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Stochastic Distribution of Channel Allocation Algorithm for 5G and Future Generation Ultra-dense Networks Applications

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ABSTRACT

Channel allocation technique (CAT) is a crucial tool for assigning channels to cells in mobile telecommunication networks. It ensures scalability and meets the increasing demand for quality services in fifth-generation (5G) and future networks like sixth-generation (6G). However, multi-access channels in CAT can lead to inter-system interference, requiring enhanced spectral efficiency through advanced long-term evolution (LTE-A) technologies. This study evaluates stochastic CAT distribution in ultra-dense tropical environments, emphasizing its potential to support 6G's higher capacity and ultra-low latency of one microsecond. The evaluation is based on the LTE-A network model in the network simulation environment (NS3), testing with various network loads (i.e., the number of users) and typical mobile network providers (Operators A, B, and C). The goal is to assess the impact of inter-cell interference on LTE/LTE-A system performance using algorithms like soft frequency fractional reuse (SFFR), soft frequency reuse (SFR), and dynamic frequency fractional reuse (DFFR). Results from simulations comparing fractional frequency reuse techniques indicate that CAT improves signal quality for users. Further research reveals that SFFR is less flexible and performs poorly in the system, while SFR and DFFR reduce interference between cells, enhancing performance at cell edges. Additionally, among mobile service providers in Nigeria and based on random user distribution, Operator A delivers superior quality of service compared to Operators B and C, reflecting better system performance over larger areas.

Keywords: Channel algorithm technique, 5G network, fractional frequency reuse, future generation, local network, mobile telecommunications, stochastic distribution, ultra-dense environment

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INTRODUCTION

The proliferation of mobile networks globally has demonstrated consistent growth over the past decade, largely due to the widespread adoption of cellular data connections. A large global population has embraced wireless cellular networks as the primary access to various communication services such as internet connectivity, banking, voice communication, entertainment, and text messaging, among others. As a result, the demand for mobile network services continues to increase daily. The integration of data connections into mobile cellular networks has enabled subscribers to engage in a wide range of activities through their mobile devices, including browsing the internet, making online purchases, listening to audio or video content, and facilitating monetary payments.

Using Nigeria as a case study, the number of subscribers to wireless internet connections has consistently risen thanks to the Global System for Mobile Communication (GSM), from 63 million in February 2014 to 87 million in April 2015 and now surpassing 100 million (Kuboye, 2017).

There has been a significant leap in technology from the first-generation (1G) to 5G, bringing new possibilities and opportunities. The recent 5G algorithm, representing cutting-edge technology, includes numerous innovative features aimed at addressing deficiencies in contemporary mobile communication solutions. These shortcomings have arisen due to evolving societal habits and increased requirements for wireless mobile communication (Alotaibi, 2023; Kuboye, 2018; Nordrum et al., 2017).

Traditionally, the cellular infrastructure strategy has focused on constructing a limited number of strong cell towers to expand cellular coverage over large areas. However, ensuring extensive coverage and establishing consistent connections with minimal latencies present significant challenges for today's infrastructure, especially for mobile service providers in Nigeria. These challenges have emerged due to the significant increase in connected mobile devices, higher bandwidth demands, and increased data consumption rates (Abejide, 2014; Nordrum et al., 2017).

Cellular systems have been a well-established solution for wireless communication over the past three decades. The rapid growth of high-speed multimedia applications, driven by advancements in cellular networks and mobile devices, has led to a growing demand for such services. Telecom operators, in response to this demand, are using the available spectrum more aggressively. However, this aggressive utilization has led to the concept of inter-cell interference (ICI), which is now causing traffic congestion in telecommunication network infrastructure (Islam & Chowdhury, 2013). The demand for faster data speeds has placed significant constraints on the existing cellular wireless infrastructure. Therefore, network designers must closely examine ICI behaviors to accurately estimate network performance for real-time applications and efficiently optimize resources (Bilal, 2017).

Stochastic distributions are models that depict the behavior of random variables over time. They can be used to model the variability of the wireless channel, which is influenced by interference, signal attenuation, and fading in wireless networks. Wireless networks can utilize stochastic processes to adapt to changing conditions and enhance their performance accordingly (Kodumuri, 2024). Therefore, a stochastic distribution is crucial in this study to optimize the distribution of users for optimal network performance. Additionally, data generated by wireless networks can be analyzed and learned from to identify patterns and trends, predict future network conditions, and make decisions that enhance network performance.

The LTE serves as the standardized nomenclature for the mobile technology initiative undertaken by the third-generation partnership project (3GPP), it transformed into a drive that developed fourth-generation (4G) and 5G mobile technology for data networks, voice and visual communication (Oguntoyinbo, 2013). The transformation that led to 4G network operation has prompted the telecom providers to adopt LTE-A (Peters et al., 2009).

The LTE-A networks provide peak downlink and uplink data speeds of up to 326 and 86.4 Mbps, respectively, with a 20 MHz bandwidth. LTE also offers adjustable bandwidth options ranging from 1.4 to 20 MHz. This feature can reduce latency to as low as 10 ms between the transmitter and the user, allowing for a transition time from inactive to active of less than 100 ms.

The LTE/LTE-A architecture consists of the user equipment (UE), which refers to the mobile devices used by end-users for wireless communication, such as cell phones and laptops with mobile broadband adapters. The advanced global terrestrial wireless communication network (UE-evolution packet core) handles communication via radio, maintaining bearer and UE settings. The Mobility Management Entity (MME) tracks user location, manages security, and handles paging procedures. The Packet Data Network Gateway (PGW) interacts with the outside world through the Serving Gateway (SGW) interface.

The simulation model of the LTE-Evolved Packet Core (LTE-EPC) data channel protocol is shown in Figure 1, depicting four sections linked together within a single unit. The model simplifies by combining PGW and SGW capabilities into an SGW/PGW unit, and UE and remote host compartments into transmission control protocol/user datagram protocol (TCP/UDP) nodes. This integration eliminates the need for S5 or S8 connections in NS3 simulations.

Frequency domain multiplexing (FDM) is the foundation for multiple access distribution in LTE networks. The downlink and uplink broadcasts use several methods, including: Single-carrier Frequency Division Multiple Access (SC-FDMA) for uplink distribution and orthogonal frequency-division multiple access (OFDMA) for downstream distribution. The SC-FDMA and OFDMA techniques offer distinct advantages compared

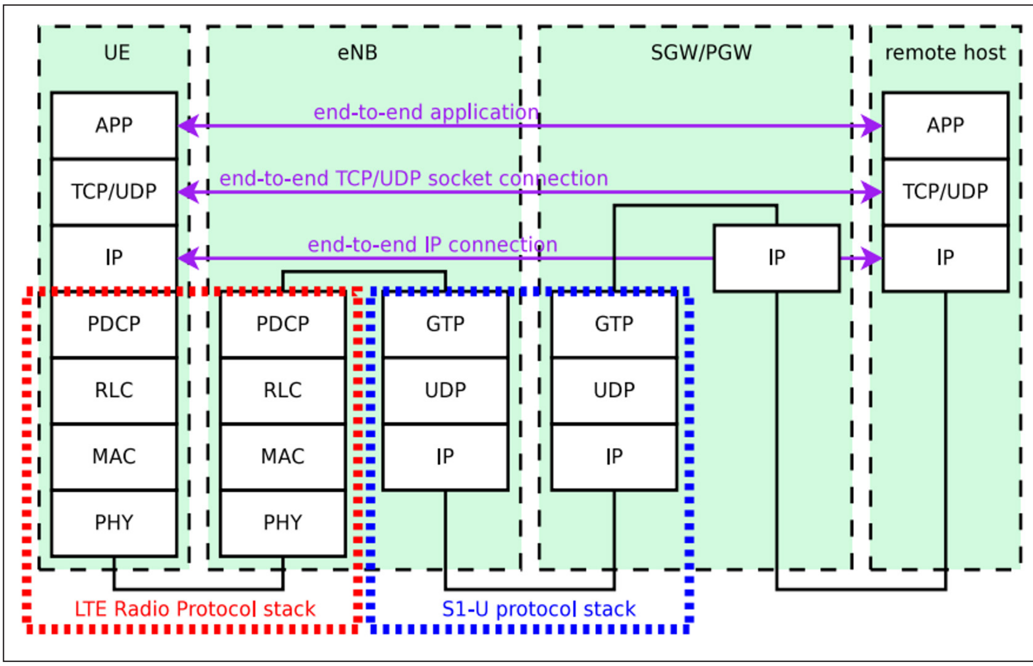


Figure 1. The architecture of the Long-Term Evolution-Evolved Packet Core (LTE-EPC) model, providing the LTE-EPC simulation model within NS3 (Liu, 2022)
Note. UE = User equipment; eNB = Evolved node B; SGW/PGW = Serving Gateway/Packet Data Network Gateway; APP = Application code; IP = Internet protocol; TCP/UDP = Transmission Control Protocol/User Datagram Protocol; PDCP = Packet Data Convergence Protocol; GTP = General Tunnelling Protocol; RLC = Radio Link Control; UDP = User Datagram Protocol; MAC = Media Access Control; PHY= Physical layer; S1-U = User Plane Interface

to earlier technologies like code division multiple access (CDMA), contributing to the robustness of communication and enabling effective management of interference. Additionally, multiple access techniques allow for the exploitation of multiuser diversity at finer granularities, enhancing the handling of frequency-selective fading and supporting various users experiencing different communication conditions during mobility (Abukharis et al., 2014; Zaki, 2012).

The performance of the system as a whole, as well as cell-edge users, is greatly impacted by interference from adjacent cells. Boudreau et al. (2009) and Himayat et al. (2010) investigated ways to mitigate ICI to assist cell-edge users experiencing slow speeds and poor quality of service (QoS). SFR, a type of inter-cell interference coordinator (ICIC) designed specifically for LTE platforms, is one such method.

The ICIC method can be categorized into two strategies: interference mitigation and avoidance.

(i) Interference mitigation focuses on reducing or suppressing ICI either at the point of sending signals or at the receiving end. Various methods fall under ameliorating inter-system interference, such as:

- Interference averaging: This technique aims to minimise ICI by averaging out its effects. It involves statistical approaches that calculate the average interference power and adaptively adjust transmission parameters to mitigate its impact.
- Interference cancellation: This technique involves actively cancelling out the interfering signals to reduce ICI. Methods like beam forming can be employed to nullify or attenuate the interfering signals, improving overall network performance.
- Adaptive beam forming: This technique utilises smart antennas to dynamically adapt their beam patterns to minimise ICI. By steering transmission beams towards intended receivers and away from interfering cells, adaptive beam forming reduces the impact of ICI on network performance.

(ii) Interference avoidance refers to a set of frequency reuse algorithms implemented to introduce limitations on the transmission power and resource allocation. Its main objective is to reduce ICI while simultaneously making the intended signal better. This scheme is characterised by its avoidance strategy, aiming to reduce ICI without imposing additional computational burdens or requiring extra hardware elements on user devices. Its effectiveness lies in optimising LTE networks to deliver high-quality services to cell-edge users without compromising the performance of the customers using the cell centre. By implementing effective ICIC techniques in wireless networks, the goal is to significantly mitigate ICI and enhance overall network performance.

The paper is divided into various sections to discuss the related work used as a literature review and the definitions of notable terms such as throughput, packet delay, and packet loss ratio (PLR). The simulation method used, results, discussion, and conclusions are also included to summarize the work and highlight potential drawbacks for future research.

RELATED WORK

A low-complexity distributed SFR scheduling system with user categorization, balanced fairness, and throughput optimisation for all users was presented by Lee et al. (2013). Within a cell, the cell-centre band (CCB) and the cell-edge band (CEB) are the two distinct spectrum bands used in the method. Cell-edge users (CEUs) are users who are more affected by interference from nearby cells than other users, who are sometimes referred to as cell-centre users (CCUs). Gawłowicz et al. (2015) extended the use of the third version of network simulation environment (NS3) LTE platform to model the frequency fractional reuse (FFR) network; however, Ozovehe and Usman (2015) used key performance indicators (KPIs) based on data from drive tests or network management systems to assess the effectiveness of a live, operational cell phone network in Niger State (Minna), Nigeria. It was found that the performance of mobile services in Nigeria is not too good, and the signal performance and retention ability are unacceptable. Li et al. (2016) proposed an FFR algorithm that performs better than the traditional FFR and SFR schemes. The results indicated that the proposed scheme proves to be efficient in interference control in the heterogeneous network. An assessment of deployed 4G-LTE services in Ghana based on drive test software and the NEC model algorithm was also conducted by Tchao et al. (2018). It was determined that 4G LTE can meet the constantly rising demand for the web when compared to the throughput required to handle data-driven bandwidth services. Using the NetSim training program, Almazroi (2018) evaluated the effectiveness of 4G broadband wireless networks and found that, in terms of bandwidth and compatibility with earlier networks, 4G has proven to be the best generation currently in use. Galadanci and Abdullahi (2018) used drive examination applications to analyse the efficiency of mobile phone networks in the Nigerian metropolis of Kano. The findings indicate that the efficiency of GSM systems in Kano is still far below the Nigeria Communication Commission (NCC) standard and well behind customers' desired outcomes. Based on the analysis of related literature, investigators have employed multiple methodologies to assess LTE network functionality. Khan et al. (2019) proposed a method for interference management compared with three existing FFR methods based on throughput and found out that the throughput increased linearly when the number of femtocells increased. In earlier studies on interference avoidance, the authors introduced different types of frequency reuse and FFR schemes available in the LTE module of NS3 (Tangelapalli & Saradhi, 2019). The results show the highest increase in throughput in downlink with SFR. Sarwar et al. (2020) worked on LTE-A interference management in OFDMA-based cellular networks; the result showed that LTE-A has become capable enough to reduce co-channel interference (CCI) and adjacent channel interference (ACI), while drive testing was the primary method used in Nigeria to evaluate real-time second and third-generation (2G and 3G) GSM wireless networks. Some recent investigations, however, did not compare mean packet delay and mean packet loss together with other measures of cellular network efficiency. To provide an overall evaluation, the current study compares the modelling results of two FFR platforms, SFFR and DFFR, and compares them to SFR, which has been extensively researched in almost all previous work on interference avoidance. In the recent work of Liu (2022), an evaluation of some frequency channel configuration methods over ultra-dense environments was conducted based on user scenarios. The paper adjusted some parameters of 19 units and compared among FFR, integer frequency reuse (IFR), transmission interference temperature limit (TX-ITL), and simultaneous water injection (SWI) method. The outcome demonstrates the TXITL-IFR3 technique's strong development prospects and ability to handle extremely dense customer requirements in ultra-dense environments. However, only the user capacity based on signal to noise ratio (SNR) was considered. Yautentzi et al. (2024) worked on the performance analysis of ultra-dense networks with frequency reuse. A simulation of an ultra-dense network coexisting with a macro network was performed, and an analysis of how it affects the co-channel interference of the small cells of the ultra-dense network was studied. The result showed that as a strategy to mitigate interference, frequency reuse is used to improve performance. With the simulation, it was possible to provide a good insight into the performance of this type of network in terms of the maximum transmission rate. As a result, the goal of this paper is to simulate fractional frequency reuse in an LTE-A network environment by examining and comparing the performance (in the context of mean throughput, PLR, and packet delay) of heterogeneous cellular systems for both SFFR and DFFR algorithms. The performance of the simulation was also tested over three major network providers in Nigeria.

DEFINITION OF NOTABLE TERMS

Firstly, it is essential to define the three parameters used in the study, namely throughput, packet delay, and PLR.

Throughput refers the level of successfully received packets (a portion of the message sent) within a defined time frame. This metric consists of two distinct parts: total throughput and average throughput. Total throughput (TTp) refers to the total volume of information received over a specific time, while average throughput (ATp) denotes the amount of information received by customers in a specific time period (Maskooki et al., 2015). TTp and ATp can be expressed as follows:

$$\mathrm{TTp} = \frac{R_x}{T_{sim}} \qquad [1]$$

$$\mathrm{ATp} = \frac{R_x}{T_{sim} \cdot N_{users}} \qquad [2]$$

where, R_x refers to the total level of bits obtained, T_{sim} refers to the level of bits transmission, and N_{users} is the total number of users.

Packet delay refers to the average time it takes for data packets to travel from one location to another, often referred to as latency. Network latency consists of the time it takes for a data packet to travel from its original location to another location within a network. In terms of user experience, network latency directly impacts the speed of a user's actions, triggering a response from the network. For example, it affects how quickly a web page can be accessed and loaded over the internet.

The ratio of the total number of delivered packets to the number of packets that were lost is known as the packet loss ratio, or PLR, and can be expressed as:

$$\mathrm{PLR} = \frac{\text{Lost packets} \times 100\%}{\text{Sent packets}} \qquad [3]$$

The following questions are addressed in this paper:

(i) Based on the packet delay, throughput, and PLR for specific mobile service providers under various network loads, how significantly do inter-cell interferences affect the cell edges?

(ii) What effect does the cell have on downlink retransmission performance?

To address the aforementioned questions, the following objectives are considered:

(i) Deduce a distribution algorithm to reduce the ICI and examine the cell edges throughput; and

(ii) Estimate the network load of selected mobile service providers based on the number of users.

SIMULATION METHOD

The term 'simulation' is a mathematical description used to predict the actions of an actual process or system over time. By employing simulations, researchers can examine how systems or things behave dynamically in scenarios that would be harmful or impractical to replicate in reality. Researchers utilise simulations to assess and predict possible effects on the overall functioning of the system while changing individual system components.

In this work, the influence of ICI on the performance of the system has been assessed based on packet loss, packet delay, and throughput using an LTE platform. The analysis is based on computer simulation for producing and analysing the data, and the algorithm uses the LTE model based on NS3, whereby subscribers interact with a distant server via routes, connectivity to the internet, and point-to-point linkages made up of UEs, cells, and base stations (eNodeB). In this study, several network entities assist in the design and modification of LTE network models on the NS3 simulation environment. Different testing with multiple network loads (i.e., the number of users) was deployed to examine the outcome of ICI on LTE system performance using the DFFR, SFFR, and SFR algorithms. The NS3 simulator was also adapted for the selected mobile network providers (Operators A, B, and C) to compare and analyse the performance of the LTE system based on the delayed PLR and throughput across various network loads. The analyses also consider their distinct transmission power ratings, while utilising the same Ad Hoc On-demand Distance Vector (AODV) routing protocol. The simulation results are reported and analysed in several statistical plots.

A model comprising 19 hexagonal cells has been employed to assess specific FFR algorithms, including SFFR, SFR, and DFFR. This model utilises a term referred to as reuse of frequency based on a factor of three at the cell edge and one at the cell centre. The selection of the reuse factors and the cells was based on the 3GPP recommendation for LTE, with each cell serviced as an eNodeB, which is based on a scheduler, a power management strategy, and bandwidth. To reduce the total testing time in NS3, the modelling parameters presented in Table 1 were typically selected using the 3GPP specifications for LTE and are similar throughout each simulation performed with the same data flow and simulation time for the selected algorithms. When modelling different network scenarios with different network loads, the UEs are randomly distributed between the cell centre and cell edge zone, which is an important parameter.

Additionally, the modelling process was predicated on the use of an identical power budget as the 3rd generation guidelines by SFR, DFFR, and the two outer areas of SFFR, or the middle and edge regions. It is anticipated that the central portion of SFFR-enabled cells will operate at a reduced power to conserve energy.

The evaluation of the adapted NS3 algorithms for Operators A, B, and C was carried out with the AODV routing protocol algorithm while considering only their different transmission power ratings as presented in Table 2. Different simulations were run for each service provider with the exact simulation period for a different number of nodes, and the results in terms of loss ratio of the packet, throughput, and delay of the packet were extracted, analyzed, and compared to ascertain the network service provider offering the most superior quality of service and system performance.

Table 1
Simulation parameters based on the 3GPP specifications for LTE

Parameters	Values
System bandwidth (MHz)	20
Carrier frequency (GHz)	2
Subcarriers bandwidth (kHz)	15
RBS' number	25
Cells' number	19
Radius of the cell (m)	1,000
SINR threshold (dB)	SFR (20); DFFR (25); SFFR (15)

Note. 3GPP = Third-Generation Partnership Project; RBS = Radio base station; SINR = Signal-to-noise ratio; SFR = Frequency Fractional Reuse; DFFR = Dynamic Frequency Fractional Reuse; SFFR = Soft Frequency Fractional Reuse

Table 2
Transmission power ratings of the selected mobile network (Ajibola et al., 2015)

Service provider (Operator)	Transmission power (dBm)
A	64
B	72
C	87

SIMULATION RESULTS AND DISCUSSION

The average packet delay of SFFR, DFFR, and SFR was calculated using the average number of UEs for both the cell edge and center cell. Figures 2(a) and 2(b) illustrate the impact of average packet delay on the number of customers in each cell, based on center and edge users, respectively. It was observed in Figures 2(a) and 2(b) that SFFR can support less than 24 users per cell at the center and less than 20 users at the edge without a significant increase in packet delay. However, DFFR can accommodate more users compared to SFFR. In general, as the number of users at the center and edge increases, so does the packet delay.

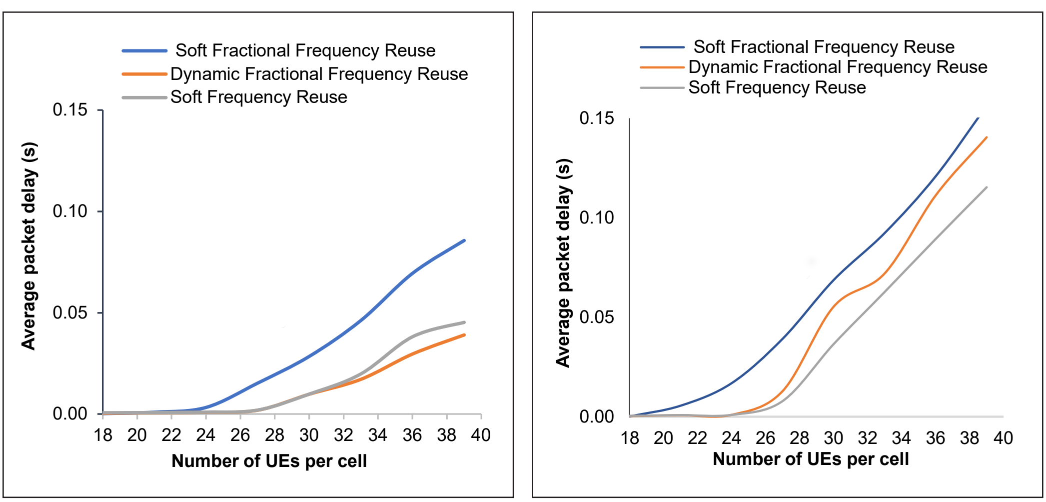
Overall, it was observed that in DFFR, the CEU has better system performance compared to SFFR. Additionally, DFFR outperforms SFFR at the CCU, where SFFR shows the lowest system efficiency and struggles to counteract ICI and fading due to reduced transmission power at the center region.

The throughput of SFFR, DFFR, and SFR was calculated based on the number of UEs and the cumulative distribution function (CDF) for both the cell edge and center cell. The results are shown in Figures 3(a) and 3(b). It was found that throughput decreases as the number of users increases for both center and edge cells. SFFR had lower interference with fewer users, resulting in lower throughput for CEU compared to DFFR and SFR. As the number of users increased, DFFR showed better performance in both center and edge cells compared to SFFR.

The throughput of each reuse scheme was also analyzed based on the CDF, as depicted in Figures 4(a) and 4(b). The results indicated that DFFR outperformed SFFR in terms of system throughput, as DFFR could support more users before experiencing a decrease in throughput. Therefore, DFFR has superior system throughput compared to SFFR.

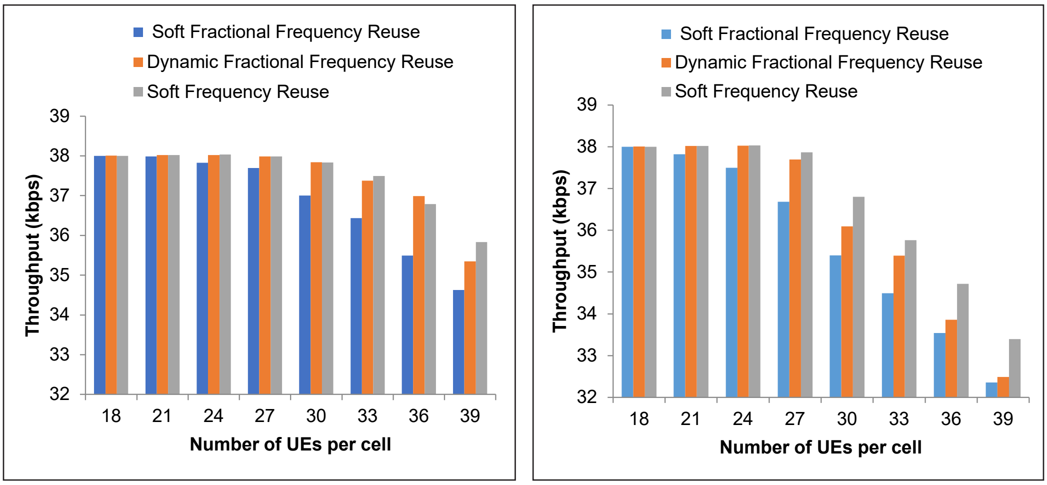
Low load implies that there is no packet loss at the cell centre or cell edges because the amount of traffic sent and received is the same. As the number of users increases, there is an increase in packet loss at both the centre cell and the cell edge. High rates of packet loss can significantly degrade the perceived audio quality for users utilising internet telephony applications.

Figure 5(a) illustrates the influence of the PLR on the number of users for the center cell. Both SFR and DFFR can accommodate more than 28 users before experiencing



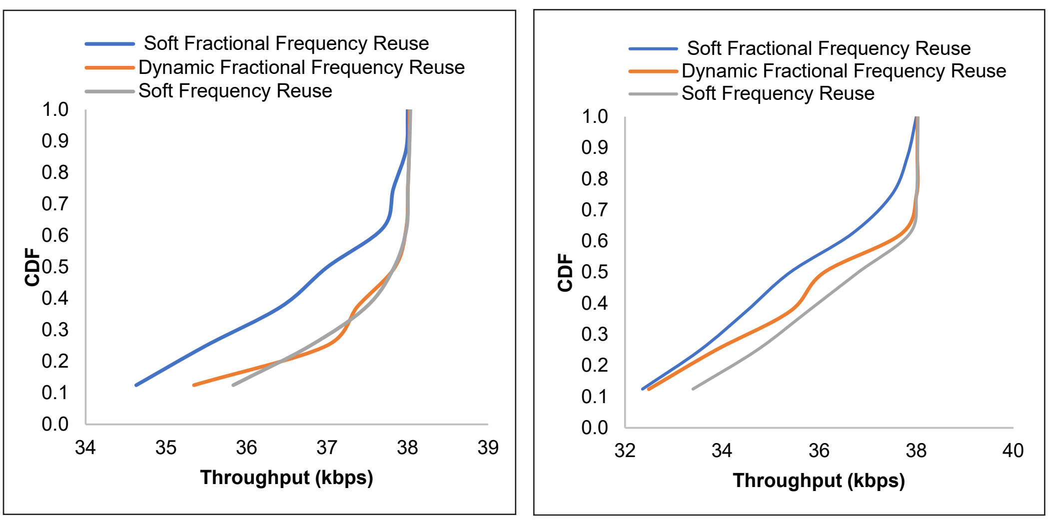
(a) (b)

Figure 2. Average packet delay for (a) cell centre users and (b) cell edge users
Note. UE = User equipment



(a) (b)

Figure 3. Average throughput per user equipment (UE) for (a) the cell centre users and (b) the cell edge users



(a) (b)

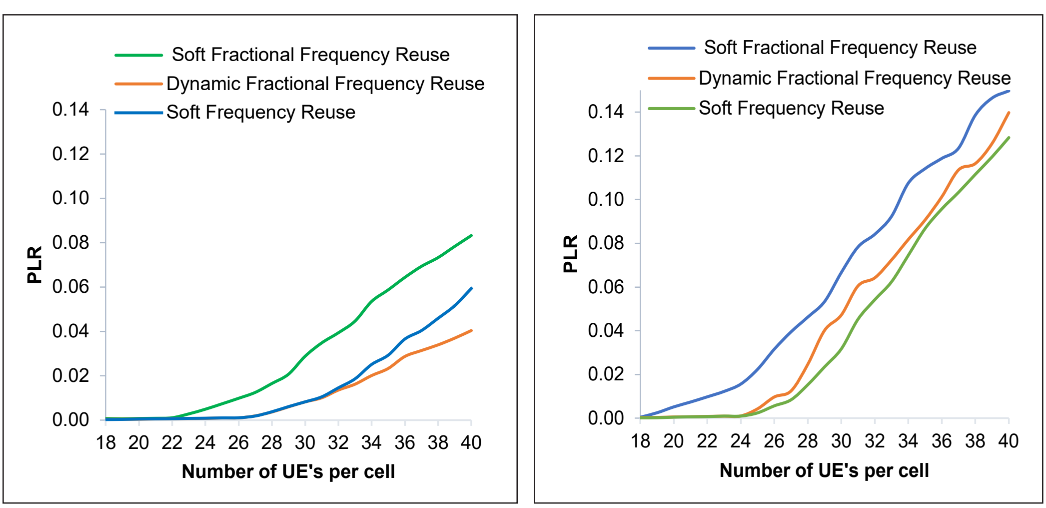
Figure 4. Cumulative distribution function (CDF) of the average throughput for (a) the cell centre users and (b) the cell edge users

drastic packet loss rates. SFFR, however, can sustain 23 users with the same QoS. DFFR outperforms SFFR by accommodating more users at the cell center before experiencing packet loss and also surpasses SFR with a lower PLR as the number of users increases from 32.

Figure 5(b) also depicts the influence of PLR on the number of users for the cell edge. It shows that cell edge users experience higher ICI with an increase in the number of users compared to Figure 6(a) (i.e., cell center). It was observed that DFFR has better system performance as it can accommodate 25 users before experiencing packet loss, compared to SFFR, which can only accommodate 19 users. DFFR also outperforms SFR as it experiences less packet loss as the number of user's increases up to 27.

An analysis of the network load of selected mobile service providers (A, B, and C) was conducted, taking into account different transmission power ratings: 64 dBm for Operator A, 72 dBm for Operator B, and 87 dBm for Operator C. Figure 6 illustrates the impact of average throughput on the number of nodes based on the selected service providers. It was observed that, under the same AODV routing protocol and considering network loads of 50, 75, 100, 125, and 150 nodes, the average throughput decreased as the number of nodes increased. Operator A showed an almost linear decrease in throughput, while Operators B and C initially experienced an increase in throughput at 100 nodes before a decrease at 125 nodes. The significant decrease in average throughput for Operators B and C with an increase in the number of loads indicates that Operator A has better system throughput performance.

Figure 7 also demonstrates the impact of packet delay on the number of nodes. It reveals that as network load increases, delay performance worsens, leading to an increase in packet delay. Operator B had more packet delay between 100 and 125 nodes due to a higher number of users compared to Operators A and C, while Operator C had more packet delay than A. Therefore, Operator B experienced more packet delay, with Operator A having the least packet delay. Figure 8 displays the signal pattern for packet reception for



(a) (b)

Figure 5. Packet loss ratio (PLR) for the (a) cell centre users and (b) cell edge users
Note. UE = User equipment

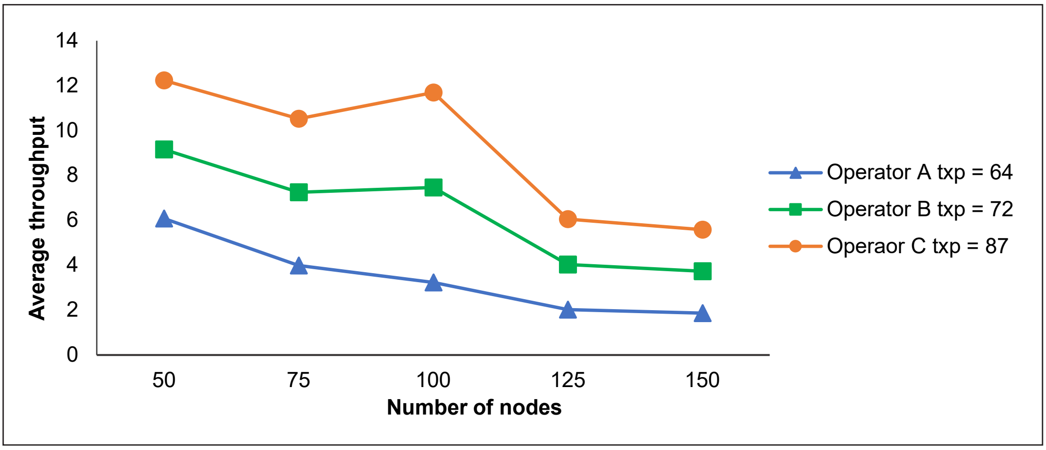


Figure 6. Comparison of the average throughput based on the selected service providers
Note. txp = Transmission power rating

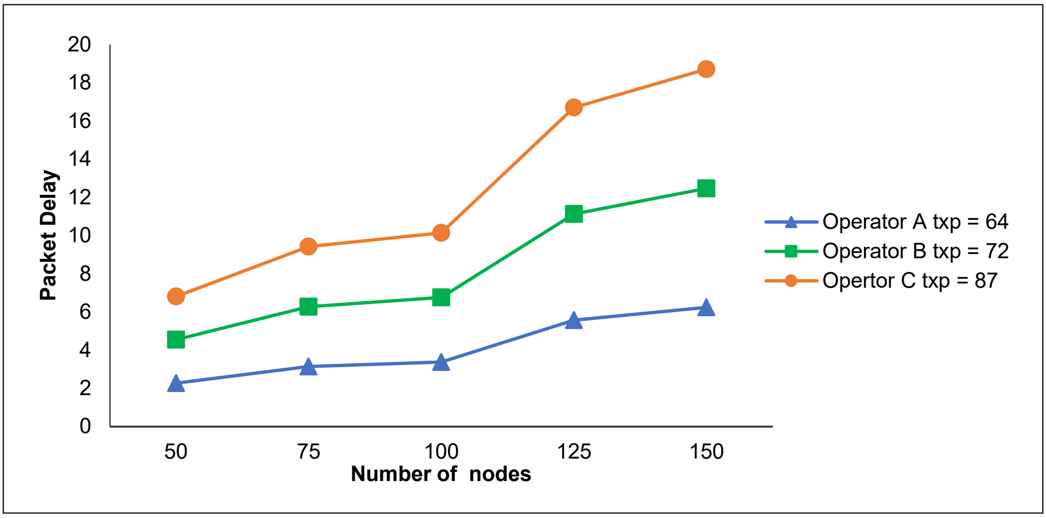


Figure 7. Comparison of the packet delay based on the selected service providers
Note. txp = Transmission power rating

the three selected service providers at a typical network load of 50 nodes. It was observed that, unlike Operator C, who had a decrease in packet reception as the model duration increased with more consumers, Operators A and B exhibited similar patterns. In general, it can be concluded that Operator A has better system performance in terms of throughput and packet delay parameters compared to Operators B and C. This is also evident in the QoS of A compared to the other service providers.

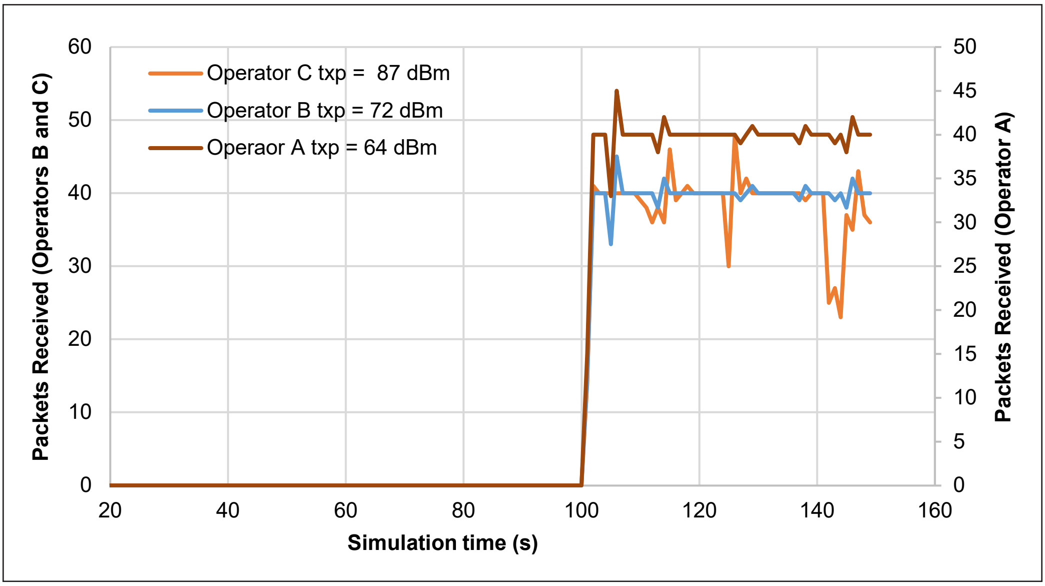


Figure 8. Comparison of the packets received based on the selected service provider for a typical node (50 nodes)
Note. txp = Transmission power rating

CONCLUSION

This study evaluates two fractional frequency reuse approaches in the downlink of the 3rd generation LTE architecture to ensure customer service quality, analysing the advantages and disadvantages of each method. The simulation highlights the distinctions among these strategies. Reducing transmission power in the central region diminishes system efficiency, as it lacks the requisite strength to mitigate inter-channel interference and fading. The SFFR bandwidth is distributed to three independent sub-bands with unconventional locations, potentially diminishing the system's flexibility, as most users are located in the central or edge regions. Consequently, in comparison to the DFFR and SFR, it attains the lowest system performance. DFFR mitigates inter-cell interference more effectively than SFR, but only slightly. SFR and DFFR facilitate the utilisation of more RBs at the cell-edge region, leading to superior system performance compared to SFFR. The evaluation of the selected mobile service providers indicates that Operator A exhibits superior system performance relative to Operators B and C, as evidenced by their quality of service throughout a broad region in Nigeria. The model can be deployed for future generation networks. Future work will involve comparing it with the real-world data and analyzing the effects of SNR among other factors.

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