Performance Evaluation of Strict Fractional Frequency Reuse and Frequency Reuse Factor-3 in 5G Networks

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***Abstract*—The need for high speed data traffic on mobile devices has risen because of the permeating use of gadgets, such as mobile smart phones, notepads and tablets that are constantly running on data. In order to meet these requirements, mobile network providers must set up both tiny cells, high-capacity and very dense, base stations (BSs). This is to cover not only a vast area but also including hotspots with quick, adaptable, and robust supply. The overall spectral efficiency of 5G networks must be improved, and the operations and deployment costs must be decreased. This paper evaluates and compares the performance of Strict Fractional Frequency Reuse (FFR) and Frequency Reuse Factor-3 (FRF-3) according to the cell throughput and cell spectral efficiency with the theoretical peak throughput and peak spectral efficiency as specified in NR 3GPP specifications. The results from the simulation revealed that the FFR performs much better than the FRF-3, however, it is still not efficient in relation to the peak values.**

Keywords—5G, frequency reuse factor (FRF), throughput, spectral efficiency, channel quality indicator (CQI) fractional frequency reuse (FFR),

I. INTRODUCTION

To attain extremely low latency, enhanced spectrum efficiency, rapid data transfer and flexibility in design and execution, 5G (Fifth Generation) is the new mobile networks of wireless systems [1]. The increasing usage of devices like smart mobile phones, notepads, smart tablets, etc., that are heavily dependent on data has heightened the demand for very fast mobile data traffic. Operators of mobile network must build both small cells and dense base stations (BSs) of high-capacity. To fulfil future users' irregular demands, the BSs are expected to cover a large region including hotspots that are quick, adaptable, and robust in nature. Overall spectral efficiency of 5G networks must be increased, as must operational and deployment costs be reduced. Furthermore, because ultra-dense networks (UDN) are the current trend in next-generation networks, intercell interference (ICI) is seeing as a difficult challenge associated with 5G networks [2].

One of the key elements in a cellular communication system that affects transfer of data at the cell-edge zone happens to be ICI, which lowers the base station's spectral efficiency. There are two methods for assigning frequencies to mobile systems. Firstly, base stations employ various frequencies to broadcast data, with each sector consuming 25% bandwidth. Here, the Frequency Reuse Factor 3 (FRF3) reuse factor is 25 percent (FRF3). This plan greatly minimizes co-channel interference between close cells, but it lowers spectrum efficiency. All cells in 3G network and 4G network share similar bandwidth (BW) and carrier frequency with reuse factor of 100%, which is referred to as frequency reuse factor 1 (FRF1). It improves efficiency of the spectrum, but also exacerbates interference from neighboring cells [3].

Another method, known as fractional frequency reuse, can exchange the frequency reuse techniques. In this method, each cell is capable of transmitting on the same frequency in the center, receiving most of the resources, while the cell edges receive different resources to lessen interference (FFR) [3]. To reduce interference and boost average spectral efficiency, FFR separates the cell's coverage area into inner and outer zones. In these zones, several FRFs are put into use.

Stolyar and Viswanathan in [4] presented a resource assignment technique for a system uplink of Orthogonal Frequency Division Multiple Access (OFDMA). The aim was to maximize the overall utility of the system, which is dependent on the obtained user throughputs. The paper proposed a dynamic reuse scheme that suites different random users placed in the cell. Intercell communication is limited to the infrequent exchange of interference costs, making the scheme semi-autonomous. The simulations in this work reveal that the scheme outperforms the traditional reuse factor scheme by a significant margin.

A new mathematical method for determining probability of coverage and the mean rate in Strict Fractional Frequency Reuse and Soft Fractional Reuse (SFR) systems was presented in [5]. The design guidelines of the system showed the benefits of both solutions and the trade-offs between Strict FFR high interference reduction and SFR superior efficiency of the resource. The work further proposed the use of Poisson model in evaluating Intercell Interference Coordination (ICIC) tactics based on base station cooperation, thereby allowing dynamic deployment of FFR alongside resource allocation schemes in order to get used to various channel situations and loads of user traffic in each of the cells.

In [6], an algorithm was developed to provide very high efficiency for center users and edge users. The frequency reuse factors for center users and edge users are allocated separately. As a result, ICI is shown to be minimal in the case of edge users. This approach strikes a compromise between efficiency and convenience for users of edge and center cells. Simulation results carried out on MATLAB showed that the proposed method offered a highest performance towards edge and center cell throughput. With the use of the frequency reuse (FR) approach, ICI is minimized in the suggested

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system. Reuse-1/Reuse-3 is used to determine and evaluate the suggested strategy. The obtained results further indicated that the method proposed provides great throughput for edge/center cell users at a reasonable cost.

In [7], a Soft Frequency Reuse (SFR) system for LTE-A that is premised on 3 segments of frequency is proposed. The Frequency Reuse Pattern (FRP) distribution technique for microcells is put in the center at the macro cell level. This technique is built on microcells exchanging measurements with their macro-cells and incorporates an intracell offloading technique to take care of the burden between each micro and macro cell edge and cell center. The technique is sometimes referred to as cognitive-assisted approach. Comparisons of the performance with various schemes using average cell capacity and outage probability have proven the goodness of 3B-ISFR.

A novel strategy of resource assignment is introduced for 5G HetNet, known as multi-level soft frequency reuse in 5G HetNet. It is written as ML-SFR HetNet [8]. The strategy enhances throughput by several orders of magnitude. A mutually exclusive spectrum is assigned among different cells in the reuse system of the ML-SFR HetNet for small cell users, macro cell users, and cell-edge users. For a generalized HetNet scenario, spectrum and power allocation expressions were derived. Also, mathematical equations for area spectral efficiency (ASE) and throughput were introduced. When compared to a standard SFR system, the simulation results showed that the suggested approach enhances throughput by about three and half times and reduces probability of outage by roughly five times.

Gebremariam et al., [9] introduced dynamic strict fractional frequency reuse (DSFFR) as a unique approach for mitigating ICI in cell networks that are small. The small cells were applied as distant radio heads that were controlled by a centralized resource pool. As a result, a joint arrangement issue was formulated such that 2 schedulers work on time scales that are different. A spatial scheduler that implements DSFFR and can modify the amount of radiating antennas and antenna beam width to split the cell region into distinct parts was proposed. Approximation techniques were used to address the joint scheduling problem, which was framed as a Knapsack problem. Numerical results showed that the technique performs better under same network conditions as static FFR.

The various FFR methods are discussed in [10], with a focus on Soft Frequency Reuse (SFR) and FFR. It also compares the SFR and the FFR procedures to the standard frequency reuse methodology. In comparison to the typical frequency reuse method, simulation findings show that adopting fractional frequency reuse strategies improves cell-edge user performance considering throughput, Signal-to-Interference-Plus-Noise Ratio (SINR) and efficiency of the spectrum. An adaptive FFR method to minimize interference emanating through randomly planted femtocells is designed in [11]. The proposed approach distributes frequency resources depending on femtocell position and the spectral efficiency of the desired cell edge. Adjusting the transmit power of each sub channel in a dispersed fashion to ensure efficient use of the spectrum was also devised. The simulation results show that the suggested approach achieves the intended results in residential buildings. However, when the frequency resource is insufficiently large or each femtocell having varying loads, the frequency resource allocation premised upon long-term channel conditions may not perform correctly.

In [12], the universal frequency reuse with Strict FFR system and SFR system having a thorough picture of the trade-offs associated with these two systems were compared. Findings from the work suggested that Strict FFR has the best probability of outage and is minimally affected by the internal radius choice than the SFR. When the user power control factor of the cell-edge is increased, the outage performance of an SFR system can increase. While Strict FFR delivers the highest total network speed and cell-edge user SINR, SFR strikes a balance between interference mitigation and resource efficiency.

In the research conducted by [13], joint SFR-based spectrum and power assignment issue in LTE and LTE-A systems that are capable of maximizing system throughput while meeting the requirement of data rate in each cell area were looked at. The adaptive SFR scheme (ASFR) was proposed as a distributed resource allocation scheme. The ASFR algorithm uses exhaustive search and descent methods to repeatedly optimize the subcarrier and power allocation in each of the cell until a stable SFR trend is established. The ASFR algorithm's convergence property is proven via theoretical research. The amount of main subcarriers and power ratio in each of the cell is modified strongly based on the system traffic needs, according to simulation results. Under various system traffic load scenarios, the ASFR algorithm was proved to significantly outperforms previous frequency reuse algorithms in terms of system performance and maintain a low cell-edge user probability of outage. It achieves about double the system transfer rate of the Reuse 1, Reuse 3 and FFR techniques, as well as a 20% increase in system throughput over the static SFR method.

[14] proposed a novel frequency reuse and assignment strategy that take care of interference from first-tier nearby cells to the cell-edge area, resulting in a large increase in the SINR at the cell edge. For wireless networks, the suggested approach provides for full frequency reuse. When compared to the common SFR system, the suggested technique achieves a higher SINR in the network given the same user position and channel condition. When compared to the traditional full reuse (FR) method and the SFR technique, numerical studies demonstrate that spectral efficiency of the cell-edge and total spectral efficiency of the cell can be greatly enhanced.

This paper analyses, using cell throughput and cell spectral efficiency, the performance of Strict Fractional Frequency Reuse and conventional frequency reuse factor-3 in NR 5G network. A comparison of the metrics in the NR 3GPP specification and the obtainable peak cell throughput and peak cell spectral efficiency is carried out. The Strict Frequency Reuse shows better performance than the conventional frequency reuse factor-3 both in the throughput efficiency and the spectral efficiency.

II. System model

This section presents the theoretical approach to evaluate and determine the SINR, peak cell throughput and peak cell spectral efficiency have been presented.

The network model consists of three (3) circular cells that connect several User Equipment (UEs) that are in inner region providing support for FRF1 or outer region that supports

FRF3. The UE CQI report determines where in either of the region the UE falls. In this case, CQI threshold is specified such that any of the UE that exceeds the set limit will be taken account of in the inner region with FRF1. The UEs that fails to attain the set limit will be considered outer zone with FRF3, i.e. cell-edge area.

It is assumed that the overall network comprises N neighboring cells. Each of the cell has several users that want to share a group of subcarriers. A situation where a user is located in the inner part of the cell or found in the outer cell is distinguished.

A. Signal to Interference Plus Noise Ratio (SINR)

The associated SINR for a user, u, served by a base station, b, in an OFDMA mobile network, can be obtained using (1).

$$SINR_u = \frac{P_b h_{bu} G_{bu}}{\sigma^2 + \sum_{z \in \mathbb{Z}} P_z h_{zu} G_{zu}} \quad (1)$$

Where P_b is the transmitting power of the base station, h_{bu} is the CDL-C channel fading power, and G_{bu} is the path loss of the channel between user, u, and the base station, b, and σ^2 is the noise power of an Additive White Gaussian Noise (AWGN) channel. The set $\mathbb{Z}$ represents all the interfering base stations, i.e., base stations that use similar sub-band like user, u. It is assumed that the same transmitting power is applied, $P_b = P_z$ in the case of all the base stations.

B. Peak Cell Spectral Efficiency

The peak cell spectral efficiency is the highest rate of data possible under normal conditions, and normalized by bandwidth of the channel (in bit/s/Hz). The highest rate of data possible is the received data bits supposing situations that are error-free and allocated to a single mobile cellular station at the time that all allocated radio frequency resources for corresponding path are used. This means that it excludes the radio resources utilized for reference signals, physical layer synchronization, guard bands as well as guard times [15].

$$SE_{pi} = \frac{v_{Layers}^{(J)} \cdot Q_m^{(J)} \cdot f^{(J)} \cdot R_{max} \cdot \frac{N_{PRB}^{BW}(J), \mu \cdot 12}{T_s^{\mu}} \cdot (1 - OH^{(J)})}{BW^{(J)}} \quad (2)$$

wherein

- Rmax = 948/1024

- For the j-th CC

- $v_{Layers}^{(J)}$ is the highest number of layers

- $Q_m^{(J)}$ is the highest modulation order

- $f^{(J)}$is the scaling factor. This factor can have minimum values of 0.75 and 1. It is the signal per band per band combination in User Equipment signal capacity.

- μ is the defined numerology

-T_s^{μ} is the mean symbol duration of OFDM in a sub frame for the numerology, μ, i.e., $T_s^{\mu} = \frac{10^{-3}}{14 \cdot 2^{\mu}}$. It should be noted that the usual cyclic prefix forms the assumption.

- $N_{PRB}^{BW}(j)$ is the highest RB assignment in the bandwidth denoted as $BW^{(J)}$and the numerology, μ. The $BW^{(J)}$ is the User Equipment (UE) supported highest BW in the specified band(s).

-$OH^{(J)}$ is the overhead. It is determined as the mean ratio of the amount of REs taken by L1/L2 control, reference signals, PBCH, synchronization signal, and guard period [16].

C. Peak Data Rate

The peak rate of data is the highest possible rate of data (in bit/s) in an ideal situation. It is the received data bits that can be allocated to a single mobile situation in the case of error-free situations and full utilization of all the allocated radio resources for corresponding path. This also means that it excludes the radio resources utilized for reference signals, physical layer synchronization, guard bands as well as guard times [9].

The DL/UL peak rate of data for TDD and FDD over Q component carriers for NR as well as LTE can be determined using (3).

$$R = \sum_{j=1}^{Q} W_j \times SE_{pj} \quad (3)$$

where W_j (j = 1…, Q) is the effective BW on component carrier j and SE_{pj} (j = 1…, Q) is the spectral efficiencies on component carrier j [16].

D. Mechanism Description

The whole of BW is sectioned into 2 parts: A sub band is allocated to the cell center users with a reuse factor of one (FRF 1) and the other sub band is further divided into three band which is assigned to the cell edge users (FRF3). The distinction between the cell edge user and cell center user is based on the CQI report from the users. A threshold y value of CQI is set so that a user reporting CQI greater than the threshold y is regarded as a cell center user and the one reporting CQI value lesser than the threshold y is regarded as a cell edge user.

III. Results and Discussion

A. Parameters for Simulation

Table 1 presents the parameters necessary for the simulations.

TABLE I: SIMULATION PARAMETER

Parameter	Value
Multiple access	OFDMA
Network size	3 cells/ 4 UEs per cell
Cell Radius	500 m
Tx power	46 dBm
Carrier Frequency	2.6 GHz
Bandwidth	20 MHz
Subcarriers spacing	30 KHz
Modulation	256 QAM

The network for the simulation comprises of three (3) cells and four (4) users per cell and are uniformly shared within a

cell. The NR 5G network has been simulated using noise power density, cell radius, and base station transmission power in this paper. They are all in accordance with the 3GPP standard.

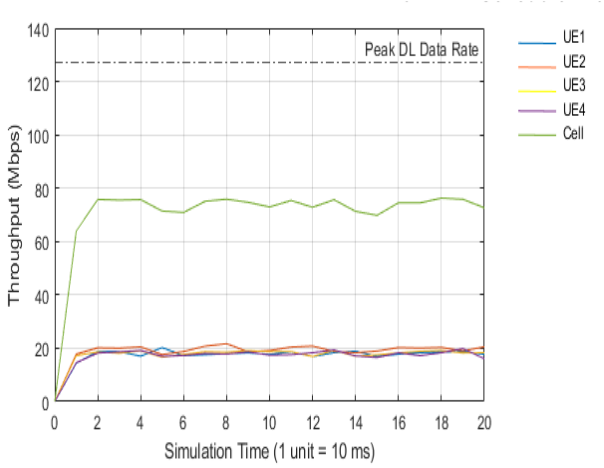


Fig 1. Plot of the throughput attained by the UEs in the cell of interest with Strict FFR

While Figure 1 shows the achieved throughput attained among the UEs in the cell of interest with Strict FFR, Figure 2 shows the resource share achieved among the UEs in the cell of interest with Strict FFR.

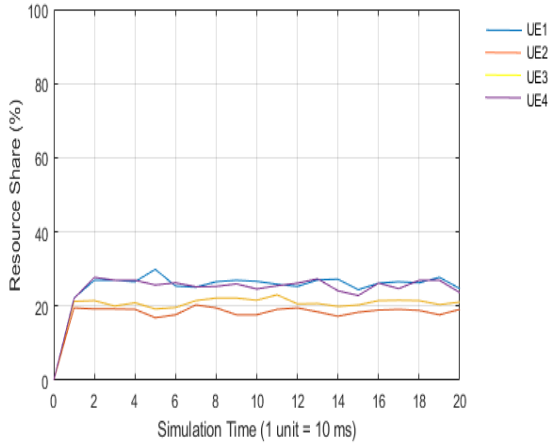


Fig 2. Plot of the Resource share attainedby the UEs in the cell of interest with Strict FFR

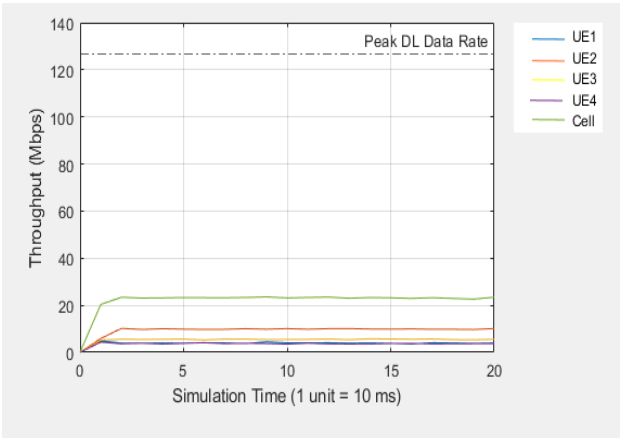


Fig 3. Plot of the throughput attained by the UEs in the cell of interest with conventional FRF-3

In Figure 3, the achieved throughput among the UEs in the cell of interest with conventional FRF-3 is shown. Figure 4 also shows the resource share achieved by the UEs in the cell of interest with conventional FRF-3.

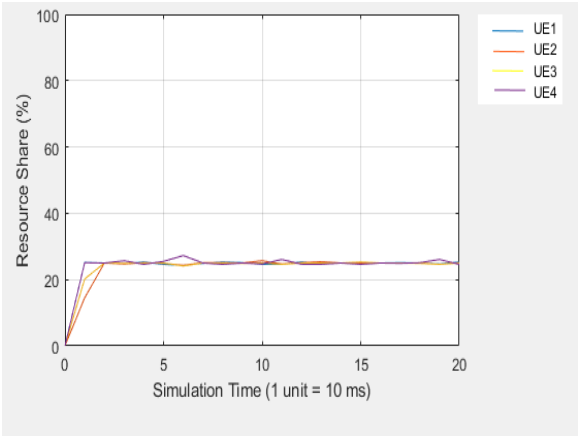


Fig 4. Plot of the resource share achieved by the UEs in the cell of interest with conventional FRF-3

In Fig. 5, the achieved cell throughput in Strict FFR is almost three times of that achieved in the FRF-3. Though this throughput is still less as compared to the theoretical peak throughput it is still better to the FRF-3.

In Fig. 6, the achieved cell spectral efficiency in Strict FFR is greater than that achieved in the FRF-3. There is a need to implement a more efficient scheme will efficiently utilize the available spectral resources.

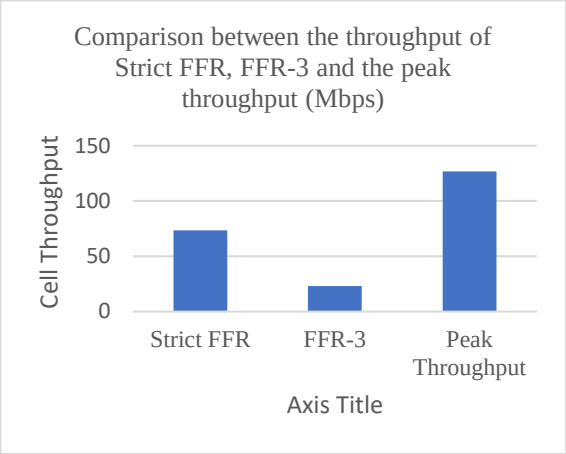


Fig 5. Chart showing the achieved throughput in conventional FRF-3, Strict FFR and peak cell throughput

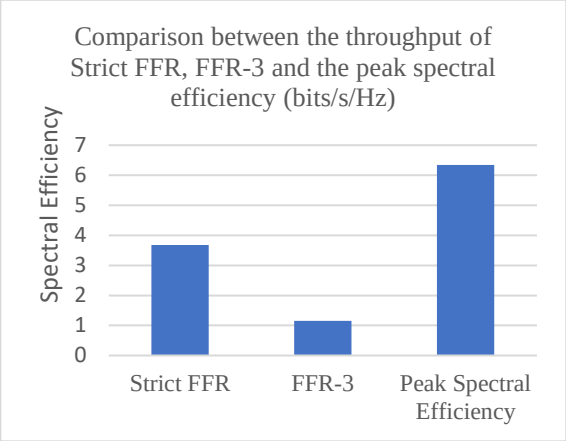


Fig 6. Chart showing the achieved throughput in conventional FRF-3, Strict FFR and peak cell spectral efficiency

IV. CONCLUSION

In this paper, a comparative analysis was carried out on the performance of Strict FFR and conventional frequency reuse factor-3 in NR 5G network according to the cell throughput and cell spectral efficiency. The conclusion drawn from the simulation done in this paper is that the Strict Frequency Reuse perform better than the conventional frequency reuse factor-3 both in throughput efficiency and spectral efficiency. These metrics used in the scope of this paper was compared to the obtainable peak cell throughput and peak cell spectral efficiency as specified in the NR 3GPP specification and it is discovered that though the Strict FFR optimally performs better than the conventional FRF-3 it is still not efficient in terms of the achievable theoretical peak values of the throughput and the spectral efficiency.

REFERENCES

[1] N. Al-Falahy and O. Y. Alani, "Technologies for 5G Networks: Challenges and Opportunities," *IT Prof.*, vol. 19, no. 1, pp. 12–20, 2017, doi: 10.1109/MITP.2017.9.

[2] N. Al-Falahy and O. Y. K. Alani, "Network Capacity Optimisation in Millimetre Wave Band Using Fractional Frequency Reuse," *IEEE Access*, vol. 6, pp. 10924–10932, 2017, doi: 10.1109/ACCESS.2017.2762338.

[3] C. Cox, An Introduction to LTE: LTE, LTE-Advanced, SAE and 4G Mobile Communications. John Wiley & Sons, Ltd., 2012.

[4] A. L. Stolyar and H. Viswanathan, "Self-organizing dynamic fractional frequency reuse in OFDMA systems," *Proc. - IEEE INFOCOM*, pp. 1364–1372, 2010, doi: 10.1109/INFOCOM.2007.119.

[5] T. D. Novlan, R. K. Ganti, A. Ghosh, and J. G. Andrews, "Analytical evaluation of fractional frequency reuse for OFDMA cellular networks," *IEEE Trans. Wirel. Commun.*, vol. 10, no. 12, pp. 4294–4305, 2011, doi: 10.1109/TWC.2011.100611.110181.

[6] S. Karthika and P. Indumathi, "Analysis of Dynamic Frequency Reuse Techniques in LTE - A Cellular Network," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 994, no. 1, 2020, doi: 10.1088/1757-899X/994/1/012034.

[7] G. Giambene, V. A. Le, T. Bourgeau, and H. Chaouchi, "Soft frequency reuse schemes for heterogeneous LTE systems," *IEEE Int. Conf. Commun.*, vol. 2015-Septe, no. Icic, pp. 3161–3166, 2015, doi: 10.1109/ICC.2015.7248810.

[8] M. S. Hossain, F. Tariq, G. A. Safdar, N. H. Mahmood, and M. R. A. Khandaker, "Multi-Layer Soft Frequency Reuse Scheme for 5G Heterogeneous Cellular Networks," *2017 IEEE Globecom Work. GC Wkshps 2017 - Proc.*, vol. 2018-Janua, pp. 1–6, 2018, doi: 10.1109/GLOCOMW.2017.8269182.

[9] A. A. Gebremariam, T. Bao, D. Siracusa, T. Rasheed, F. Granelli, and L. Goratti, "Dynamic strict fractional frequency reuse for software-defined 5G networks," 2016 IEEE Int. Conf. Commun. ICC 2016, 2016, doi: 10.1109/ICC.2016.7510890.

[10] G. Kumar and G. Saini, "Implementation of Fractional Frequency Reuse Schemes in LTE-A Network," in Lecture Notes in Networks and Systems, vol. 46, Springer Singapore, 2019, pp. 313–321.

[11] H. Lee, D. Oh, and Y. Lee, "Mitigation of Inter-Femtocell Interference with Adaptive Fractional Frequency Reuse," pp. 0–4, 2010.

[12] T. Novlan, J. G. Andrews, I. Sohn, R. K. Ganti, and A. Ghosh, "Comparison of fractional frequency reuse approaches in the OFDMA cellular downlink," GLOBECOM - IEEE Glob. Telecommun. Conf., 2010, doi: 10.1109/GLOCOM.2010.5683973.

[13] M. Qian, W. Hardjawana, Y. Li, B. Vucetic, X. Yang, and J. Shi, "Adaptive soft frequency reuse scheme for wireless cellular networks," IEEE Trans. Veh. Technol., vol. 64, no. 1, pp. 118–131, 2015, doi: 10.1109/TVT.2014.2321187.

[14] H. Wu, H. Gao, and X. Xiong, "ICIC based on adjacent cells interference elimination for cell edge," Int. Conf. Commun. Technol. Proceedings, ICCT, vol. 2017-Octob, pp. 991–996, 2018, doi: 10.1109/ICCT.2017.8359783.

[15] ITU-R, "M2410 - Minimum requirements related to technical performance for IMT-2020 radio interface(s)," Work. Party 5D, vol. November, no. Report ITU-R M.2410-0, pp. 1–11, 2017.

[16] TR 137 910, "TR 137 910 - V16.1.0 - 5G; Study on self evaluation towards IMT-2020 submission (3GPP TR 37.910 version 16.1.0 Release 16)," vol. 0, 2020.