Simulation Based Energy Efficiency Analysis and Evaluation of DUDe 5G Networks

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***Abstract* - Meeting the escalating demands for data traffic in fifth-generation networks and beyond requires efficient solutions like Heterogeneous Networks, which enhance spectral and energy efficiency by deploying small cells close to users. Traditional Downlink and Uplink Coupling often limits uplink efficiency due to power imbalances across base stations. Downlink and Uplink Decoupling addresses this by allowing separate access points for uplink and downlink, optimizing user association and energy use. This research expands upon previous conference work by introducing a new scenario that evaluates Downlink and Uplink Decoupling's performance at a 25 decibel milliwatts user equipment power setting, along with an additional experiment for 1500 user devices in the 20 and 30 decibel milliwatts scenarios. The extended analysis offers deeper insights into the energy efficiency and resource allocation of Downlink and Uplink Decoupling under various network conditions, confirming its suitability for scalable, efficient fifth-generation networks.**

Keywords - Downlink and uplink decoupling; Downlink and uplink coupling; Energy efficiency; Heterogeneous networks; Resource allocation evaluation.

I. INTRODUCTION

Modern 5G Networks offer great benefits compared to the 4G Long-Term Evolution (LTE) technology, with some of them being high speed, low latency and increased bandwidth. However, the volume of mobile traffic and the number of connected devices is predicted to increase significantly in the 5G era, which will lead to inevitable implications regarding the resource allocation and the total throughput of the networks. An important issue of modern 5G Networks is the energy efficiency evaluation [1]. The 4G technologies had already achieved extreme densification by utilizing Small Base Stations (BSs) throughout the network, leading to the modern Heterogeneous Networks (HetNets) [2]-[5].

In 4G HetNets the User Equipment (UE) devices were associated with the same BS for both Downlink (DL) and Uplink (UL) signals, resulting in the method known as Downlink/Uplink Coupling (DUCo) (see Figure 1). This access scheme, though, has a major drawback. The existence of major inequalities between the transmit power among high powered Macro BS and low powered Small BSs, results in suboptimal BS association and thus in performance degradation, affecting the UL. A fine solution to this problem is the decoupling of DL and UL signals in the current HetNets, commonly referred to as Downlink/Uplink Decoupling (DUDe), where the UE is connected to the optimal Macro BS for the DL and the optimal Small BS (Micro-Pico-Femto) for the UL. The UL and DL are treated as separate network entities and a UE can connect to different serving nodes in the UL and DL, resulting in improved user/BS association and improved resource allocation.

BS association in cellular networks has traditionally been based only on the received signal strength, despite the fact that transmit power and interference levels vary significantly. This approach was adequate in homogeneous networks with Macro BSs that all have similar transmit power levels. However, with the development of HetNet, there is a significant difference between the transmission power of different types of BSs, as stated above, making this approach extremely inefficient.

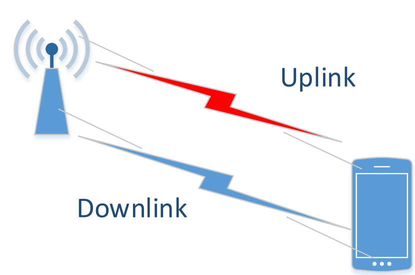

Figure 1. DUCo Example.

The motivation of this work is the improvement of energy efficiency in 5G networks. Energy efficiency is crucial for the success of 5G networks, as these networks will require a significant increase in energy consumption compared to their predecessors. With the proliferation of 5G-enabled UE and the explosion of data traffic, the demand for energy-intensive infrastructure components, such as BSs and data centers, will rise dramatically. By optimizing network architecture, using low-power components, and implementing intelligent power management strategies, operators can significantly reduce energy usage without sacrificing performance.

DUDe has the potential to significantly improve the energy efficiency of 5G networks. By separating the uplink and downlink channels, operators can dynamically allocate network resources to match the requirements of different applications and services. This results in a more efficient use of resources and reduces the energy consumption of network components, such as BSs and routers. Additionally, decoupling can enable intelligent power management strategies, such as sleep mode for low-traffic devices, further reducing energy consumption.

The main objective of this paper is to validate the findings of previous research by investigating the performance of the system in terms of the number of users and considering different decibel (dBm) values. The paper aims to fill the research gap by conducting a comprehensive analysis that incorporates various factors and parameters. By doing so, the paper intends to provide a deeper understanding of how the system performs in real-world conditions and assess its suitability for different deployment scenarios.

The rest of this paper is organized as follows. Section II presents similar research work. Section III presents the DUDe technology and its key features. Section IV presents the mathematical model used in our simulation environment. Section V presents the analysis of the algorithms compared in our scenarios. Section VI presents the simulation environment used for the implementation of our experiments. Section VII presents the results of the simulation and provides a detailed analysis of the findings. Finally, Section VIII concludes the paper and provides suggestions for future research.

II. State of the Art

DUDe has been researched by various studies. In one of these studies, researchers consider the resource allocation problem in LTE-U networks using DUDe, formulating the problem as a game theoretic model incorporating UE association, spectrum allocation and load balancing, for which they propose a decentralized expected Q-learning algorithm to solve [6]. Another paper proposes an UL and DL Supplementary UL (SUL) decoupling technology and an UL enhancement technology to coordinate New Radio Time Division Duplexing (NR TDD) and New Radio Frequency Division Duplexing (NR FDD. Lastly, several researchers study the concept of DUDe where DL BS association is based on received power DL, while UL is based on path loss [7].

However, another paper proposed a DUDe model where Macro-BS selection for DL is based on received power (as usual), but Micro, Pico and femto-BSs selection for UL is not based solely on path loss (link quality), but on a combination of parameters such as: link quality, BS load and BS backhaul capacity [8]. Authors in [9] focus on how to use DUDe technology improves the distribution of network resources based on UE distribution. The study found that by considering the capacity limitations of each type of BS, the DUDe technology results in a more even distribution of UEs within the network.

Paper [10] highlights the limitations of traditional resource allocation techniques in efficiently managing bandwidth within 5G networks. DUDe technology offers a dynamic approach by adjusting resource allocation based on UE demand and network conditions, thereby optimizing bandwidth distribution. Experimental results from this study have shown that DUDe effectively balances UE equipment distribution across BS, reducing the bandwidth usage of Macro BSs and consequently enhancing the Quality of Service (QoS) for UEs. These findings underscore the potential of DUDe in Macro BS offloading, providing valuable insights for network operators and researchers aiming to develop advanced resource allocation strategies in 5G networks.

Paper [11] provides an in-depth analysis of how DUDe enhances resource allocation by introducing an additional lower frequency signal on the uplink, complementing the existing signal. This approach effectively rebalances the uplink/downlink disparity at the BS edge, improving coverage and network capacity. Through extensive literature review and industry trend analysis, the study examines the benefits and challenges of DUDe, focusing on its impact on network performance, UE experience, and future advancements. Utilizing a simulation-based methodology, the research evaluates DUDe's effectiveness in terms of coverage, capacity, latency, and energy efficiency. The findings demonstrate that DUDe significantly enhances network performance, particularly in environments with high data transmission demands, and reduces outage rates in networks with high minimal throughput requirements. These insights are crucial for researchers and network operators aiming to implement efficient resource allocation strategies to optimize 5G network performance.

Authors in [12] address the high energy consumption associated with mmWave Small Cell Base Stations (SCBSs), which are integral to 5G networks. Dynamic TDD is employed to improve SCBS throughput by allowing flexible TDD time fractions. Given the coexistence of mmWave SCBSs with microwave Macro Base Stations (MBSs), DUDe is proposed to mitigate transmit power imbalances. This research formulates the joint optimization of energy efficiency and resource allocation for dynamic TDD with DUDe, analyzing the trade-off between throughput and energy efficiency using a generalized a-fair scheduler. The findings indicate a significant throughput gain of 28.4% with minimal impact on energy efficiency for dynamic TDD systems with DUDe compared to static TDD systems. These results demonstrate that dynamic TDD with DUDe improves throughput (52.45%) with only a marginal decrease (2.3%) in energy efficiency compared to static TDD without DUDe. These insights are crucial for developing efficient resource allocation strategies that balance throughput and energy efficiency in 5G networks.

In paper [13], the authors address the challenges of uplink power control in HetNets using the DUDE mode. They identify that traditional BS association rules, which are based on maximum downlink received power, are inadequate for current heterogeneous cellular networks. To mitigate co-channel interference from Small UE (SUE) and DUDE UE to Macro UE (MUE), the authors extend three existing power control schemes from homogeneous networks to HetNets. They compare the convergence and optimality of these schemes through theoretical analysis. Additionally, the authors propose an Improved Distributed Power Control (IDPC) scheme. Simulation results demonstrate that the IDPC scheme significantly enhances system performance, particularly in scenarios with a high number of UEs experiencing severe mutual interference. The findings confirm that IDPC is more suitable for uplink power control in DUDE mode HetNets, improving QoS and average signal-to-interference-plus-noise ratio (SINR).

Authors in paper [14] explore the optimization of joint uplink and downlink scheduling and resource allocation in a millimeter-Wave (mmWave)-based cellular network using dynamic Time Division Duplexing (TDD). Recognizing the potential of mmWave SCBSs to enhance data rates and network capacity in 5G networks, the study also addresses the transmit power imbalance between Macro BS and SCBSs through DUDe. The authors formulate the scheduling and resource allocation problem within a dynamic TDD system as an optimization problem, employing a generalized α-fair scheduler. They derive the dynamic TDD and UE scheduling time fractions for a relaxed version of the problem, showing that the results are a function of the system load. Simulation results validate the derived dynamic TDD results, demonstrating a 17% throughput gain in certain scenarios. The findings indicate that the proposed approach outperforms existing schemes, offering a robust solution for dynamic resource allocation in mmWave-based 5G networks.

III. DUDe Energy Efficiency Overview

DUDe is a complex technique that requires meticulous planning and coordination to be implemented effectively. This method involves assigning separate frequency bands and resources to DL and uplink UL channels, necessitating close collaboration between network operators and device manufacturers to ensure seamless integration and maximize benefits.

One of the most compelling advantages of DUDe is its potential to significantly reduce energy consumption in wireless communication systems. These systems typically consume substantial amounts of energy, which not only increases operational costs but also has adverse environmental effects, contributing to global warming. By decoupling the DL and UL channels, DUDe optimizes energy utilization within the network infrastructure. This process, illustrated in Figure 2, minimizes the energy required to operate the network by reducing interference and improving signal quality. Consequently, the system operates more efficiently, leading to considerable energy savings over time. These savings not only reduce operational costs for network operators but also support environmental sustainability efforts by lowering the carbon footprint associated with wireless communications [15]- [18].

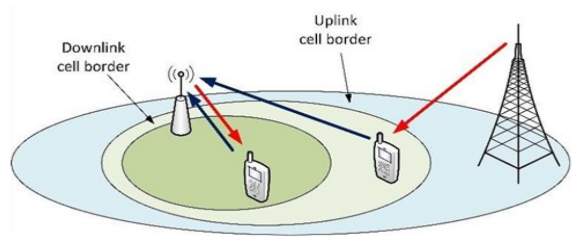

Figure 2. DUDe Example.

In addition to energy efficiency, DUDe offers significant improvements in network performance and reliability. By eliminating interference through the decoupling of DL and UL channels, DUDe enhances overall signal quality and network stability, resulting in a more reliable and robust network. This reliability translates into a superior UE experience, as the reduction in interference improves the quality of service and extends the lifespan of network components by reducing strain on the infrastructure.

Furthermore, DUDe facilitates more flexible and efficient resource allocation. With separate frequency bands and resources for DL and UL channels, network operators can allocate resources dynamically based on current demand and usage patterns. This flexibility helps mitigate the risk of congestion, ensuring that the network can handle high traffic volumes without compromising service quality. During periods of high network demand, efficient resource allocation ensures that UEs receive the expected quality of service. This dynamic resource management is particularly beneficial in urban areas and during peak usage times when network congestion can be a significant issue. By improving resource allocation, DUDe helps maintain high UE satisfaction and operational efficiency.

In conclusion, DUDe is a promising radio resource management technique that offers substantial benefits for both network operators and end- UEs. By decoupling the DL and UL channels, DUDe reduces energy consumption, enhances network performance and reliability, and enables more efficient resource allocation. The implementation of DUDe represents a significant advancement in the evolution of wireless communication systems, aligning operational efficiency with environmental sustainability.

IV. Mathematical Model Analysis

To determine the minimum distance between UE and BS antennas, a mathematical model defined in TR 38.901 Section 7.4.1 is used [19]. The paper does not delve into a detailed analysis of this particular model, so this paper do not extensively scrutinize its equations from (1) to (3) as a result. The model calculates the Path Loss (PL) in different scenarios, such as Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) conditions.

$$PL_{\mathrm{RMa-LOS}} = \begin{cases} PL_1 & 10m \le d_{\mathrm{2D}} \le d_{\mathrm{BP}} \\ PL_2 & d_{\mathrm{BP}} \le d_{\mathrm{2D}} \le 10\mathrm{km} \end{cases} \quad (1)$$

$$PL_1 = 20\,log_{10}(40\pi d_{3D} f_c/3) + min(0.03h^{1.72}, 10)\,log_{10}(d_{3D}) - min(0.044h^{1.72}, 14.77) + 0.002\,log_{10}(h) d_{3D} \quad (2)$$

$$PL_2 = PL_1(d_{BP}) + 40\,log_{10}(d_{3D}/d_{BP}) \quad (3)$$

$$\text{SNR} = \text{Psignal}/\text{Pnoise} \quad (4)$$

The path loss is calculated using equations (1), (2), and (3). Equation (1) defines the path loss in LOS conditions and NLOS conditions based on the distance between the UE and the BS antennas. Equation (2) calculates the path loss based on the three-dimensional distance, carrier frequency, user height, and other parameters. Equation (3) modifies the path loss based on the breakpoint distance and the three-dimensional distance.

Once the minimum distance for each user from different types of BS is determined, the next step is to compute the Signal-to-Noise Ratio (SNR) to find the BS type that provides the best connection. Equation (4) represents the SNR as the ratio of the signal power to the noise power [20].

V. Energy Efficiency Algorithm

Our HetNet includes Macro BS (MB) Small BS (Pico and Micro) and UEs. Consider a set of MBs (M = 1, 2, 3, 4.......| M|), a set of Small BSs (Pico => p = 1, 2, 3, 4.... |P|, Micro => m= 1, 2, 3, 4 |m|) and a set of UEs (U = 1, 2, 3, 4.......|U|). The MBs are placed at high levels to provide continuous uninterrupted coverage to large BSs. In addition, the BSs with the least sensitivity are placed at lower levels within an area, and as a result, the coverage of the NLOS locations is as wide as possible in the entire area, even in the most remote/obstructed points to efficiently serve static users or users who are constantly in motion within the area.

Algorithm 1 Algorithm for 20dBm or 30dBm Transmit Power

```
//Initialize variables
Macro_BSs
Micro_BSs
Pico_BSs
N = total number of UEs
occurrences_for_scenarios
SNR_matrix = zeros(N, occurrences_for_scenarios)
// calculate best SNR for each UE for occurrences_for_scenarios
for i in range(N):
    for j in range(occurrences_for_scenarios):
        // calculate SNR for current occurrences_for_scenarios
        SNR = calculate_SNR(UE_i, occurrences_for_scenarios _j)
        SNR_matrix[i][j] = SNR
    end
end
// calculate standard SNR value for each UE for each
//occurrences_for_scenarios
standard_SNR = zeros(N, occurrences_for_scenarios)
for i in range(N):
    for j in range(occurrences_for_scenarios):
        // calculate standard SNR for current snapshot
        standard_SNR[i][j]=sum(SNR_matrix[i][j])/occurrences_for_sce
        narios
        // calculate transmit power for each UE for each
        //occurrences_for_scenarios
        transmit_power = zeros(N, snapshots)
    end
end
for i in range(N):
    for j in range(occurrences_for_scenarios):
        // calculate transmit power for current snapshot
        transmit_power[i][j] = calculate_transmit_power(UE_i,
        standard_SNR[i][j])
        // build coupled scenario and distribute UEs in the network
        coupled_power = zeros(N)
    end
end
for i in range(N):
    // if transmit power is less than 20 or 25 or 30 dBm, keep value
    if transmit_power[i][-1] < 20  if transmit_power[i][-1] < 25 if
    transmit_power[i][-1] <30:
        coupled_power[i] = transmit_power[i][-1]
        // if transmit power is above 20 dBm, change value to 20 dBm

        // if transmit power is above 25 dBm, change value to 25 dBm

        // if transmit power is above 30 dBm, change value to 30 dBm
    else:
        coupled_power[i] = 20 or 25 or30
        // build decoupled scenario and distribute UEs in the network
        decoupled_power = zeros(N)
end
for i in range(N):
    // calculate transmit power using decoupling technology
    decoupled_power[i] = calculate_decoupled_transmit_power(UE_i,
    standard_SNR)
    // compare energy efficiency between coupled and decoupled
    //scenarios
end
if sum(coupled_power) > sum(decoupled_power):
    output("Decoupling technology is more energy efficient.")
else:
    output("Coupling technology is more energy efficient.")
```

Figure 3. Algorithm 1.

The Energy Efficiency Algorithm (Algorithm 1), depicted in Figure 3, explores two different scenarios for distributing UEs in a network: DUCo and DUDe. The algorithm initializes key variables, including the number of Macro, Micro, and Pico BSs, the total number of UEs, and the number of snapshots used in the simulation.

Initially, for each UE and each snapshot, the algorithm calculates the SNR of each UE in the network, storing these SNR values in a matrix. Subsequently, it computes the standard SNR value for every UE in each snapshot by averaging the SNR values across all snapshots, and these values are stored in a standard SNR matrix. Following this, the algorithm calculates the transmit power for each UE in each snapshot and stores these values in a transmit power matrix. The algorithm then constructs the DUCo and DUDe scenarios by distributing the UEs within the network. For the DUCo scenario, it sets the transmit power of each UE to the last value in the transmit power matrix for that UE unless the value exceeds a threshold (20 or 25 or 30dBm in the simulations). If the value surpasses this threshold, it is capped at the pre-selected limit. This ensures that the power levels remain within acceptable bounds, optimizing energy efficiency and maintaining regulatory compliance. In the DUDe scenario, the algorithm calculates the transmit power for each UE based on the standard SNR values. It runs the scenarios over numerous snapshots (1000 in our simulations) to mitigate the impact of random variations or uncertainties in the simulation outcomes. This approach ensures a robust comparison between DUCo and DUDe scenarios.

In summary, Algorithm 1 provides a comprehensive evaluation of energy efficiency in HetNet configurations, comparing DUCo and DUDe scenarios. The results validate that DUDe is a more sustainable and efficient method for managing radio resources in 5G networks. Future research could focus on optimizing bandwidth allocation using DUDe, further enhancing energy efficiency, minimizing interference, and maximizing throughput. Integrating advanced technologies like machine learning could also improve dynamic resource management, solidifying DUDe's role in future wireless communication systems.

VI. Simulation Environment

Specifically, a 5G DUDe network is considered, which consists of 2 Macro BSs, 4 Micro BSs, and 8 Pico BSs, each equipped with specific transmit power in dBm. Furthermore, it should be noted that the capacity of the Macro BSs is 2000 users, the capacity of the Micro BSs is 200 users, and the capacity of the Pico BSs is 46 users. This information is crucial in determining the optimal number of users that can be allocated to each type of cell. A total of N number of users are distributed within the network, each with their own transmit power in dBm. The gain from all BS antennas, including bandwidth and noise in the network, is also considered. For the implementation of our model and scenarios, MATLAB [21] was used, due to the fact that the application provides appropriate libraries and, consequently, functions, which make it easy and reliable to create a demanding algorithm like the one above. In addition, Figure 4 depicts the layout of our network, where the two Macro BS are located at the center, surrounded by Small BSs that are distributed around them.

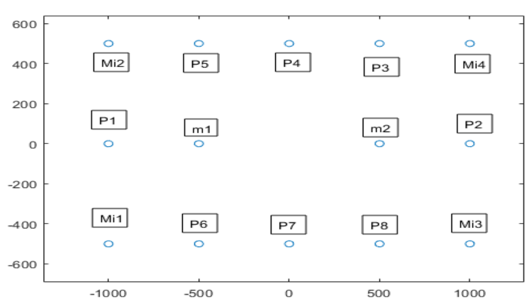

Figure 4. Topology of our network. (m) for Macro (mi) for Micro and (p) for Pico.

It is important to mention that users are randomly located between 1 and 2 meters apart from each other. The connection of the users is done in such a way that, for the DL processes the user will be connected to the Macro BS. During UL processes, the user will connect to the Small BS, which can either be Micro or Pico BS. The selection of the appropriate Small BS is based on the lowest path loss value, in addition to the transmission power.

Once the path loss has been calculated, the SNR is calculated using the variables mentioned in Table I. Utilizing the highest SNR, each user is connected to the best BS choice from the three categories, namely Macro BS, Micro BS, and Pico BS.

The direct result of this is that our model guarantees the non-interruption of the connection and less power consumption since the BS does not consume resources to serve users with great losses.

TABLE I. Simulation Parameters

Parameter	Value
Amount of BSs	Macro BS = 2 Micro BS = 4 Pico BS = 8
Transmit power(dBm)	UE = 20, 30 Macro BS = 45 Micro BS = 33 Pico BS = 24
BS height (m)	Macro height = 30 Micro height = 10 Pico height = 5
Antenna gain (dBi)	Macro BS = 21 Micro BS = 10 Pico BS = 5
Bandwidth (MHz)	20
Environmental parameters	UEs = 200,500,1000,1500,2000 Position = random
Power Noise	Pnoise = -74+10log(Bandwidth(hz))

The purpose of the evaluation is to demonstrate the superior energy efficiency of the DUDe technique compared to the DUCo technique in a 5G network. This goal is achieved by calculating a common SNR value for each type of BS (Macro, Micro, Pico) using the mathematical formula presented in Section III.

Next, the transmission power is calculated for different scenarios involving 200, 500, 1000, 1500 and 2000 UEs for each BS instance. The findings reveal that for the same SNR value, the power consumption of the DUCo technique is significantly higher than that of the DUDe technique.

VII. Results Evaluation and Analysis

Two scenarios, DUDe and DUCo, are implemented with transmit power of 20dBm, 25dBm and 30dBm. As the performed evaluation shows, the DUDe scenario requires less transmission power compared to the DUCo scenario, making a network that uses the DUDe technique in a more energy-efficient and environmentally friendly way.

The limit for UE transmission power (20dBm, 25dBm 30dBm) in our scenarios and in general in mobile telecommunications is set by the Mobile Broadband Standard Partnership Project (3GPP) [22].

Also, in the context of the diagrams provided, initially the average SNR values was determined for each UE across 1000 snapshots. These average SNR values are our target for subsequent calculations. When calculating the required transmission power for each UE to achieve these target SNR values, a threshold was taken into consideration: if the calculated power exceeds 20dBm or 30dBm, the transmission power was set to those respective limits, regardless of the calculation outcome.

A. Evaluation and analysis of 1st scenario

In this evaluation scenario, DUDe and DUCo was compared in terms of energy efficiency by setting the UE transmission power at 20dBm. The results of the evaluations are displayed in Figures 5 to 9. In the diagrams presented in these figures, the x axis is the average transmission power of the UEs in dBm and the Cumulative Distribution Function (CDF) of the performance metric F(x) axis is the possibility of successful DUDe or DUCo scenario. The implementation of the scenario was successful in meeting the goal of achieving the same result with less transmission power in the DUDe method. This means that our scenario was able to accomplish the desired outcome while using less transmission power, which is a significant achievement in the field of mobile telecommunications.

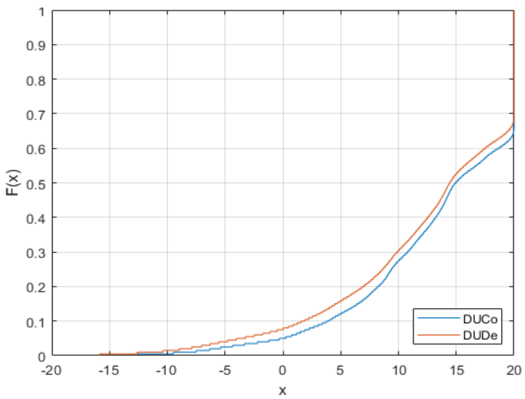

Figure 5. DUDe/DUCo comparison with 20dBm UE limit for N=200.

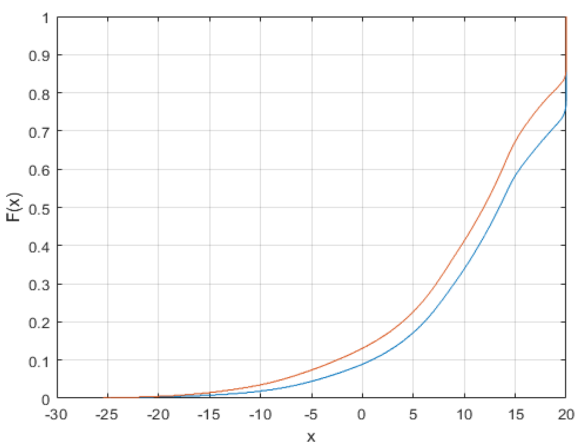

Figure 6. DUDe/DUCo comparison with 20dBm UE limit for N=500.

Based on the provided diagrams, it is evident that the DUDe method exhibits a higher likelihood of establishing successful connections compared to the DUCo method. For instance, at a UE transmit power of 10 dBm, the DUDe method demonstrates a 50% chance of establishing a successful connection, whereas the DUCo method achieves a success rate of less than 40% across all three simulations involving (200, 500, 1000, 1500, and 2000) UEs. These results suggest that DUDe technology consistently outperforms DUCo technology, offering at least 20% more successful connections. This higher success rate implies that DUDe technology provides better reliability and improved connectivity for UEs in wireless communication systems.

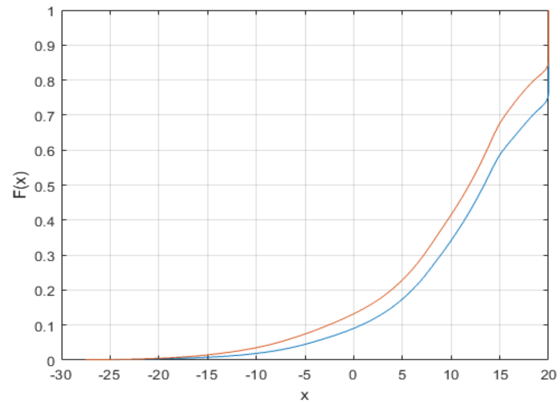

Figure 7. DUDe comparison with 20dBm UE limit for N=1000.

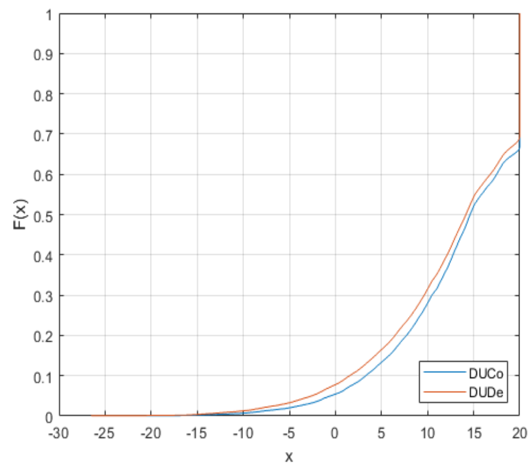

Figure 8. DUDe comparison with 20dBm UE limit for N=1500.

The research includes probability diagrams that illustrate the likelihood of successful connections for both DUDe and DUCo technologies. These diagrams visually support the claim of superior performance by showing the higher probability of successful connections with DUDe technology. As more successful connections result in fewer retransmissions and less energy-intensive signaling processes, DUDe technology can contribute to reducing overall energy consumption compared to DUCo technology. This combination of higher success rates and lower energy consumption underscores the efficiency and preference for DUDe technology.

Similarly, when considering an SNR of 15 dB, the diagrams illustrate that the probability of achieving low consumption with the DUDe method is 80%, whereas the DUCo method reaches only 62%. The difference between the two technologies, approximately 29%, further substantiates the hypothesis that DUDe technology achieves lower power consumption for the same performance level. These findings provide robust evidence that DUDe is more energy-efficient than DUCo. The significant advantage of DUDe in terms of reduced power consumption highlights its potential for practical implementation, aligning with the objective of developing sustainable and environmentally friendly 5G networks. The research demonstrates that DUDe not only enhances connectivity and reliability but also promotes energy efficiency, making it a preferable choice for modern wireless communication systems.

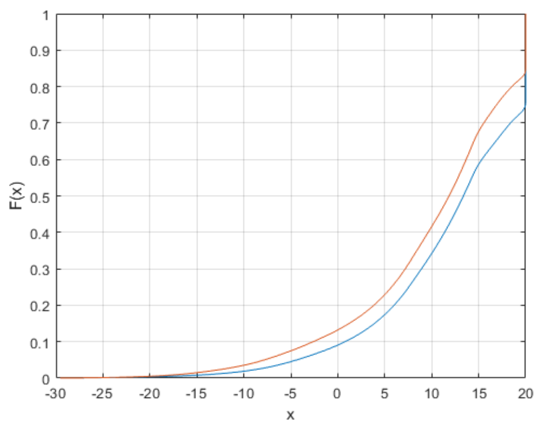

Figure 9. DUDe comparison with 20dBm UE limit for N=2000.

The extended analysis of the diagrams and simulation results clearly indicates that DUDe technology surpasses DUCo technology in both connection success rates and energy efficiency. By minimizing retransmissions and optimizing signaling processes, DUDe reduces overall energy consumption, thereby contributing to more sustainable network operations. The superior performance of DUDe, as evidenced by the probability diagrams and research findings, reinforces its suitability for implementation in 5G networks aimed at achieving higher efficiency and environmental sustainability. Continued research and development in this area will further solidify the advantages of DUDe and support its broader adoption in future wireless communication infrastructures.

B. Evaluation and analysis of 2nd scenario.

In the conducted evaluation, in the second scenario, DUDe and DUCo were meticulously compared to assessing their energy efficiency, with UE transmission power set at 30dBm. The outcomes of these evaluations are vividly illustrated in Figures 10 to 14. In these diagrams, the x-axis represents the average transmission power of the UEs in decibels (dBm), while the F(x) axis denotes the probability of a successful DUDe or DUCo scenario. This second scenario also adheres to a 30dBm limit imposed by 3GPP, which caps the maximum transmission power allowable for signal transmission in this context.

Despite this power limitation, the findings remain consistent with those observed in the first scenario. It was determined that the DUDe method demonstrates greater environmental friendliness compared to the DUCo method when implementing a heterogeneous 5G network. This conclusion is valid even within the constraints of the 30dBm limit. It is noteworthy, however, that the difference in energy consumption between the DUDe and DUCo methods is less pronounced in the second scenario compared to the first. Nonetheless, this does not alter the overall conclusion that the DUDe method is more energy-efficient and exerts a more positive environmental impact.

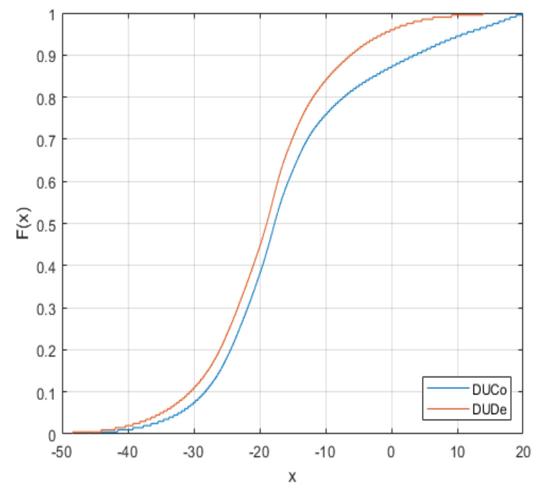

Figure 10. DUDe comparison with 30dBm UE limit for N=200.

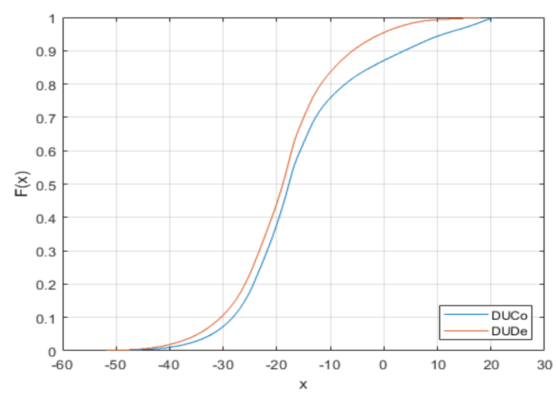

Figure 11. DUDe comparison with 30dBm UE limit for N=500.

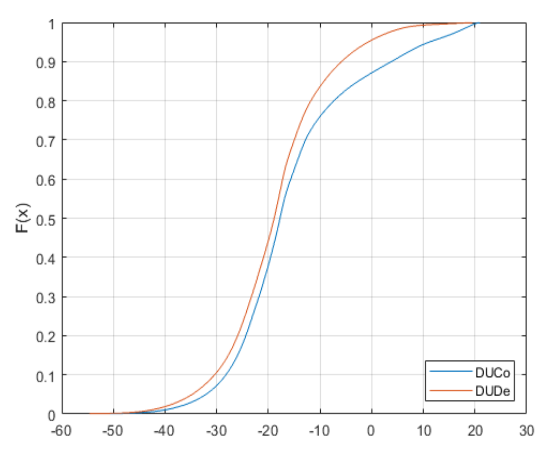

Figure 12. DUDe comparison with 30dBm UE limit for N=1000.

Figures 10 to 14 clearly indicate that increasing the transmission power of a UE significantly enhances the probability of establishing a DUDe association. Specifically, when the transmission power exceeds 2dBm, there is a 70% or greater likelihood of forming a DUDe connection. This data suggests that the DUDe communication algorithm is more efficient, requiring less transmission power to achieve similar results compared to the DUCo scenario.

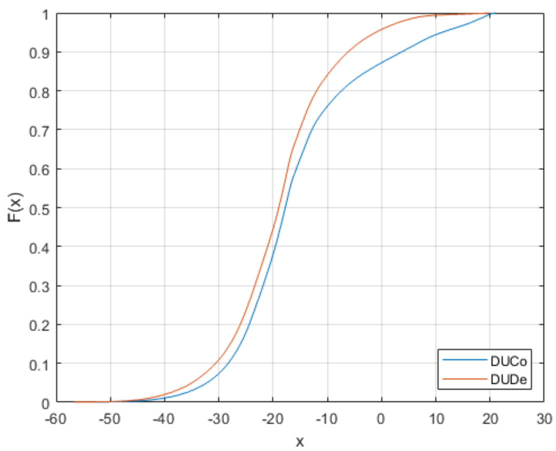

Figure 13. DUDe comparison with 30dBm UE limit for N=1500.

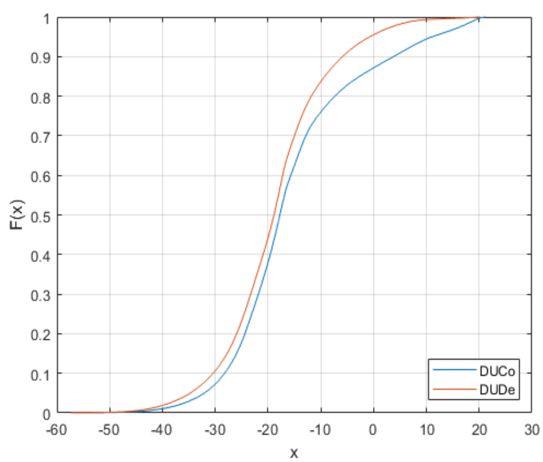

Figure 14. DUDe comparison with 30dBm UE limit for N=2000.

Moreover, the diagrams demonstrate that the DUDe method consistently exhibits a higher probability of creating a successful connection than the DUCo method. For example, at a 10 dBm transmission power level, the DUDe method achieves a 100% probability of establishing a successful connection. In contrast, the DUCo method requires a significantly higher transmission power—double that of DUDe—to attain the same success rate across various simulations (200, 500, 1000, 1500, and 2000 UEs).

The analysis conclusively shows that while the 30dBm limit is an important consideration in the implementation of a 5G network, it does not detract from the conclusion that the DUDe method is the superior choice for achieving a more energy-efficient and environmentally friendly network. The consistent results from the data and diagrams underscore the significant advantages of DUDe in terms of reduced power consumption, improved efficiency, and enhanced UE satisfaction.

Furthermore, the inherent flexibility and dynamic resource allocation capabilities of the DUDe method contribute to its superior performance. By allowing for the decoupling of downlink and uplink channels, DUDe optimizes the usage of available resources, leading to a more efficient network operation. This optimization not only conserves energy but also ensures that the network can handle high traffic volumes without compromising service quality.

C. Evaluation and analysis of 3rd scenario.

Figures 15 through 19 present a comparative performance analysis between the DUDe and DUCo approaches under a 25dBm power constraint is illustrated. These experiments were conducted for scenarios with 200, 500, 1000, 1500, and 2000 UEs, respectively.

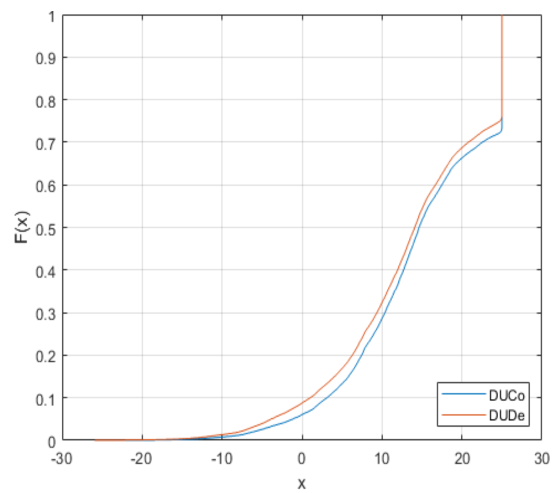

Figure 15. DUDe comparison with 25dBm UE limit for N=200.

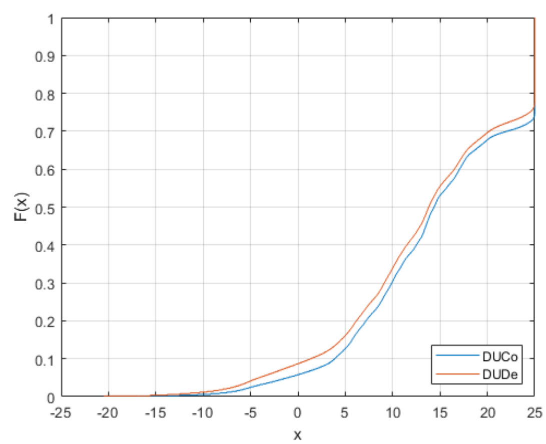

Figure 16. DUDe comparison with 25dBm UE limit for N=500.

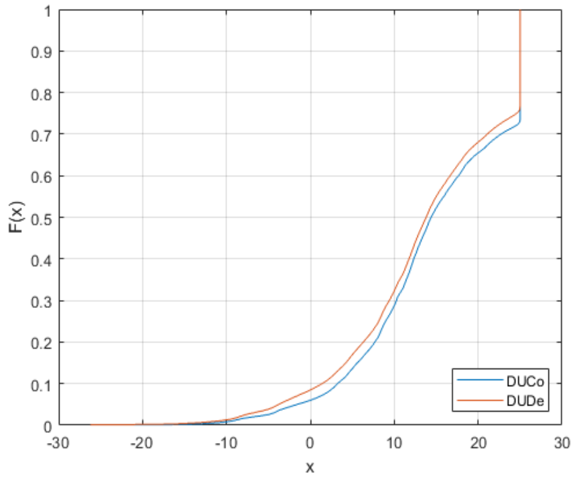

Figure 17. DUDe comparison with 25dBm UE limit for N=1000.

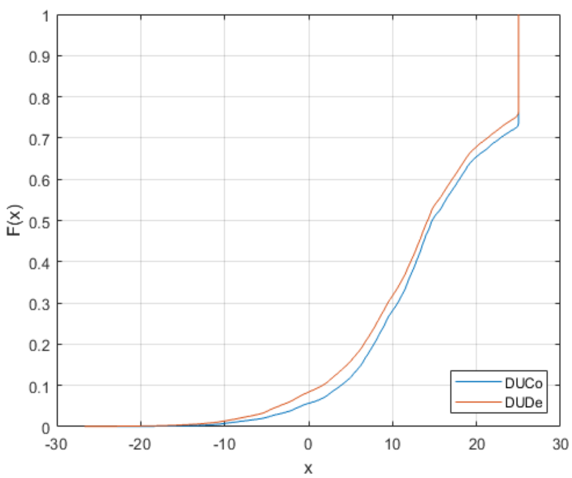

Figure 18. DUDe comparison with 25dBm UE limit for N=1500.

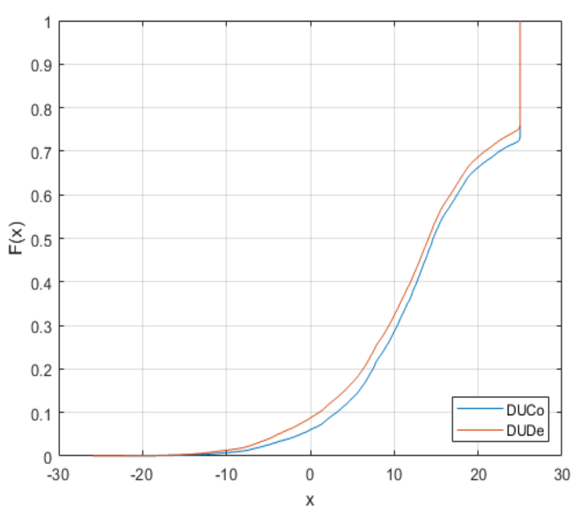

Figure 19. DUDe comparison with 25dBm UE limit for N=1500.

Figure 15 illustrates the scenario for 200 UEs. The CDF of the performance metric F(x) reveals that the DUDe approach (in red) provides better performance than the DUCo approach (in blue). For instance, at F(x)=0.5 the value of x is approximately 14dBm for DUDe, compared to about 13dBm for DUCo. This indicates a moderate performance improvement with the decoupled approach even with lower network loads.

Figure 16, depicting the scenario for 500 UEs, shows a clearer distinction between the two approaches. At F(x)=0.5, the value of is around 14.5dBm for DUDe and approximately 13.5dBm for DUCo. This improvement demonstrates the effectiveness of the DUDe approach in managing increased network loads.

Figure 17 represents the scenario for 1000 UEs. Here, the performance gained with DUDe becomes more pronounced. The DUDe curve remains to the right of the DUCo curve throughout the distribution. At F(x)=0.6, the value of x is about 18dBm for DUDe, while it is around 16dBm for DUCo. This significant difference underscores the advantage of the decoupled approach in more congested network conditions.

Furthermore, Figure 18, showing the scenario for 1500 UEs, further confirms the superior performance of the DUDe approach. The CDFs reveal that at F(x)=0.7, the value of x is approximately 21dBm for DUDe, compared to around 18dBm for DUCo. This greater separation between the curves indicates that DUDe continues to perform better as the network load increases.

Figure 19 illustrates the scenario for 2000 UEs, where the performance gain with DUDe is the most substantial. At $F(x)$=0.5, the value of is significantly higher for DUDe, reaching around 18dBm, compared to about 15dBm for DUCo. This result highlights DUDe's effectiveness in extremely high-density network environments.

These results suggest that the DUDe approach consistently offers better performance, particularly as the network load increases. The performance gain is evident across all scenarios, with more significant improvements observed in higher UE densities. For example, the value of x at F(x)=0.7 is approximately 20dBm for DUDe and 17dBm for DUCo in the 2000 UEs scenario, illustrating a clear advantage. Similarly, at F(x)=0.9, DUDe achieves around 23dBm, while DUCo reaches about 21dBm, reinforcing the trend.

This consistent performance advantage of the DUDe approach is attributed to its superior management of interference and more efficient resource allocation. As network density increases, these factors become increasingly critical, making DUDe a preferable choice for future 5G networks with high UE density.

In the set of Figures 5 to 19, in both scenarios, 'x' represents the average transmission power of the UEs Upon analyzing these figures, the following conclusion can draw: Increasing the transmission power of a UE results in a greater than 60% likelihood of establishing a DUDe association. Especially when the transmission power exceeds 10 dBm, the likelihood of DUDe correlation notably increases to over 50%. Also, with a stronger signal, which means a higher SNR value, a steady increase was observed in the DUDe correlation probability. Based on the insights gained in Figures 5 to 19 and the data presented, it can be asserted that the DUDe scenario requires less transmission power to achieve similar outcomes compared to the coupled scenario. This observation has several benefits: it implies reduced BS power consumption, more efficient user service, and a higher overall level of user satisfaction compared to the coupled scenario.

VIII. Conclusion and Future Work

In conclusion, this study has conducted a thorough comparison of the energy efficiency between DUCo and DUDe within a 5G HetNet. The findings clearly demonstrate that DUDe is a more energy-efficient method for achieving comparable network performance, as it requires less energy consumption. The evidence from our analysis indicates that DUDe holds a significant promise for reducing energy use in 5G networks. By decoupling the downlink and uplink transmissions, DUDe optimizes resource utilization and reduces energy consumption while maintaining high-quality network performance.

This research underscores the potential of DUDe to contribute to more sustainable and efficient network operations. The advantages of separating DL and UL transmissions are evident in the enhanced energy savings and improved network reliability observed in our evaluations. These benefits not only support cost-effective network management but also align with broader environmental goals by lowering the overall carbon footprint of wireless communication systems.

Looking ahead, future research could explore further optimization of bandwidth allocation using the DUDe approach. By strategically allocating bandwidth to each cell, it is possible to enhance energy efficiency even further, minimize interference, and maximize throughput. This would involve developing advanced algorithms for dynamic bandwidth management that can adapt to varying network conditions and demands. Additionally, examining the scalability of DUDe in different network configurations and deployment scenarios would provide valuable insights for its broader implementation.

Further investigation into the integration of DUDe with emerging technologies, such as machine learning and artificial intelligence, could also yield significant improvements in network efficiency and performance. These technologies can enable more intelligent and adaptive resource management, further enhancing the benefits of the DUDe method.

In summary, DUDe presents a compelling case for adoption in future 5G network deployments due to its superior energy efficiency and potential for resource optimization. Continued research and development in this area will be crucial for realizing the full potential of DUDe and achieving more sustainable and high-performing wireless communication networks.

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