Energy Efficiency Analysis of DUDe 5G Networks

Chrysostomos-Athanasios Katsigiannis
Computer Engineering and Informatics Department
University of Patras
Patras, Greece
up1072490@upnet.gr

Apostolos Gkamas
Department of Chemistry
University of Ioannina
Ioannina, Greece
gkamas@uoi.gr

Konstantinos Tsachrelias
Computer Engineering and Informatics Department
University of Patras
Patras, Greece
up1096511@upatras.gr

Christos Bouras
Computer Engineering and Informatics Department
University of Patras
Patras, Greece
bouras@upatras.gr

Vasileios Kokkinos
Computer Engineering and Informatics Department
University of Patras
Patras, Greece
kokkinos@upatras.gr

Philippos Pouyioutas
Computer Science Department
University of Nicosia
Nicosia, Cyprus
pouyioutas.p@unic.ac.cy

***Abstract*— In this paper we evaluate the energy efficiency of Downlink/Uplink Decoupling (DUDe) systems by considering the energy consumption of each Base Station (BS) and the communication overhead between the BSs and User Equipment (UE). Through extensive simulations, the energy efficiency of DUDe systems is evaluated under various scenarios, such as different user densities, Base Stations (BSs) configurations, and traffic patterns. The simulation results indicate that the proposed DUDe system can achieve significant energy savings compared to traditional centralized 5G systems. The impact of various parameters on energy efficiency is also analyzed, providing guidelines for designing energy-efficient DUDe systems. The paper emphasizes the significance of energy-efficient design in 5G networks, as it can significantly reduce the operational costs and carbon footprint of the network.

Keywords — Downlink/Uplink Decoupling (DUDe), Downlink/Uplink Coupling (DUCo), Resource Allocation, Energy Efficiency, Heterogeneous Networks, Downlink (DL), Uplink (UL)

I. INTRODUCTION

As the demand for high-speed and reliable mobile communication continues to surge, the development of efficient and sustainable wireless networks becomes increasingly critical. Fifth generation (5G) networks hold immense potential to meet these demands, offering unprecedented data rates, ultra-low latency, and massive connectivity. One crucial aspect in the design and operation of 5G networks is optimizing energy efficiency to minimize the environmental impact and reduce operational costs. In recent years, researchers and industry experts have been exploring innovative technologies and strategies to enhance the energy efficiency of 5G networks. Among these, DUDe technology has emerged as a promising solution. DUDe technology aims to address the inherent challenges associated with power consumption and transmission power imbalances between different network elements, such as Macro cells and Small Cell Base Stations (SCBSs) [1], [2], [3], [4].

Furthermore, there is a considerable amount of ongoing scientific research focused on enhancing the performance of 5G networks through the utilization of DUDe technology. The research work [5] compares the performance of two resource allocation strategies, namely Downlink/Uplink Combined Access (DUCa) and Downlink/Uplink Decoupled Access (DUDa), in a 5G HetNets (Heterogeneous Networks) network. The objective is to achieve Energy Efficiency (EE) and maximize data flow in the network. The authors of [6] tackle the intricate challenges of interference management in 5G and D2D communications within HetNets by introducing a novel framework for joint cell-association, subchannel allocation, and power control. This approach employs downlink/uplink decoupling (DUDe) to enhance network performance, utilizing a minimum path-loss criterion for base-station selection and a combined greedy coloring and modified Munkres algorithm for efficient resource distribution. A specialized algorithm for power control further ensures compliance with User Equipment (UE) power and data rate requirements, evidencing notable improvements over conventional methods.

The motivation behind this research paper stems from the increasing demand for energy-efficient designs in 5G networks. As the world becomes more reliant on advanced communication technologies, the energy consumption of network infrastructure has become a pressing concern. Traditional centralized 5G systems often exhibit high energy consumption due to their centralized processing and communication architecture. In response to this challenge, the paper proposes DUDe systems as a potential solution to enhance energ efficiency. This paper aims to evaluate the energy efficiency of DUDe systems by considering the energy consumption of individual components and the communication overhead between them. Ultimately, the authors underscore the importance of energy-efficient designs in 5G networks, emphasizing their potential to significantly reduce operational costs and the carbon footprint of the network.

The rest of the paper is organized as follows: Section II is a comprehensive review of the relevant technology, with an emphasis on its potential benefits for a 5G HetNets in the realm of energy consumption. Section III presents a mathematical model that will be used throughout the paper to analyze the data. Section IV is dedicated to describing and analyzing the algorithms used in the simulations. Section V presents details of the simulation environment. In Section VI, the simulation results are presented and analyzed, with diagrams and explanations to support the findings. Finally, Section VII provides the conclusions of the research and outlines potential areas for future research and development.

II. DUDE ENERGY EFFICIENCY OVERVIEW

In a HetNet model, the coverage area of a Macro cell in the DL is much larger than that of a smaller Base Station (BS). This inequality is attributed to differences in the transmission power of the DL. It is also attributed to the levels of the BSs and the benefits of the antennas. On the other hand, in the UL process, all transmitters have the same maximum transmission power. Therefore, a device associated with a Macro cell in the DL process could be associated with another Base Station for the UL to benefit from reduced signal loss. The positive impacts of these actions are twofold. For users transmitting at maximum power to connect to a closer BS, they experience a higher Signal-to-Noise Ratio (SNR). Furthermore, for a specific SNR value, it is possible to reduce transmission power due to reduced signal attenuation in the UL scenario where the device connects to the nearest BS rather than a Microcell [7], [8], [9], [10], [11].

DUDe minimizes interference in the UL. This allows devices the choice to connect to different BSs, crucial as UL interference comes from various device transmissions across cells received by a BS. In contrast, DL interference for a user relies on BS transmission power, beamforming, and distances to other stations. This decoupling introduces freedom for connections with less interference, boosting efficiency. Understanding energy systems is another key component of DUDe energy efficiency. It involves comprehending the intricacies of energy infrastructure, energy flows, and the interplay of different elements within a given system. This enables energy managers and decision-makers to identify bottlenecks, inefficiencies, and areas where energy can be optimized. By employing energy audits, modeling, and simulation tools, organizations can gain a deeper insight into their energy profiles and develop targeted strategies for improvement. Decision-making within the DUDe framework involves translating insights gained from data analysis and understanding energy systems into actionable measures. This includes implementing energy-efficient technologies, adopting best practices, and optimizing operational procedures.

Overall, DUDe energy efficiency offers a framework that integrates data-driven analysis, a thorough comprehension of the subject matter, well-informed decision-making, and active involvement of stakeholders. This approach aims to facilitate improvements in energy efficiency. Through the application of this framework, organizations and communities can make substantial energy savings, diminish their environmental impact, and contribute to a more sustainable future.

III. BRIEF MATHEMATICAL MODEL ANALYSIS

In order to determine the minimum distance between each user and the antennas of the various BSs the mathematical model defining in TR 38.901 Section 7.4.1 [12], is used (the analysis of the above mathematical model is out of the scope of this paper):

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

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

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

Once we have determined the minimum distance for each user from different types of antennas, the next step is to compute SNR [13] to determine the antenna type that is nearest for establishing a connection. The SNR is calculated by the following equation:

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

where P denotes the average power. It is crucial to measure the power of both the signal and the noise at corresponding locations in the system, using the same system bandwidth, to ensure accurate evaluation. In the subsequent step, we proceed to convert the SNR values expressed in decibel milliwatts (dBm) into milliwatts (mW). This conversion is performed to assess the energy consumption of the DUDe and DUCo technologies based on the distance and distribution of the users. The mathematical equation utilized for this conversion is as follows:

$$\text{P (W)} = 10\text{\^{}}((\text{dBm} - 30)\,/\,10) \quad (5)$$

IV. ENERGY EFFICIENCY ALGORITHM

This section describes an algorithm designed to analyze energy consumption and user allocation in a wireless communication system which consists of various types of BS (Macro, Micro and Pico) and a number of UEs. The primary objective is to determine the most efficient strategy for connecting users to BS while taking into consideration factors such as path loss, SNR, and BS types. By comparing the total energy consumption for decoupling and coupling approaches, the algorithm aims to identify which method achieves better user allocation and lower energy consumption. Firstly, the algorithm generates random positions for each UE. After that the algorithm uses the model of TR 38.901 Section 7.4.1 (implemented by the matlab nrPathLoss function), which likely accounts for factors such as distance and interference. This calculation takes into account parameters such as the scenario (e.g., urban Microcellular environment), building height, street width, frequency, line-of-sight information, and the positions of the BSs and UEs. The resulting path loss values provide an estimate of the signal attenuation between the BS antennas and UEs. The algorithm computes the received power from each BS antenna, which is influenced by factors such as antenna gains, UE gains, transmit power of the UE, and path loss. Using the received power and the network noise, the code calculates the SNR, which represents the quality of the received signal. The SNR is then converted from the logarithmic decibel milliwatts (dBm) scale to linear milliwatts (mW) for further analysis.

In addition, the algorithm determines the energy consumption for downlink/uplink decoupling and coupling approaches. It iterates over the UEs and scenarios, evaluating the SNR comparisons between Macro, Micro, and Pico BS. Based on the SNR values, the algorithm updates the energy allocation values, likely deducting energy consumption associated with the chosen BS. The code compares the total energy consumption for decoupling and coupling. If the total energy consumption for decoupling is greater than that of coupling, the algorithm concludes that downlink/uplink decoupling achieves better user allocation and lower energy consumption. Conversely, if the total energy consumption for coupling is lower, it suggests that downlink/uplink coupling is the more efficient strategy.

Algorithm 1 Algorithm for calculating energy consumption for DUCo and DUDe scenarios.

```
Initialize variables
decoupling_total_energy_Macro = 0
coupling_total_energy_Macro = 0
num_ues = N
occurrences_for_scenarios = 1000
// Generate random positions for each UE using nrpatholoss
for i=1: occurrences_for_scenarios
        set nue = num_ues
        set num_ues = zeros(3,nue)
        set num_ues (1:2,:) = 2e3*(rand(2,nue)-0.5)
        set num_ues (3,:) = 1 + rand(1,nue)

        set pathlossconf = nrPathLossConfig;
        set pathlossconf.Scenario
        set pathlossconf.BuildingHeight
        set pathlossconf.StreetWidth
        set freq
        set coordinates of bs
        set nbs = size(bs,2)
        set los = randi([0 1],nbs,nue)
        set pathloss= nrPathLoss(pathlossconf,freq,los,bs,ue)
        set pathloss
%end for
//Calculate SNR
received power from Macro cell for transmit power
Rp = gain of antenna + gain of ue +transmit power of ue – pathloss
SNR = Rp- noise of network
//Transform dBm SNR to mWatts
SNRmWatts = 10^(SNRdbm -30) / 10)
// Calculate energy allocation for downlink/uplink decoupling and Downlink/uplink coupling
//DUCo Since the Macro antenna is in closer proximity, it is likely to provide a stronger SNR compared to other types of antennas, so the user should connect to it.
for i in range(num_ues):
  for j in range(occurrences_for_scenarios):
    If (snrMacro_UE>snrMicro_UE) && (snrMacro_UE>snrPico_UE)
        coupling_total_energy_Macro = coupling_total_energy_Macro - energy_for_Macro_UE
  end_for
end_for
//DUDe Since the Macro antenna is in closer proximity, it is likely to provide a stronger SNR compared to other types of antennas, so the user should connect to it.
for i in range(num_ues):
  for j in range(occurrences_for_scenarios):
    If (snrMacro_UE>snrMicro_UE) && (snrMacro_UE>snrPico_UE)
        decoupling_total_energy_Macro = decoupling_total_energy_Macro - energy_for_Macro_UE
  end_for
end_for
if decoupling_total_energy > coupling_total_bandwidth_energy:
  print ("Downlink/uplink decoupling achieves better user allocation and lower energy consumption.")
else:
   print ("Downlink/uplink coupling achieves better user allocation and lower energy consumption.")
```

V. Simulation Environment

We have developed a 5G HetNets for conducting simulations, encompassing a 2 x 2 km urban square area. The network comprises three different types of BS: Macro BS, Micro BS, and Pico BS. In this network, there are two Macro BSs strategically positioned at a height of 30 meters. These BSs are characterized by their high transmission power of 45 dBm and a gain of 21 dBi. Macro BSs provide coverage over a larger area and are typically used for wide-area coverage in urban environments. Additionally, we have incorporated four Micro BSs into the network, positioned at a height of 10 meters. These BSs possess a slightly lower transmission power of 33 dBm and a gain of 10 dBi. Micro BSs are designed to cover smaller areas and are often deployed in locations with high user density, such as shopping centers or office buildings.

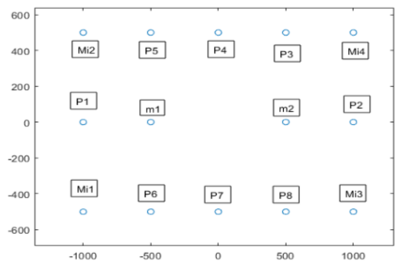

Fig.1. topology of our network. (m) for Macro (Mi) for Micro and (P) for Pico

Furthermore, the network consists of eight Pico BSs, placed at a height of 5 meters. Pico BSs have the lowest transmission power among the three types of BS, operating at 24 dBm. These BSs offer a gain of 5 dBi. Pico BSs are primarily used to provide localized coverage and fill in coverage gaps in areas with high user demand, such as indoor environments or busy streets. By incorporating these different types of BSs with varying heights, transmission powers, and gains, our network aims to optimize coverage and capacity for users in different areas of the urban square. This heterogeneous setup allows for efficient and reliable wireless communication services in a variety of scenarios within the network The purpose of implementing a heterogeneous network with Macro, Micro, and Pico BSs is to enhance the efficiency of resource distribution and facilitate effective communication among users. To ensure reliable communication, users are randomly positioned within the network, with a minimum distance of 1 to 2 meters between them to prevent overlap and interference.

To provide a visual representation of the network layout, Fig. 1 illustrates the spatial arrangement of the BS. The Macro BSs are positioned at the center, while the smaller Micro BSs and Pico BSs surround them. This configuration ensures that the network covers a wide area through the Macro BSs, while the Micro BSs and Pico BSs cater to smaller, more localized areas.

TABLE I. Simulation Parameters

Parameter	Value
Transmit power(dBm)	UE=20, Macro BS = 45, Micro BS = 33, Pico BS = 24
BS height (m)	Macro height = 25, Micro height =15, Pico height = 10

BS Antenna gain (dBi)	Macro cell = 21, Micro cell = 10,Pico cell = 5
Bandwidth (MHz)	20
Environmental parameters	UE1=500/UE2=1000/UE3=2000, Position=random
Power Noise	Pnoise= -74+10log(Bandwidth(Hz))

For reference, Table I summarizes the key parameters of the heterogeneous network. It provides an overview of the BSs types, their respective heights, transmission powers, and gains. These parameters play a crucial role in determining the coverage range, signal strength, and overall performance of each BSs type within the network. To avoid confusion, it's essential to note that although the setup and network settings mirror our previous research endeavors [14], this study explores a different research subject. Consequently, the conclusions drawn from this particular investigation vary from our earlier findings. Finally, to prevent any potential confusion, we maintained uniformity by utilizing the identical topology and network parameters as employed in our prior research for the execution of these specific experiments. However, it's important to emphasize that despite these similarities, we are indeed discussing a distinct approach and methodology for conducting these experiments.

VI. Simulations Results

We conducted a comparative simulation between DUDe and DUCo technologies for 500, 1000, and 2000 users. We repeat each simulation 1000 times and we present the mean results of the 1000 simulations. Our objective was to demonstrate that DUDe technology provides a smoother distribution of users within the network, ensuring that users are evenly distributed among the 14 BSs. This prevents any single BS from being overloaded with users, which can consume large amounts of current, as observed with the earlier DUCo technology.

In particular, the Macro BS of the network, where DUCo technology attracts the largest number of users, tend to experience high user loads and increased power consumption. This not only leaves the rest of the network BSs underutilized but also forces the Macro BS to consume excessive amounts of current. Through our simulations, we were able to prove that DUDe technology is more energy-efficient, as it helps distribute users more evenly across the network. This optimized distribution reduces power consumption overall, resulting in a positive environmental impact. It is worth noting that among the parameters we considered, the SNR played a significant role. Users located farther from the BS (weaker signal) require greater current for satisfactory service, regardless of whether DUDe or DUCo technology is employed.

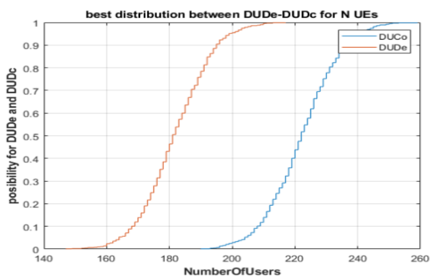

Fig.2. Distribution comparison between DUDe/DUCo for 500 UEs

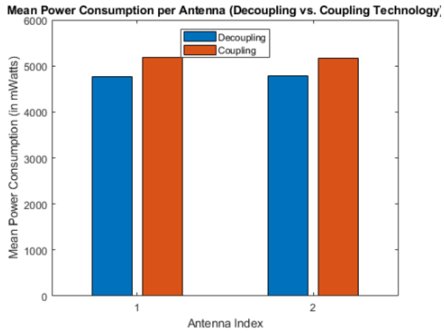

Fig.3.Comparison Energy Consumption for 500 UEs in Macro BSs

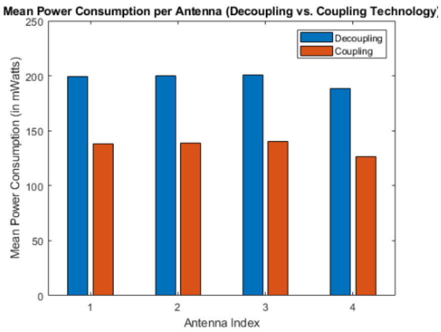

Fig.4.Comparison Energy Consumption for 500 UEs in Micro BSs

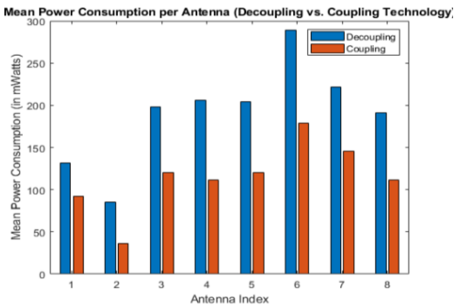

Fig.5.Comparison Energy Consumption for 500 UEs in Pico BSs

Our simulation results confirm our initial hypothesis that DUDe technology offers superior network regulation compared to DUCo technology. This is evident from the fact that DUDe technology effectively prevents Macro BSs from becoming overloaded by consuming excessive current, unlike DUCo technology. Fig. 2 shows the mean UE assignment per BS during the simulation involving 500 UEs, the average distribution for DUDe technology was approximately 160 users, while for DUCo technology it was around 200 users. This represents a difference of approximately 22.22% in favor of DUDe technology. Fig 3 through Fig.5 shows the energy consumption in each BS organized by BS type (Macro, Micro and Pico) during the simulation with 500 UEs. Notably, DUDe technology exhibited an average power consumption of 4758 mWatts for Macro 1 BS and 4779 mWatts for Macro 2 BS. In contrast, DUCo technology consumed an average of 5189 mWatts for Macro 1 BS and 5168 mWatts for Macro 2 BS. This translates to a percentage difference of approximately 8.6% and 7.8% respectively, favoring DUDe technology.

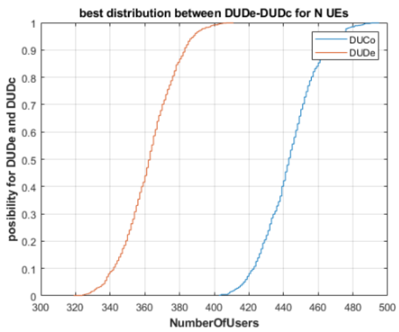

Fig.6. Distribution comparison between DUDe/DUCo for 1000 UEs

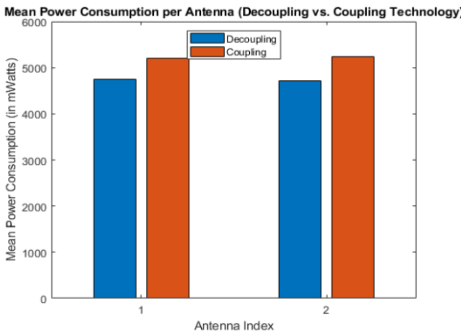

Fig.7.Comparison Energy Consumption for 1000 UEs in Macro BSs

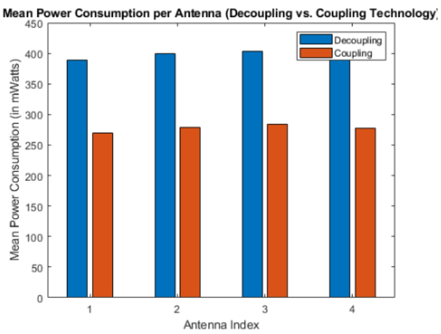

Fig.8.Comparison Energy Consumption for 1000 UEs in Micro BSs

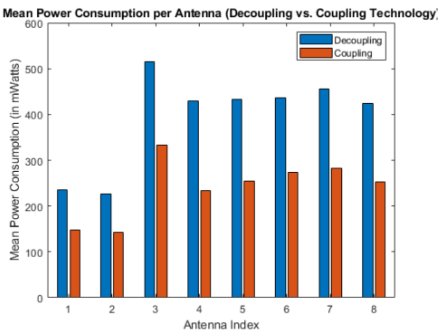

Fig.9.Comparison Energy Consumption for 1000 UEs in Pico BSs

Continuing with our analysis for 1000 UEs, Fig. 6 shows the mean UE assignment per BS during the simulation involving 1000 UEs. As this figure shows DUDe technology had an average distribution of approximately 320 users, while DUCo technology had around 420 users. This represents a difference of approximately 27.02% in favor of DUDe technology. Fig.7 through Fig.9 show the energy consumption in each BS organized by BS type (Macro, Micro and Pico) during the simulation with 1000 UEs. For Macro 1 BS, DUDe technology consumed an average of 4747 mWatts, and for Macro 2 BS, it consumed 4709 mWatts. On the other hand, DUCo technology consumed an average of 5199 mWatts for Macro 1 BS and 5237 mWatts for Macro 2 BS. The percentage difference in power consumption, favoring DUDe technology, was approximately 9.08% for Macro 1 BS and 10.6% for Macro 2 BS.

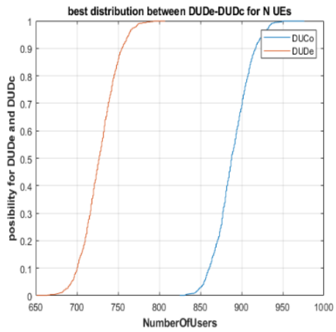

Fig.10. Distribution comparison between DUDe/DUCo for 2000 UEs

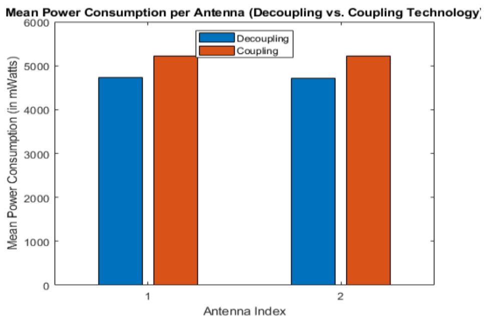

Fig.11.Comparison Energy Consumption for 2000 UEs in Macro BSs

In the case of 2000 UEs, Fig. 10 shows the mean UE assignment per BS during the simulation involving 1000 UEs. As this figure shows, DUDe technology had an average distribution of approximately 750 users, while DUCo technology had around 850 users, representing a difference of approximately 12.50% in favor of DUDe technology. Fig.11 through Fig.13 show the energy consumption in each BS organized by BS type (Macro, Micro and Pico) during the simulation with 1000 UEs. DUDe technology exhibited an average power consumption of 4734 mWatts for Macro 1 BS and 4718 mWatts for Macro 2 BS. In contrast, DUCo technology consumed an average of 5213 mWatts for Macro 1 BS and 5229 mWatts for Macro 2 BS. The percentage difference in power consumption, favoring DUDe technology, was approximately 9.63% for Macro 1 BS and 10.27% for Macro 2 BS. We should also acknowledge that the energy consumption of larger BS is higher compared to smaller BSs. In the case of DUDe, where users are evenly distributed among multiple BS, the energy consumption increases due to the larger number of users being served. This demonstrates that DUDe effectively prevents Macro BS from being overloaded with a high number of users, which would result in significant electricity consumption like in DUCo. As the number of users in the network grows, the difference in energy consumption between DUDe and DUCo becomes more pronounced. Ultimately, the choice between DUDe and DUCo depends on factors such as network capacity, coverage, and overall efficiency, while considering the trade-off between energy consumption and balanced user distribution. We have to highlight that in all the performed simulations DUDe approach has better total energy consumption in all BSs (more information in Table II) comparing with DUCo and the DUDe offers from 5,95% to 10.60% less total energy consumption compared to DUCo.

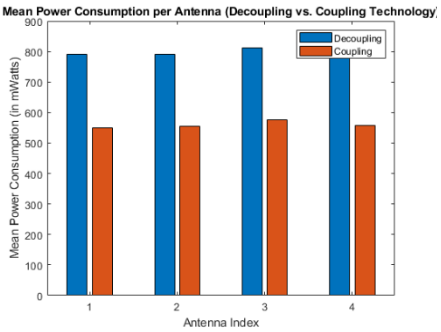

Fig.12.Comparison Energy Consumption for 2000 UEs in Micro BSs

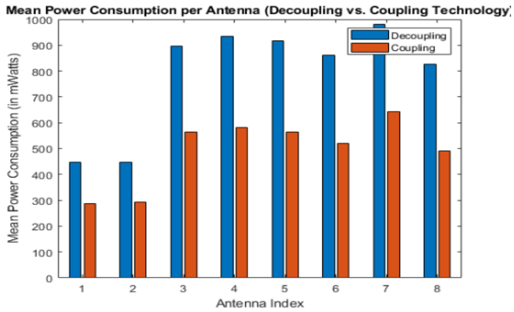

Fig.13.Comparison Energy Consumption for 2000 UEs in Pico BSs

TABLE II. TOTAL ENERGY CONSUMPTION FOR ALL BS

Scenario	500UE	1000UE	2000UE
DUDe	4464 Watts	8938 Watts	18806 Watts
DUCo	4964 Watts	9904 Watts	19960 Watts
Difference	10.60%	10,25%	5,95%

In conclusion our rigorous simulations and analysis have provided evidence to support our initial hypothesis. The results consistently demonstrate that DUDe technology surpasses DUCo technology in terms of network regulation and power consumption. As the number of UE increases, the advantages of DUDe technology become even more pronounced.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we introduced DUDe technology as a novel approach for achieving optimal energy efficiency in 5G networks. We demonstrated the benefits of DUDe, particularly in terms of user allocation and total energy consumption reduction when compared to DUCo techniques. Through extensive simulations and evaluations, we showcased the effectiveness of DUDe in improving network performance while minimizing energy usage.

One significant advantage of DUDe is its ability to significantly reduce total energy consumption in 5G networks. By dynamically optimizing power allocation, resource utilization, and network configuration, DUDe minimizes unnecessary energy expenditure. The decoupling of DL and UL transmissions allows DUDe to allocate power more precisely, avoiding wasteful energy consumption. Our results demonstrated a substantial reduction in total energy consumption compared to DUCo techniques, highlighting the energy efficiency gains achieved by DUDe. Further research can explore the integration of DUDe with other energy-saving mechanisms and network optimization strategies to maximize energy efficiency. Additionally, conducting real-world experiments and field trials will provide valuable insights into the practical implementation and performance of DUDe in diverse network environments.

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