits per symbol, and coding rate, affect theoretical maximum throughput. Typically, Mobil Sub Station (MCS) determines the throughput (Modulation and Code Scheme). A communication system's throughput can be influenced by a variety of factors, including the constraints of the

underlying analog physical channel, the available computational capacity of the system components, end-user behavior, and so on. When various protocol overheads are considered, the practical rate of data transfer might be much lower than the maximum attainable throughput; the useful portion is called good put (Abbasloo, *et al* 2020) [29]. These figures of merit are critical in the design and optimization of wireless networks, as they allow engineers to balance the trade-offs between capacity and quality of service. By carefully managing the reuse of frequency bands and minimizing interference, network operators can provide reliable and high-speed wireless connectivity to users (Pons *et al* 2023) [30].

Some existing and emerging frequency reuse schemes

Many frequency reuse Schemes have been used over the years, including:

- a. Fixed frequency reuse
- b. Dynamic frequency reuse
- c. Fractional frequency reuse
- d. Soft frequency Reuse
- e. Clustered frequency reuse
- f. Coordinated multipoint (CoMP) transmission
- g. Sectorisation approach
- h. Edge Computing and Frequency Reuse

Fixed frequency reuse

Fixed frequency reuse is a concept used in wireless communication systems, particularly in cellular networks, to efficiently utilize the available frequency spectrum as shown in figure 3 and 4 below. The idea is to divide a geographical area into smaller cells, each using a specific set of frequencies. These frequencies are carefully allocated to minimize interference between neighboring cells and maximize overall network capacity.

In this method, the frequency band is divided into a defined number of channels, and those channels are subsequently reused throughout the network in a fixed manner. According to (Andrews *et al.* 2007) [31] if there are four channels, they might be used in a pattern where every fourth cell uses the same channel. Although it is not necessarily the most effective use of spectrum, this strategy is reasonably easy to put into practice.

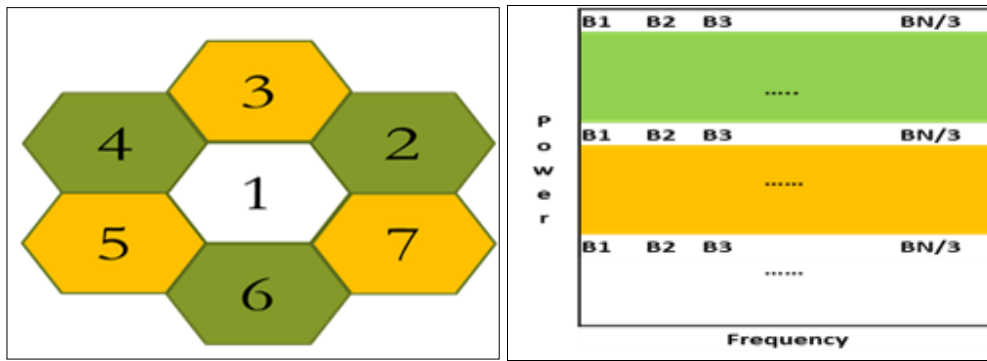


Fig 3: Reuse Factor of 3

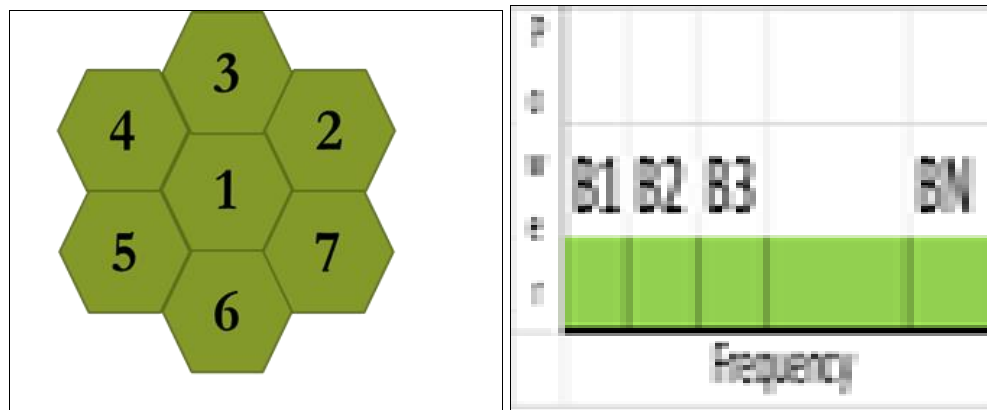


Fig 4: Reuse factor of 1

Fixed Frequency Reuse's performance has only been studied in a small number of experiments, but the findings indicate that it can enhance wireless network performance in specific situations. A research by (Andrews *et al.* 2007) ^[31] for instance, examined the effectiveness of fixed frequency reuse in LTE-advanced systems with various reuse factors. The effectiveness was assessed using average cell throughput as well as cell edge user throughput. From this research, it was discovered that a carefully selected reuse factor in relation to cell size (which results in a varied level of inter-cell interference) can increase average cell throughput by up to 3-5% and cell-edge user throughput in the local area (LA) by considerably more.

Notably, Fixed Frequency Reuse may also result in underutilization of frequencies in low-demand locations, which could reduce network effectiveness. Numerous research have suggested dynamic frequency allocation techniques to overcome this problem, which can adaptively distribute frequencies to various places based on the demand at the time.

Dynamic frequency reuse

Dynamic Frequency Reuse (DFR) is a more advanced approach compared to fixed frequency reuse in wireless communication systems, particularly in cellular networks. Unlike fixed frequency reuse, DFR allows for adaptive allocation of frequencies based on the real-time demand and traffic conditions within the network. This dynamic adjustment enables more efficient spectrum utilization and improved system performance. The method, which includes dynamically distributing frequency channels based on the current network load, is more adaptable than fixed frequency reuse. For example, a study by (Karthika & Indumathi, 2020) ^[32] proposed an optimization algorithm

that can adaptively adjust the frequency allocation based on the current traffic demand and the channel conditions, leading to a significant improvement in spectral efficiency. To guarantee that capacity is maximized in this method, channels can be redistributed to different cells as necessary. An algorithm is formulated in this work to deliver optimal efficiency for both edge/center users. In this algorithm, edge and center users are assigned with separate frequency reuse factors. Hence, in case of edge users ICI is found to be minimum. This scheme balances efficiency for edge/center cell users. The simulation results indicate that the proposed methodology offers maximum performance towards edge/center cell throughput. ICI is eliminated in the proposed system with the application of FR methodology. The proposed scheme is assessed with Reuse- 1/Reuse-3. Results showed that this developed methodology offers excellent reasonable throughput for edge/center cell users. They divided the entire band into the inner and outer regions for the investigation where Cell Center Users (CCU) are served by the Inner preprocessing frequency reuse-1, and Cell Edge Users (CEU) are served by the Outer group having frequency reuse3. Users were divided into edge and middle users based on SINR. The available -range was divided into $\beta F-3$ and $\beta F-1$. For the inner band, F-1, Frequency Reuse-1 was used, and for the outer band, F-3, Frequency Reuse-3. It was discovered that the proposed strategy performs better than alternative reuse methods. For instance, the suggested technique delivers 9.7% increases when compared to reuse 3 and 0.57 percent decreases when compared to reuse 1 when SINR is 20 dB. For users of cell centers, Reuse 1 offers improved throughput. This method offers a higher throughput compared to other reuse factors since it assigns the reuse factor to users on a dynamic basis

based on SINR. The edge users receive greater throughput in Reuse-3.

Lopez-Pérez (2009) proposed situations where the traffic and the channel conditions are dynamic and change quickly over time by introducing Vertical-Dynamic Frequency Plan (DFP), an improvement to the DFP algorithm was based on the idea of Fractional Frequency Reuse Schemes; it was able to increase network capacity and throughput by about 15%.

Fractional frequency reuse

Fractional Frequency Reuse (FFR) is a cellular network optimization technique that aims to strike a balance between the simplicity of fixed frequency reuse and the adaptability of dynamic frequency reuse. In FFR, the coverage area of a cell is divided into different zones, and each zone is assigned a specific frequency reuse pattern as shown in figure 5 below. The primary goal of FFR is to manage interference, particularly at the cell edges, where interference tends to be higher. It is a technique used in wireless communication systems to allocate different fractions of frequency bands to different parts of a cell to improve the Signal-to-Interference-plus-Noise Ratio (SINR) and reduce interference. Many studies have evaluated the

performance of FFR in improving SINR, and the results show that it can be effective in improving SINR by reducing inter-cell interference.

Lam & Tran (2021) [34] in their paper modeled the Ultra Dense Network (UDN) network systems utilized FFR in which the associated users of each BS were classified into groups. By which each group was served by a predetermined power level. Throughout the mathematical transformation, the user coverage probability was derived. The paper introduced a simple approach to obtain user coverage probability in the case of a general path loss model and the approximated closed-form in the case of SPLM. In this paper, the uplink of the cellular network PPP model using Strict FR and Soft FR algorithms, which was recommended by 3GPP. The analytical results which were verified by the Monte Carlo simulation focus on the network performance parameters such as the CCU and CEU classification probabilities, the average transmit power, and average coverage probability. The performance of Strict FR and Soft FR were analyzed and compared together through the paper. The results showed that Strict FR outperforms Soft FR in terms of user performance while Soft FR was seen to achieve higher cell data rate than Strict FR.

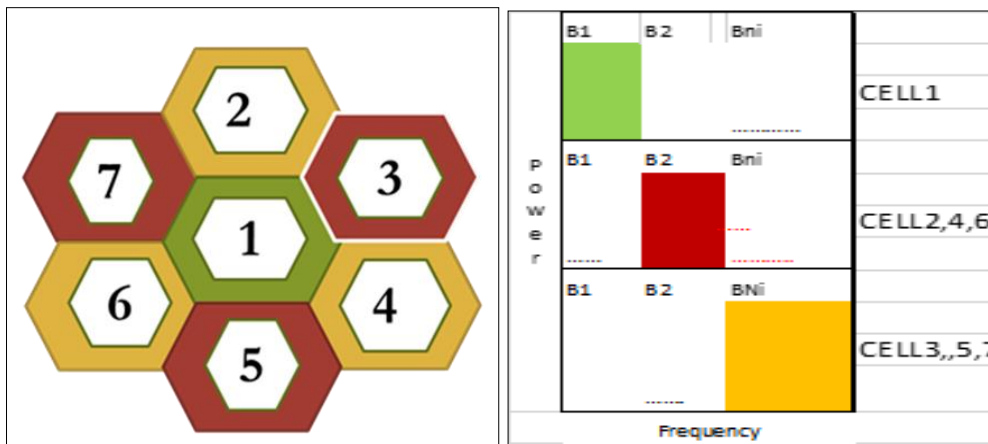


Fig 5: Fractional Frequency Reuse

Soft frequency Reuse

Soft Frequency Reuse (SFR) is another advanced technique used in cellular networks to optimize spectrum utilization and manage interference. Unlike traditional fixed frequency reuse and fractional frequency reuse, SFR allows for more flexible and adaptive control of frequency allocation. This approach is a type of fractional frequency reuse that involves dividing the frequency band into two parts, one for macro cells and the other for small cells. In this scheme, the small cells reuse the same frequency band as the macro cells, but with a reduced power level to mitigate interference (Chen & Yuan, 2009) [35]. This scheme can improve network capacity and coverage, particularly in dense urban areas. Several studies have evaluated the performance of SFR in improving spectral efficiency, and the results showed that it can be effective in providing more capacity to high-demand areas and improving spectral efficiency. Hossain & Becvar (2021) [36] evaluated Soft Frequency Reuse using the allocation of resource plans based on Machine Learning in the Networks with Flying Base Stations. In this paper, they proposed a novel SFR scheme, named F-SFR, in order to dynamically and adeptly allocate resource plans among the FlyBSs in a coverage area depending on the current network

topology. The objective of the resource plan allocation algorithm was to allocate the transmission power and bandwidth among different levels of the coverage area of each FlyBSs such that the distance between the FlyBSs allocated with the same resource is maximized. This maximization of the distance reduces interference. It was shown that with respect to the state-of-the-art SFR schemes, the proposed F-SFR attains a notable improvement in the cell-edge users' throughput. The improvement varies from 16% to 26% depending on the number of FlyBSs deployed in the service area. Furthermore, the proposed scheme achieves up to 25% improvement in the user satisfaction ratio in terms of the experienced throughput. In addition, the proposed F-SFR does not compromise fairness in throughput among the users. For instance, a study considered by Akhtar *et al* (2020) [37] on soft frequency reuse scheme together with decoupled association (DA), this scheme was able to mitigate interference and to achieved load balancing. Results indicated that the proposed unified model achieves enhanced coverage probability due to reduced interference and DA outperforms all other methods used in the state-of-the-art. They performed analysis of DA along with SFR scheme. The numerical results showed that

SFR scheme with DA becomes more resilient to interference and, thus results in improved coverage probability as well as efficient utilization of resources. It is also observed that severe densification of BSs adversely affects coverage probability due to increased interference.

Clustered frequency reuse

Clustered frequency reuse is a technique used in wireless communication systems, particularly in cellular networks, to efficiently manage the allocation of radio frequencies and minimize interference among neighboring cells. The concept involves dividing the geographical area covered by a cellular network into clusters, and each cluster consists of a group of cells (Idrees *et al* 2022) [38].

In a traditional cellular network, the same set of frequencies is used across all cells, and interference can occur when neighboring cells use the same frequencies. Clustered frequency reuse aims to mitigate this interference by dividing the cells into clusters and assigning different sets of frequencies to cells within the same cluster. The idea is to reuse the same set of frequencies in a pattern that minimizes interference between neighboring cells (Idrees *et al* 2022) [38]. In this scheme, cells in the same cluster use the same frequency, while cells in different clusters use different frequencies (Song, *et al*, 2021) [9]. This scheme can provide a good balance between interference reduction and spectral efficiency. Several studies have evaluated the performance of CFR in terms of throughput, and the results show that it can significantly increase the network throughput. For example, a study by (Lee *et al*. 2022) [40] in their study on optimal frequency reuse and power control in Multi-UAV wireless networks, hierarchical Multi-Agent reinforcement learning perspective proposed a joint optimization of the power allocation and the sub-band allocation to maximize the network throughput in a CFR-based LTE network. In this paper, they propose a hierarchical multi-agent Q-learning-based optimal frequency reuse and power control algorithm to maximize network-wide EE in uplink multi-UAV wireless networks. First, to mitigate an intercell interference problem, the focused was on obtaining the optimal frequency reuse factor with centralized outer-loop RL. Additionally, UTs' transmit power was optimally adjusted by using distributed inner-loop RL.

The study showed that the proposed method can improve the network throughput significantly compared to the traditional FFR technique.

Coordinated multipoint (CoMP) transmission

Coordinated Multipoint (CoMP) transmission is a technique used in wireless communication systems, particularly in cellular networks, to enhance the overall system performance by coordinating the transmission and reception among multiple base stations (BSs) or cells. The primary goal of CoMP is to improve system capacity, coverage, and reliability. In traditional cellular networks, user devices connect to a single serving cell, and handovers occur as the user moves across different cells (Irram *et al* 2020) [41]. CoMP takes a different approach by allowing multiple cells to coordinate their transmissions, receptions, and resource allocation for a given user or group of users. This coordination can occur at both the transmission and reception phases. There are two main types of CoMP:

- 1. Joint Transmission (JT):** In joint transmission, multiple base stations simultaneously transmit the same data to a user device. The signals from different base stations combine constructively at the user device, improving signal quality and reliability, especially in areas with poor coverage or high interference.
- 2. Coordinated Scheduling/Beamforming (CS/CB):** In coordinated scheduling or beamforming, multiple base stations coordinate their transmissions to schedule resources and optimize beamforming. This helps in mitigating interference and enhancing the signal quality for users in the overlapping coverage areas of multiple cells.

This approach involves coordinating the transmission and reception of multiple cells to provide better coverage and reduce interference. (Qamar, 2017). This approach can improve network capacity, coverage, and spectral efficiency, particularly in areas with high user density. Coordinated multipoint (CoMP) transmission is a technique that allows multiple base stations to jointly transmit data to a user to improve the SINR (Signal-to-Interference-plus-Noise Ratio) and system capacity. The technique can help to mitigate the inter-cell interference and improve the user's SINR by coordinating the transmission from multiple base stations.

Sectorisation approach

This is a frequency reuse approach in telecommunications that involves dividing a cell into several sectors, each served by a directional antenna. By using directional antennas, sectorisation allows the same frequency band to be reused in different sectors without causing significant interference (He *et al*, 2016). This approach can increase network capacity and improve coverage, particularly in densely populated areas. The sectorization approach in frequency reuse can reduce congestion and interference in a cellular network by dividing the cells into smaller sectors, each served by a different set of frequencies also. This method enables more efficient frequency reuse within the same cell while reducing interference between neighboring cells. Several studies have demonstrated that sectorization can improve network capacity and reduce congestion dramatically.

Cell sectoring is a technique for increasing cellular system capacity by eliminating co-channel interference. Traditional sectoring is fixed sectoring with three or six sectors of equal size. It is effective to reduce interference when there is uniform traffic in a cell. When the cell has non-uniform traffic but uses uniform fixed sectoring, certain sectors may be heavily congested while others may have spare capacity. Each beam can track a specific user by employing Smart Antenna (SA) (Anpalagan & Sousa 2001) [43].

Table 2: Showing Number of Users Versus spectral efficiency performances on reuse factors of 1 and 3 (Rani & Kumar, 2016) [55].

Number of users	Spectral Efficiency	
	Reuse 1	Reuse 3
30	13	8
40	15	9
50	16	9
60	17	9.5
70	18	10

Table 3: Showing Number of Users Versus Network Load performances on reuse factors of 1 and 3 (Rani & Kumar, 2016) ^[55].

Number of Users	Network Load	
	Reuse 1	Reuse 3
5	1	1
10	18	22
15	38	90
20	50	100

Table 4: Showing Throughput Values on reuse factors of 1 and 3 (Rani & Kumar, 2016) ^[55]

Throughput	Reuse 1	Reuse 3
0.5	0.1	0.2
1	0.35	0.7
1.5	0.7	0.95
2	0.9	1
2.5	0.95	1
3	0.95	1

Emerging Technology in Frequency Reuse Techniques.

Below are some emerging technologies that has shown some level of prospects in frequency reuse application.

- a. Machine Learning-based Optimization
- b. Cognitive Radio Networks
- c. Non-Orthogonal Multiple Access (NOMA)
- d. Millimeter-Wave Frequency Reuse
- e. Spatial Domain Techniques
- f. Dynamic TDD/FDD Configurations
- g. Advanced Antenna Technologies
- h. Network Slicing in 5G and Beyond
- i. Quantum Communication for Secure Spectrum Sharing

Machine Learning-based Optimization

To maximize frequency reuse dynamically, machine learning approaches like neural networks and reinforcement learning are being investigated. In order to improve spectral efficiency, these algorithms can learn patterns and make decisions in complicated and dynamic situations. One of the most important contributions to the improvement of mobile communications is machine learning (ML). In conclusion, machine learning in mobile communications tackles a number of issues, including security, network optimization, and improving user experience. The efficiency and dependability of mobile networks are greatly enhanced by machine learning's capacity to evaluate massive datasets and generate predictions based on patterns. Figure 8 below shows relationship and connection between dataset and ML and network systems. An overview of machine learning-based methods for resolving optimization issues in signal processing and communications was studied by Dahrouj *et al.* in 2021^[44]. This provides a comprehensive overview of the many learning-based strategies that are used to solve optimization problems and highlights their latest applications in the fields of signal processing and communications. This overview paper is a first step toward developing a framework for the optimization theory and applications paradigm to incorporate learning-based practical procedures, which is expected to be an important topic for many future research paths.

Cognitive radio networks

Intelligent radios that can dynamically sense and adapt to the radio frequency spectrum are used in cognitive radio networks. In this way, licensed users are not interfered with and accessible spectrum bands can be used opportunistically. Cognitive radio maximizes spectrum usage, which improves frequency reuse. Advanced wireless communication networks known as Cognitive Radio Networks (CRNs) use cognitive radio technology to dynamically and intelligently control radio frequency spectrum usage. Enabling radios or communication equipment to adaptively and autonomously alter their operating parameters based on real-time information and environmental variables is the basic notion underlying cognitive radio. This modification makes it possible to better interact with other radio frequency spectrum users and utilize the spectrum more effectively. A core network and a secondary network are the two main networks that comprise a cognitive radio network (CRN). The principal radio base station and its users make up the primary network, which also owns the licensed spectrum. The major network and the secondary network share the unutilized spectrum. It is composed of users and the cognitive radio base station (Arun & Karthikeyan, 2019) ^[45]. According to Liang *et al.* (2011) ^[46], CR is thought to be one of the most promising technologies for wireless communications in the future. It will take cooperation from several research communities, including communications theory, networking engineering, signal processing, game theory, software-hardware joint design, reconfigurable antenna, and radio-frequency design, to make radios and wireless networks truly cognitive

Non-Orthogonal Multiple Access (NOMA)

NOMA is a multiple access strategy that permits the sharing of time and frequency resources among several users. By allowing the simultaneous transmission of numerous signals on the same frequency, this method improves spectral efficiency. One method that is currently being developed for more effective frequency reuse is NOMA. The advantages and difficulties of NOMA as a potential technology in dense networks were examined by Makki *et al.* in 2020 ^[47]. Through simulations and in line with the debates in the 3GPP Release 15 study-item on NOMA, it was demonstrated that, in terms of BLER, it might or might not perform better than the standard OMA-based schemes like MU-MIMO. Nevertheless, NOMA's relative performance increase for the relevant use-case scenarios at hand was not so great as to dissuade the 3GPP from moving forward with it as a work item. However, because of its special qualities, several methods for simplifying its implementation can be developed, thereby making NOMA more applicable to real-world applications For upcoming wireless communication systems, such as from 5G and beyond, where better system capacity and efficient spectrum utilization are crucial goals, OMA is seen as a potential solution. However, issues like user pairing, power allocation, and receiver complexity must be resolved in order to put NOMA into practice. In order to establish NOMA as a practical and effective multiple access method in actual wireless networks, researchers are still investigating and developing it.

Millimeter-Wave Frequency Reuse

The spectrum band with wavelengths ranging from 10 millimeters (30 GHz) to 1 millimeter (300 GHz) is referred to as the millimeter wave (MM wave) or millimeter band. The International Telecommunication Union refers to it as the extremely high frequency (EHF) band (ITU). In order to prepare for 5G and beyond, novel frequency reuse solutions are being developed for millimeter-wave frequencies (e.g., 28 GHz, 60 GHz). In millimeter-wave deployments, methods like beamforming and directed communication are used to maximize reuse and control interference. Alani and Al-Falahy (2017) ^[53] FFR interference coordination was employed in their study to reduce interference in dense networks operating at higher carrier frequencies, namely in the 26 GHz range. In the millimeter wave range, frequency reuse schemes are crucial for increasing network capacity and enhancing performance. Because of the dense network, FFR has been used in this situation as an interference coordination strategy to counteract ICI. While maintaining the peak throughput at a specific threshold, the novel approach has demonstrated a notable improvement in network performance in terms of cell-edge user data throughput and average cell data throughput. or both three and eight sectored sites, the optimal values of the normalized bandwidth β FR have been determined, providing the best balance between cell-edge and center user performance. Additionally, eight sectored base stations have the ability to increase network capacity above three and six sectored base stations with the correct optimization.

Spatial Domain Techniques

Massive MIMO (Multiple Input, Multiple Output) and spatial modulation are two new spatial domain approaches that improve frequency reuse. By physically separating users and utilizing a large number of antennas, massive MIMO lowers interference and increases system capacity. Zhang and associates (2020) ^[54] Spatial domain approaches, as used in wireless communication, especially in cellular networks, refer to strategies used to control the spatial distribution of radio resources, antennas, and other network components in order to improve the network's efficiency and performance. These methods are essential for minimizing interference between nearby cells and making the best use of the frequency spectrum that is available. In conclusion, the management of interference, the best possible utilization of radio resources, and the enhancement of cellular network performance and efficiency all depend on spatial domain approaches in wireless communication. These methods are essential for satisfying the growing need for wireless services in a situation where spectrum is limited.

Dynamic TDD/FDD Configurations

Researchers are investigating dynamic Time-Division Duplex (TDD) and Frequency-Division Duplex (FDD) arrangements. More flexible frequency reuse is made possible by the capacity to dynamically transition between TDD and FDD modes dependent on traffic patterns and network conditions. Wireless communication systems employ methods such as dynamic time division duplex (TDD) and frequency division duplex (FDD) to regulate the distribution of time and frequency resources for communication between base stations and user devices. In conclusion, dynamic TDD and FDD designs allow wireless

communication systems to adjust to shifting traffic demands and network conditions. These wireless network deployment configurations maximize resource usage, improve spectrum efficiency, and provide flexibility.

Advanced Antenna Technologies

Improved frequency reuse is being facilitated by the development of cutting-edge antenna technology including reconfigurable antennas and intelligent reflecting surfaces (IRS). With the use of these technologies, radio wave environments can be more intelligently altered to maximize signal coverage and quality. The term "advanced antenna technologies" describes creative and complex methods used in antenna design and execution to raise the capabilities, effectiveness, and performance of wireless communication systems. These solutions are designed to address issues including interference, signal deterioration, and scarce spectrum resources. The latest performance improvement strategies and approaches for enhancing bandwidth, gain, and efficiency as well as the mutual coupling reduction strategies employed in array of multiple elements, or MIMO antenna elements, are researched by Ahmad *et al.* in 2022 ^[48]. A variety of tactics and methods were examined in order to significantly improve the performance of antennas utilized for 5G and ultra wide band applications. Particularly for 5G and wideband applications, metamaterials improved an antenna's performance in a variety of ways. In addition to contributing to bandwidth expansion, MMTs can lessen mutual coupling between arrays of multiple elements and the closely collocated antenna elements in MIMOs. Included is the function of the EBG structure slots in the radiators with various geometrical shapes in improving the bandwidth, gain, and efficiency of the antenna performance.

Network Slicing in 5G and Beyond

Network slicing makes it possible to design virtual networks that are unique and suited to particular use cases. By allowing various slices to have distinct frequency allocations based on their needs, this idea is applied to frequency reuse, increasing overall network efficiency. A fundamental idea of 5G, network slicing is anticipated to be even more important in upcoming wireless communication technologies, such as 6G and beyond 5G (B5G). Creating several virtual networks, each suited to distinct use cases and specifications, is known as network slicing. Because these slices live on a shared physical infrastructure, network resources can be effectively allocated and tailored to meet the different requirements of different services and applications. An essential architectural component that allows for the flexibility and adaptability required to meet the many and changing needs of the future's increasingly networked and data-intensive applications is network slicing. The idea of network slicing will probably always be important for designing and optimizing communication networks, even as technology develops.

In their paper, Domeke *et al.* (2022) ^[50] listed a number of applications where network slicing might be advantageous. Network slicing facilitates the performance of autonomous driving by offering ultra-high reliability and low latency communication between the vehicles and the network, even at high speeds; it also provides mobility management and seamless continuity. Specifically, by designing dedicated slices for this use case, it is possible to guarantee that the

functioning of the service is not adversely affected by shared infrastructure.

Energy consumption: By transmitting and monitoring vital data, regulating the required signals or switches, and many other functions, network slicing, with its centralized network view, can be important in quickly and accurately responding to power outages.

Quantum Communication for Secure Spectrum Sharing

Research is being done on quantum communication principles for safe spectrum sharing. The implementation of quantum-resistant algorithms and quantum key distribution could contribute to secure and interference-free frequency reuse. Information can be secured and improved through the use of quantum mechanical concepts in quantum communication. By taking advantage of the special qualities of quantum physics to protect the integrity and confidentiality of communication channels, it can contribute to safe spectrum sharing. In situations like wireless networks, where spectrum sharing is essential, quantum communication techniques hold great promise for secure communication. It is noteworthy that the development and application of quantum communication technology is still in its infancy. Even though spectrum sharing has a large potential for improved security, further study and technology improvements will be needed for practical deployment and integration with current communication infrastructures. In their work, Cavaliere *et al.* (2020) [51] draw attention to the great range of solutions that define quantum communications, which need to be appropriately matched with the many different market sectors in the telecoms industry, each having its own unique criteria prior to deployment.

Edge Computing and Frequency Reuse

Edge computing is the process of processing data at the "edge" of the network, or close to the source of data generation, as opposed to depending only on a centralized cloud-based system. With this decentralized method, latency, bandwidth consumption, and real-time processing for applications like augmented reality, driverless vehicles, and the Internet of Things (IoT) will all be improved. Because edge computing capabilities allow for more targeted data processing, they are having an impact on efforts for frequency reuse. This may affect the way that frequencies near edge computing nodes are reused to maximize bandwidth and latency. In the realm of computing and telecommunications, Bella *et al.* (2022) refer to edge computing and frequency reuse as two separate ideas, yet they might be related in the context of wireless communication networks. Applications that need real-time processing and low latency replies must use edge computing. Edge computing can improve many applications' performance and efficiency by bringing computation closer to the data source. Edge computing can be used in wireless communication networks at the edge of the infrastructure, which is closer to the end users. Deploying computing resources at base stations or other edge devices is part of this. By utilizing edge computing in wireless networks, data processing can be done more quickly and with less need to send massive volumes of unprocessed data to central cloud servers.

Directions For Future Research

The direction of research in frequency reuse varies depending on the specific application and technology being used. Overall, the direction of research in frequency reuse is focused on developing new techniques and technologies to improve the efficiency and performance of wireless communication systems. However, for the purpose of this survey write up, we will be considering the following direction for future research: M

Strict reuse factor Technique (nth value)

This uses an interference strategy to change the reuse distance (nth value) or the frequency reuse factor to address channel interference. It is a measurement of the frequency repetitions within a certain area or network. The aim of this strategy is to attain an improved channel interference outcome by modifying the reuse factor (nth value) while maintaining optimal spectral efficiency. The result will be contrasted with comparable findings from other studies.

Enhanced or Combine Frequency Reuse Technique

To improve inter-cell interference control output at the cell edge and to increase total cell capacity, combine a few interference control approaches. The methods include creating strategies to maximize spectrum use, reduce interference, and enhance overall network performance that go beyond conventional frequency reuse methods. These include energy-efficient frequency reuse, spatial frequency reuse, and adaptive modulation and coding (AMC) with frequency reuse.

Dynamic Spectrum Access (DSA)

Creating dynamic and adaptive frequency reuse plans that may change in real time in response to the shifting radio frequency environment may be the subject of future research. Dynamic Spectrum Access makes it possible for secondary users to access underutilized frequency bands without interfering negatively with major users, hence facilitating a more efficient use of the available spectrum.

Machine Learning-Driven Frequency Reuse:

Optimizing frequency reuse can be achieved by utilizing machine learning algorithms, which can offer intelligent decision-making capabilities. These algorithms are able to forecast interference events, learn from past data, and dynamically modify frequency reuse patterns in order to improve performance under various network conditions.

Conclusion

To sum up, frequency reuse is an essential component of wireless communication networks that helps to maximize spectral efficiency, control interference, and improve network performance as a whole. Reusing frequencies effectively is essential to solving problems including throughput constraints, interference problems, and network congestion.

Efficient spectrum use has its roots in traditional frequency reuse systems, like set frequency reuse patterns. Although these systems have shown to be successful in a variety of contexts, they have difficulty dynamically responding to shifting network conditions. More flexibility and adaptability are provided by advanced interference coordination approaches, such as fractional frequency reuse and spatial frequency reuse, which improve performance in contexts that are dynamic and heterogeneous.

As new technology and methods arise, the field of frequency reuse is changing. Non-orthogonal multiple access (NOMA), machine learning-driven optimization, and cognitive radio networks offer promising solutions for dynamically resolving interference, improving throughput, and reducing congestion. The combination of these new techniques with frequency reuse tactics holds the potential to completely transform wireless communication as we approach 6G and beyond by reaching previously unheard-of levels of efficiency and dependability.

Reusing frequencies effectively requires striking a balance between throughput enhancement, congestion relief, and interference control. Novel approaches are required to meet the growing demands for large device connection, low latency, and high data rates. Adaptive modulation and coding, game theory techniques, and heterogeneous networks are a few factors to take into account while designing frequency reuse schemes to satisfy the changing needs of various user situations and applications. The investigation of frequency reuse must continue in order to fulfill the increasing demands of wireless communication, both in terms of improving current systems and embracing emerging technology. Frequency reuse will continue to be essential as we push the limits of data rates, latency, and connection, and new avenues for wireless communication network optimization will be opened by future research.

Network operators, researchers, and regulators can make well-informed decisions about creating and implementing efficient spectrum management solutions to meet the demands of a rapidly changing wireless communication environment by being aware of the advantages and disadvantages of different techniques of frequency reuse or schemes.

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