FFR-based radio resource allocation for RIS-aided D2D communication in multicell cellular network

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ABSTRACT

Device-to-device (D2D) communication and reconfigurable intelligent surfaces (RISs) are two technologies that are attractive components of future wireless networks. D2D allows nearby devices to communicate directly, which helps boost network efficiency by reducing the load on base stations. However, since D2D often uses the same frequency bands as regular cellular users (CUEs), it can cause interferences. RIS, on the other hand, enhances signal coverage by intelligently reflecting signals toward their intended destinations, but it can also unintentionally reflect interfering signals, especially in crowded multicell networks during downlink transmission. To address these interference challenges, this paper explores the application of a fractional frequency reuse (FFR) strategy purposed for networks that integrate both D2D and RIS technologies in multicell cellular network scenarios. The simulation outcomes imply that the proposed FFR method notably expands performances i.e., raising the signal quality in term of signal-to-interference-plus-noise-ratio (SINR) from 0.47 dB to 1.93 dB, enhancing throughput from 10.8 Mbps to 13 Mbps, and improving the bit error rate (BER) to 21 errors per 100 bits, demonstrating its effectiveness in improving network reliability and efficiency.

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1. INTRODUCTION

Device-to-device (D2D) communication has been considered as a remarkable technology in improving connectivity for 5G and future mobile networks [1]. It is distinct to traditional cellular systems that rely on base stations to relay data, D2D allows two adjacent devices to communicate directly one to another [2], [3]. This direct link offers several advantages, such as more efficient use of the wireless spectrum, lower energy consumption, increased network capacity, reduced transmission delays, better radio resource distribution, lower latency, and faster data speeds [4], [5]. Due to these benefits, D2D is seen as a key enabler for building more efficient and responsive next-generation wireless systems.

In licensed frequency bands, D2D users share the identical legacy spectrum as traditional cellular users (CUEs), managing this shared access falls to the Evolved Node B (ENodeB), which handles tasks like identifying device pairs, setting up connections based on channel quality, assigning radio resources, as well as controlling interferences. D2D communication works in two main modes, depending on how it shares the spectrum: in-band and out-band modes [6]. In-band D2D uses the cellular network's licensed frequencies and comes in two forms: underlay and overlay. In underlay mode, D2D devices reuse the identical resources as regular CUEs, which improves spectrum efficiency [7], but it can increase interferences. Overlay mode avoids this by assigning separate resources to D2D users i.e., a portion of radio resources is dedicated for D2D users, helping to limit interferences. Out-band D2D, on the other hand, operates over unlicensed frequency bands, keeping it separates from the cellular network to reduce interferences and improve flexibility. However, interferences especially in densely used networks remains a major challenge. It brings most of ongoing researches to focus on finding smarter ways to manage interferences and to make better use of available spectrum resources [8].

In addition, reconfigurable intelligent surfaces (RISs) are rapidly gaining much attentions as a transformative technology in wireless communications. RISs work by intelligently controlling on how signals are reflected and directed through the wireless environment [9]. RIS can be thought as a smart, programmable surface that can helps shape the signal paths. It makes more efficient wireless connections [10]. This technology is expected to significantly boost network capacity, to expand coverage, to lower energy usage, and to reduce infrastructure costs. Therefore, it is expected ultimately to improve the performance and reliability of next-generation wireless networks [11], [12].

RISs and relay systems are both designed to improve weak or obstructed wireless signals by creating clearer and more direct paths. However, there is a key difference on how they function. Relay systems actively amplify and retransmit signals in which it requires extra power. In contrast, RIS operates passively, smartly reflects signals without additional energy [13], [14]. Reasons on what makes RIS even more practical is its size and its flexibility. RISs are compact, lightweight, and easy to install or to remove. They can be mounted almost anywhere. It can be attached on walls, ceilings, billboards, or building exteriors. It makes them a versatile solution to enhance network coverage [15].

When D2D users are spread out across multiple cells and combined with RIS technology, interferences become a greater issue, particularly during downlink transmissions. This gets even more complicated with in-band underlay, where D2D devices and traditional CUEs share the identical frequencies in which it leads to more interferences. To overcome this issue, it is essential to use effective interference management techniques. One effective approach is fractional frequency reuse (FFR)-based radio resource allocation in which it helps better organize how radio resources are allocated. In addition, it reduces interference effects and it boosts network efficiency.

Eslami *et al.* [16] work on boosting uplink performance in a complex network which is made up of macrocells, femtocells, and D2D users. Their goal is to maximize the overall data rate while it ensures power limits and quality-of-service (QoS) requirements to be met. In order to perform this, the authors use an FFR-based interference management approach that breaks the challenge into three parts. These three parts are: i) deciding which users can connect (admission control), ii) managing power levels, and iii) allocating sub-channels. In another study, Amiriara *et al.* [17] explore on how D2D systems are supported by RIS handled co-channel interferences. They introduce a deep neural network (DNN) model that can predict outage probabilities in real time in which it helps improve system reliability and performance.

Considering these concepts further, this paper introduces a soft-FFR approach to help minimize interference effects from the ENodeB and at the same time it boosts the signal quality for D2D users. Unlike previous studies that mainly focus on uplink resource allocation in heterogeneous networks or outage probability analysis in RIS-assisted systems, our current paper emphasizes interference mitigation for D2D communications in multicell cellular networks in which RIS is deployed in it. The proposed method divides frequency channels based on microcell coverage areas. Keeping this implementation, it is expected to control interferences which are generated by the base station and nearby users. By incorporating the soft-FFR scheme and RIS technology, the proposed approach aims to enhance signal propagation and improve spectrum utilization. As a result, the system is expected to provide more reliable communication performance for both D2D users and conventional CUEs in dense network environments.

This paper is organized as the following. Straightforward after this introduction section, section 2 explains the proposed system. It includes how the simulations were set up and which performance measures were used to assess it. Section 3 takes a closer look at the simulation results and discusses a detailed analysis. Finally, section 4 wraps the research finding up with the main conclusions.

2. SYSTEM DESCRIPTION AND SIMULATION PARAMETER

2.1. Baseline system versus proposed fractional frequency reuse scheme

Firstly, this research examines a three-cell microcell network setup without using the proposed method in which we call it as baseline system. The network operates with a frequency reuse factor (FRF) of 1, allowing each microcell to access the full system bandwidth for both uplink and downlink. CUEs and D2D user pairs (DUEs) are randomly and evenly scattered across the area. We consider that the users either DUE and CUE are static, not mobile during the simulation observation, thus the channel model does not include fading channel. And then, we apply the proposed FFR approach to the baseline system. In summary, the study compares two models: the standard baseline system and one that incorporates the new FFR strategy. In the simulation, RISs are placed along the borders of the microcells to help improve signal reception for DUEs by reflecting signals from transmitters to receivers. However, RIS can also reflect unwanted signals, which may increase interference within the network.

In this setup, both the D2D and the microcellular systems join to use the identical frequency band, meaning the D2D operates as an in-band underlay. The total bandwidth of 10 MHz is split into four sub-channels or sub-bandwidth. The 10 MHz bandwidth has been chosen as it is one of standard bandwidth for the 4G/5G cellular networks. About 25% of the bandwidth is dedicated solely to CUEs, while the remaining 75% is shared between DUEs and CUEs, following the description as shown in Figure 1. The system prioritizes CUEs, giving them access to more channels than DUEs. Figure 2 shows the baseline scenario used in the simulations, where we can see the DUE receiver facing significant interference from the transmit power of the ENodeBs and other D2D transmitters. However, when RIS is added to the network, it helps strengthen the signals for DUEs, especially those near to the RIS, improving their overall signal quality.

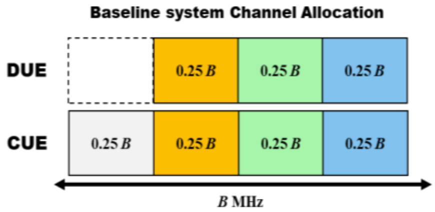


Figure 1. Channel allocations of DUEs and CUEs for baseline system

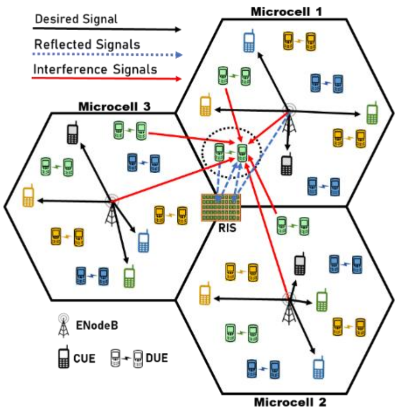


Figure 2. Baseline system based on D2D communication in RIS-aided multicellular network

FFR is a technique that divides frequency channels based on different parts of a cell, separating it into inner and outer zones. In this paper, a soft-FFR approach is applied. In our soft-FFR approach, most channels are shared among the inner cell areas. Meanwhile the outer areas use different channels to prevent interference between neighboring cells. Figure 3 illustrates how the channels are allocated with our proposed FFR method. Figure 4 illustrates the interference suffered by a DUE located in the inner part of a cell. For the DUE in Microcell 1, interference comes from other DUE transmitters in Microcells 1, 2, and 3, as well as from ENodeBs in Microcells 1 and 3. Interestingly, the ENodeB in Microcell 3 does not cause interference because the FFR technique removes 25% of the channels in each microcell, which helps minimize overlapping signals.

2.2. Performance parameters' analysis

In networks that use RIS technology, signals can travel in two ways. These are direct link which is called as line-of-sight (LOS) path and non-direct link or called as non-line-of-sight (NLOS) path when obstacles block the signal. The LOS signals follow a standard free-space path loss model, which measures how much the signal weakens over distance. For NLOS signals, an extra loss factor called L_{Obs} is added to account for the impact of obstacles. The obstacles can be metal, glass, concrete, or stone that can block or weaken the signal. To model how RIS improves communication, this paper uses a two-ray channel model from [18], shown in Figure 5, which helps calculate the power of the received signal, based on (1):

$$P_{Rx} = (N+1)^2 P_{Tx}\left(\frac{\lambda}{4\pi d}\right)^2 \quad (1)$$

where P_{Rx} refers to the power received by the receiver and P_{Tx} is the power sent out by the transmitter, both measured in watts. The symbol N represents how many elements the RIS has, λ represents the signal wavelength in meters, and d is the spatial distance which separates the transmitter and receiver (in meters).

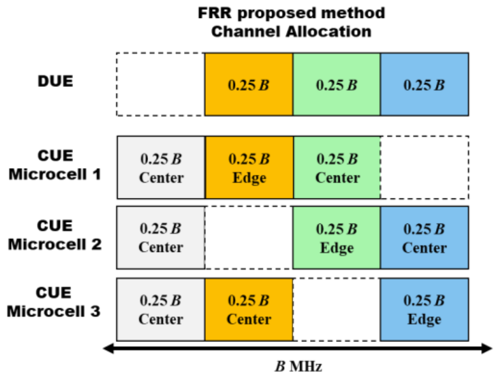


Figure 3. Channel allocations of DUEs and CUEs for the considered FFR method

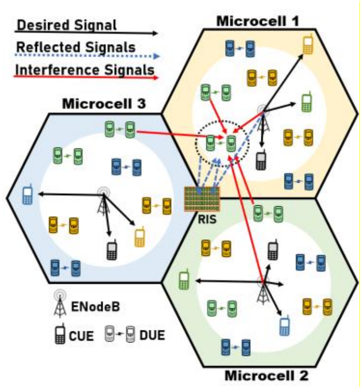


Figure 4. Overview of the FFR technique applied to D2D communication within a multicellular network using RIS support

The evaluation of signal-to-interference-plus-noise-ratio (SINR) focuses on the DUE receivers depicted in Figure 5, where a pair of DUEs is engaged in downlink communication. These receivers can suffer interferences from multiple sources, mainly from the ENodeB and other nearby DUE pairs. While RIS technology helps strengthen the signal of the user receives, it can also introduce additional interference from other devices. The SINR for the observed DUE receiver, denoted as γ_{DUE}, can be calculated using (2) [19]:

$$\gamma_{DUE} = \frac{P_{DUE}}{\sum_{i=1}^{x} I_i + \sum_{j=1}^{y} I_j + P_N} \quad (2)$$

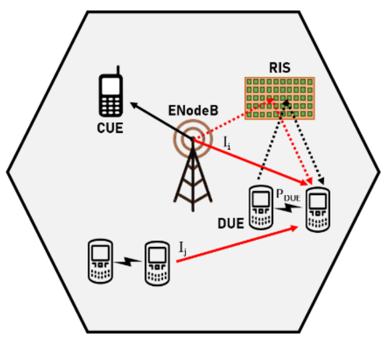


Figure 5. DUE receiver network scenario analysis with the RIS-aided

In this case, P_{DUE} is the power of desired signal for the DUE receiver, measured in watts or milliwatts. The letters x and y show how many interfering sources there are caused by other DUEs and by from ENodeBs, respectively. P_N represents the noise power at the receiver being studied. Meanwhile, I_i is the interference coming from the *i*-th DUE, and I_j is the interference caused by the *j*-th ENodeB that is using the same frequency channel.

Throughput (C) is basically the amount of data that gets delivered within a certain time frame, or simply the fastest data rate the system can achieve. For a DUE, the throughput (C_{DUE}), shown in bits per second (bps), can be calculated using (3) [20]:

$$C_{DUE} = B \log_2(1 + \gamma_{DUE}) \quad (3)$$

In this case, B refers to the total bandwidth for the system in hertz (Hz). The bit error rate (BER) shows the percentage of bits that are received incorrectly compared to the total bits transmitted by the transmitter to the receiver. The BER performance is influenced by the modulation scheme and channel conditions. In this study, the transmission system uses a M-QAM modulation scheme with modulation order $M = 16$. Following the BER formulation presented in [21], the BER for the DUE, denoted by β_{DUE}, is calculated as in (4):

$$\beta_{DUE} = \frac{3}{4} Q\left(\sqrt{\frac{4}{5} E_b/N_0}\right) \quad (4)$$

The $Q(.)$ function is a mathematical tool used to evaluate the probability of errors at a given point. Meanwhile, E_b/N_0 is the energy per bit divided by the noise power spectral density. It serves as a way to gauge the signal quality for each bit transmitted. As shown in (5) it depicts how this value connects to E_s/N_0 in which it is the energy per symbol over noise power spectral density.

$$\frac{E_s}{N_0} = \frac{E_b}{N_0} \log_2 (M) \quad (5)$$

Table 1 summarizes the simulation settings and parameters used in this research. To ensure dependable results, the simulation was carried out 10,000 times using the Monte Carlo method in MATLAB 2021. This method helps determine how many iterations are needed to produce accurate and consistent outcomes. The study focuses on comparing the performance of DUEs and CUEs in a network supported by RIS. It analyzes both the baseline system setup and the system improved with the proposed FFR approach. Note that the number of RIS elements is chosen to be 100 elements. It is to give a good trade-off in the increase of signal quality, the device size, and hardware complexity level [22].

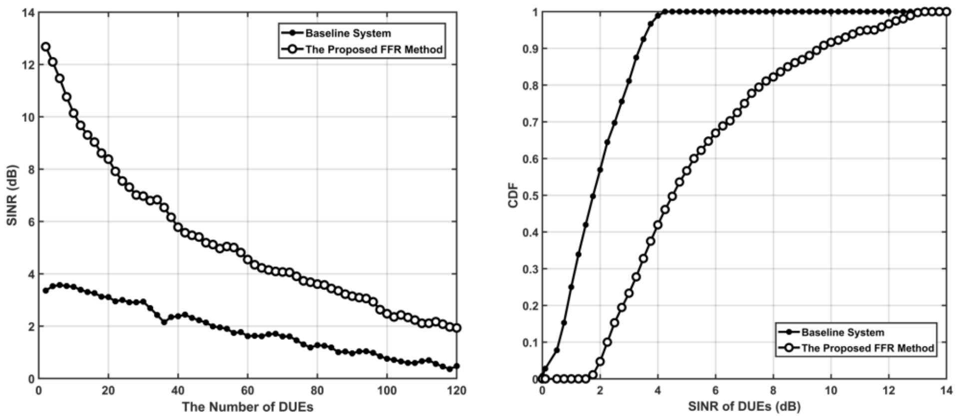
Table 1. Simulation parameter setting

No.	Parameters	Value
1	The quantity of microcells	3
2	FRF for microcells	1
3	The radius of microcells [23]	500 m
4	ENodeB power [23]	40 dBm
5	DUE transmitter power [24]	23 dBm
6	DUE pair distance [7]	10 m
7	The quantity of CUE (each microcell)	120 users
8	The quantity of DUE pairs (each microcell)	120 users
9	The quantity of RIS elements, N	100
10	Total system bandwidth, B	10 MHz
11	Working frequency, f	1900 MHz
12	Obstacle loss, L_{Obs}	10 dB
13	Modulation scheme	16-QAM
14	Simulation iterations	10,000

3. RESULTS AND DISCUSSION

In this section, we take a close look at the simulation results for SINR, throughput, and BER for both DUEs and CUEs. We compare how the baseline system setup performs against the network when using the proposed FFR method. To better understand how reliable the service is, we also examine the cumulative distribution function (CDF) and complementary CDF (CCDF), which show the chances of experiencing signal drops or reduced quality.

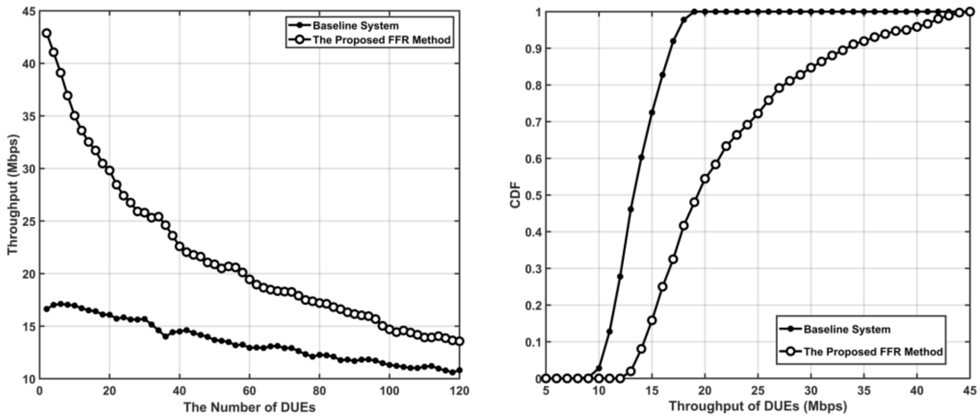
Figure 6 presents the SINR performance of DUE receivers obtained from the simulation results. Figure 6(a) illustrates how the signal quality for DUEs, measured by SINR, tends to drop as more users. The number of DUEs is up to 120 users. It connects to the network. In the conventional system setup, the SINR declines to just 0.47 dB. With the proposed FFR method, it improves significantly to 1.93 dB, an increase about 1.5 dB. This means users get a stronger and clearer desired signal, which helps the network performs better overall. Figure 6(b) observes deeper into how often different SINR levels occur. For values at or below 3 dB, the baseline system experiences this nearly 82% of the time, whereas the FFR method reduces it to just 23%. This means that about 77% of the time, the FFR approach delivers SINR above 3 dB. It implies that the FFR approach performs better than the baseline system.



(a) (b)

Figure 6. Simulation outcomes showing; (a) SINR at the DUE receivers and (b) the CDF of SINR for the DUE receivers

Figure 7 shows the simulation results of throughput performance for DUE receivers as the number of users increases. Figure 7(a) illustrates the actual data transfer speeds (throughput) that DUEs experience. When there are 120 DUEs, the baseline system delivers 10.8 Mbps. With the proposed FFR method, this improves to 13 Mbps. It shows a noticeable increase in speed. Figure 7(b) takes a closer look using a CDF analysis. It reveals that the proposed FFR method consistently outperforms the baseline system. Specifically, the throughput of proposed method falls at or below 15 Mbps only about 18.3% of the time. Meanwhile, the baseline system hits that level much more frequently, 72.5% of the time. It demonstrates that the FFR method provides faster and steadier data rates.

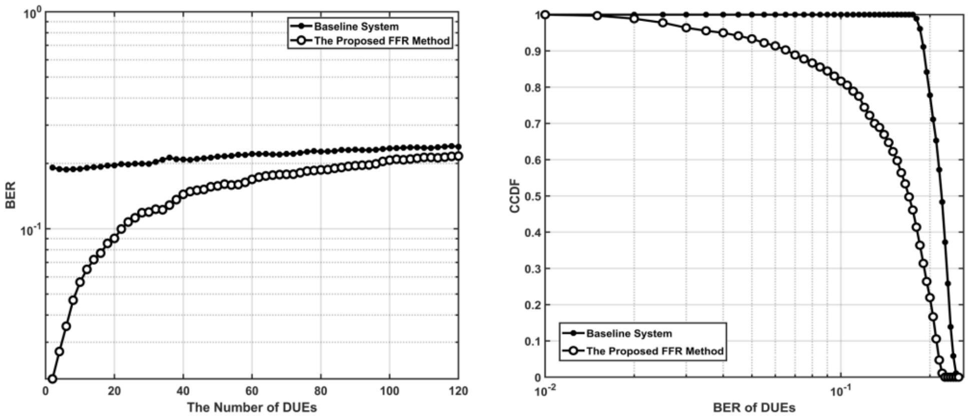


(a) (b)

Figure 7. Simulation results illustrating; (a) throughput at the DUE receivers and (b) the CDF of throughput for the DUE receivers

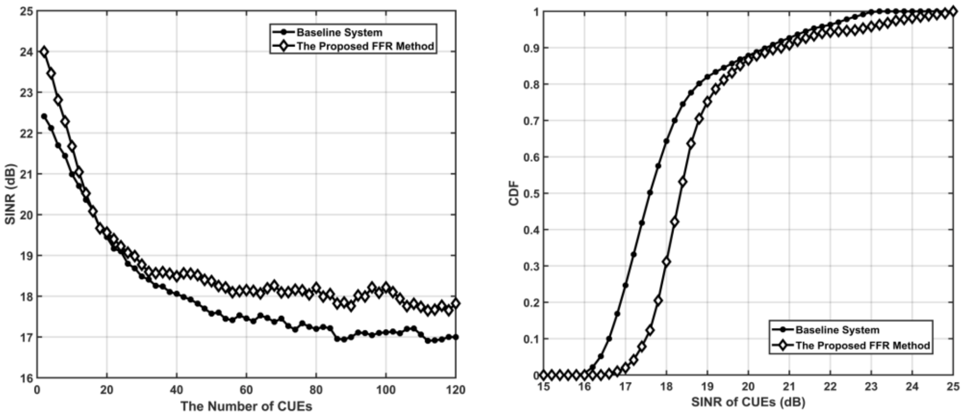
Figure 8 presents the BER performance for DUE receivers. Figure 8(a) shows a comparison of BER for DUEs between the two systems being tested. With 120 DUEs, the baseline system experiences bit errors up to 23×10^{-2} during data transmission. Meanwhile the proposed method lowers that to 21×10^{-2}. In practical terms, this means the FFR method can reduce the number of bit errors by around 21 when sending 100 bits of data. Figure 8(b) explores deeper with a CCDF analysis of the BER. It reveals that for error rates above 20×10^{-2}, the baseline system sees these higher error rates in 75.8% of cases. Meanwhile, the proposed method brings that down significantly to just 21.7%. This clearly shows how the proposed approach helps improve transmission reliability for DUEs.

Figures 9 to 11 depict how CUEs perform in networks with DUEs. It compares scenarios with and without the proposed FFR method. Figure 9 evaluates the simulation results for the parameter of SINR. In Figure 9(a), we can see that the SINR values for CUEs as their numbers increase. It finds 16.9 dB for the baseline system and a higher 17.8 dB with the proposed FFR method. This means the FFR approach helps strengthen the signal for CUEs. It improves their overall service quality. Figure 9(b) takes a closer look by showing a CDF of the SINR values. It reveals that for SINR values up to 18 dB. The 65.8% of cases are from the baseline system, while only 24.1% comes from the system using the FFR method. It clearly highlights the benefits of the proposed approach.



(a) (b)

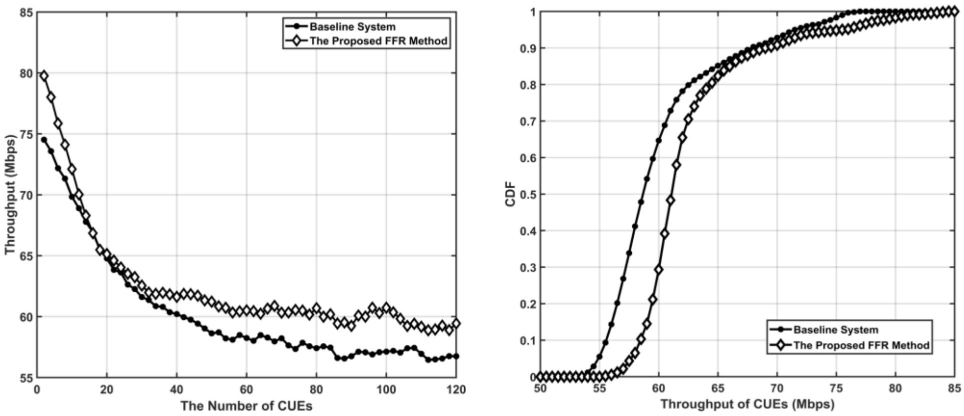
Figure 8. Simulation results showing; (a) BER at the DUE receivers and (b) the CCDF of BER for the DUE receivers



(a) (b)

Figure 9. Simulation results depicting; (a) SINR of CUEs and (b) the CDF of SINR for CUEs

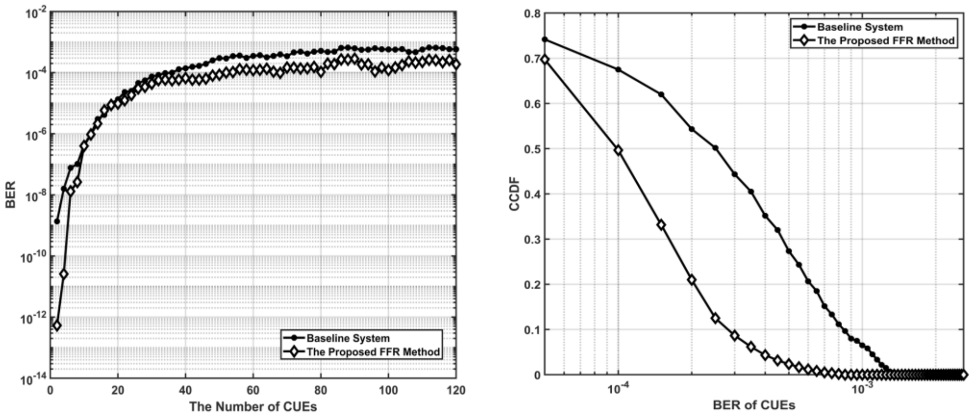
Figure 10 depicts the simulation results for the throughput. Figure 10(a) shows that the throughput results follow a similar trend to the SINR outcomes in which the proposed soft FFR method outperforms the baseline system. When the number of CUEs is 120, the throughput for FFR approach reaches 56.7 Mbps, which it is 2.7 Mbps higher than the baseline's which is 54 Mbps. Figure 10(b) takes a closer look using a CDF analysis, showing that 65.8% of the baseline system's throughput values are 60 Mbps or less, while only 24.1% of the FFR method's values fall into this range. This means the FFR method delivers throughput above 60 Mbps; nearly 76% of the time, demonstrating its ability to consistently provide better and more reliable performance.



(a) (b)

Figure 10. Simulation results illustrating; (a) the data speeds achieved by CUEs and (b) the distribution of these speeds shown through the throughput's CDF

Figure 11 evaluates the simulation results for the parameter of BER. Figure 11(a) compares the BER experienced by CUEs in both the baseline and proposed systems. When the number of CUEs reaches 120, the proposed FFR approach achieves a significantly lower BER of 2×10^{-4}, compared to 6×10^{-4} in the baseline system. Figure 11(b) shows the CCDF of BER values. For BER values above 1×10^{-4}, 67.5% of the results in the baseline system fall into this range, while only 49% do so in the proposed system. These results suggest that the FFR method can effectively reduce the likelihood of higher BERs for CUEs. It offers up to a 51% improvement when it aims for BERs below 1×10^{-4}.



(a) (b)

Figure 11. Simulation results illustrating; (a) BER of CUEs and (b) the CCDF of BER for CUEs

Table 2 presents a comparison between our approach and earlier research studies. This paper introduces a specialized FFR technique designed for multicell networks that combine D2D communication with RIS technology in downlink transmissions. The findings reveal that and it is compared to the conventional system. Our proposed method enhances signal quality (SINR) by 1.93 dB. It also increases data throughput to 13 Mbps. It is significantly cuts down the BER as well. In general, it highlights its strong overall performance.

Overall, the simulation results demonstrate that the proposed integration of D2D communication, RIS technology, and the FFR scheme may reduce interference. At the same time, it improves overall network performance. The improvements in SINR and throughput indicate potential benefits for future dense cellular networks where efficient spectrum utilization and interference management are crucial. However, the results are obtained under simulation conditions. The simulation use simplifying assumptions, such as static users and ideal RIS configurations. In practical deployments, factors like user mobility, varying traffic demands, and RIS hardware limitations may affect performances. Therefore, further studies are suggested to evaluate the proposed approach in more realistic environments. It is also suggested to explore adaptive RIS control and resource allocation strategies for large-scale networks.

Table 2. Comparison of other researches

Ref.	Method	Results
[16]	FFR-based interference management scheme to maximize weighted sum rate in a three-tier HetNet (macrocell, femtocells, and D2D users).	The proposed FFR scheme obtains a system sum rate reaching 93–96% of the optimal Branch-and-Bound method.
[21]	A joint optimization of RIS placement and D2D transmit power under interference and power constraints for reducing outage probability.	The proposed jointly optimal design significantly reduces outage probability with performance gains of 44%.
[25]	Analytical approach using a R5pD in FFR/SFR-based OFDMA networks, optimized with proportional fair (PF) scheduling to balance average cell throughput.	The proposed design achieves average cell throughput of up to 200 Mbps, where SFR and FFR outperform at the 0.7 and 0.1 Mbps threshold.
[26]	Dynamically changing the cell-center size and optimizing how power is distributed to boost efficiency in heterogeneous networks that use FFR.	The new method boosted energy efficiency by 41.95% and 36.60% over the earlier approach.
[27]	Resource allocation distributed strategy for D2D multicast underlay cellular networks.	The proposed scheme consistently improves throughput up to 30% gains over benchmark methods.

4. CONCLUSION

This study proposes a new way to enhance cellular networks by combining D2D communication with RIS technology. The aim is to boost the quality of service for both D2D users and regular CUEs. Since D2D devices and CUEs share the same frequency bands, interferences from base stations and other D2D devices can become a significant problem. To tackle this, the paper introduces a FFR technique that allocates frequency channels based on microcell zones to help reduce interference effects. Based on the simulation results, this approach successfully improves signal quality by 1.93 dB. In addition, it improves throughput to 13 Mbps. It lowers the BER as well to 21×10^{-2} compared to the traditional system. These results demonstrate that the integration of RIS with the FFR-based interference management scheme can effectively enhance network performance for both D2D and CUEs.

However, this study has several drawbacks. The proposed method is evaluated only through simulation in a simplified ideal multicell scenario. Furthermore, practical factors such as user mobility, dynamic traffic conditions, and hardware constraints of RIS are not fully considered. Future works may extend this study by implementing more realistic network environments and conditions. It is also suggested to optimize RIS configuration dynamically. Furthermore, it is suggested to evaluate the proposed approach in large-scale or real-world experimental testbeds.

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AUTHOR CONTRIBUTIONS STATEMENT

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C	: **C**onceptualization	I	: **I**nvestigation	Vi	: **Vi**sualization
M	: **M**ethodology	R	: **R**esources	Su	: **Su**pervision
So	: **So**ftware	D	: **D**ata Curation	P	: **P**roject administration
Va	: **Va**lidation	O	: Writing - **O**riginal Draft	Fu	: **Fu**nding acquisition
Fo	: **Fo**rmal analysis	E	: Writing - Review & **E**diting		

CONFLICT OF INTEREST STATEMENT
Authors state no conflict of interest.

INFORMED CONSENT
We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY
Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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