# Simulation Based Energy Efficiency Analysis of DUDe 5G Networks

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

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

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

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

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

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

***Abstract*— To be able to respond to the explosively increased data traffic demand of 5G and beyond networks (Internet of Things (IoT), Voice/Video calls, Peer2Peer (P2P) software, etc.), one of the most promising technologies is composed of Heterogeneous Networks (HetNets). In HetNets, base stations are brought closer to users with the placement of small base stations, which results in better spectral and energy efficiency for cellular systems. However, the HetNet topology challenges traditional cellular systems. One of the most important challenges is user association. Aiming to avoid the drawback caused by Downlink/Uplink Coupling (DUCo) access in HetNets user association, a Downlink/Uplink Decoupling (DUDe) Access approach has emerged. By allowing access points in the uplink and downlink association to be different, DUDe greatly improves the uplink performance of HetNets. In this paper, we evaluate the energy efficiency and resource allocation of the DUDe approach.**

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

## 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. The 4G technologies had already achieved extreme densification by utilizing small Base Stations (BSs) throughout the network, leading to the modern HetNets [1]-[4].

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, mainly 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 cell BS for the DL and the optimal small cell (Micro-Pico-Femto) for the UL. Basically, 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/cell association and improved resource allocation.

Cell 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 base stations 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 base stations, as stated above, making this approach extremely inefficient.

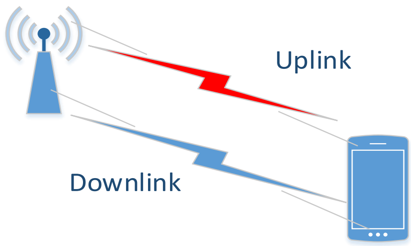


Figure 1. DUCo Example.

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 base stations 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 base stations 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 (dB) 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 the paper is organized as follows. In Section II, we present a comprehensive review of the relevant technology, with an emphasis on its potential benefits for a 5G heterogeneous network in the realm of energy consumption. In Section III, we present a mathematical model that will be used throughout the paper to analyze the data. In Section IV, we describe and analyze the algorithms used in the simulation. In Section V, we present details of the simulation environment. In Section VI, we present and analyze how to use the DUDe technology to improve the distribution the simulation results, with diagrams and explanations to support the findings. Finally, we conclude our research work and outline potential areas for future research and development in Section VII.

## II. DUDe Energy Efficiency Overview

DUDe has been researched by various studies. In one of these studies, researchers consider the resource allocation problem in LTE in unlicensed spectrum (LTE-U) networks using DUDe, formulating the problem as a game theoretic model incorporating user association, spectrum allocation and load balancing, for which they propose a decentralized expected Q-learning algorithm to solve [5]. 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) [6]. Lastly, several researchers study the concept of DUDe where DL cell association is based on received power DL, while UL is based on path loss.

However, another paper proposed a DUDe model where Macro-cell selection for DL is based on received power (as usual), but Micro, Pico and Femto-cells selection for UL is not based solely on path loss (link quality), but on a combination of parameters such as: link quality, cell load and cell backhaul capacity [7].

The authors of [8] focus on how to use DUDe technology to improve the distribution of network resources based on user 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 users within the network.

DUDe is a complex technique that requires careful planning and coordination to be implemented effectively. It involves assigning different frequency bands and resources for the DL and UL channels, which requires careful coordination between network operators and device manufacturers. One of the key advantages of DUDe is its ability to reduce energy consumption. Wireless communication systems consume a significant amount of energy, which can have a negative impact on the environment and contribute to global warming. By decoupling the DL and UL channels, as shown in Figure 2, DUDe can reduce the amount of energy needed to operate the network, leading to energy savings over time. By eliminating interference through decoupling, DUDe can improve network performance and reliability, leading to a better user experience [9]- [12].

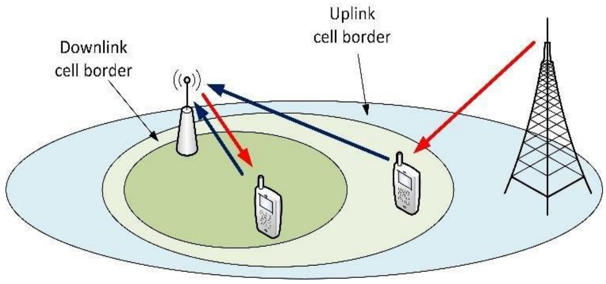


Figure 2. DUDe Example.

DUDe also has the potential to improve the efficiency of wireless communication systems by allowing for more flexible resource allocation. With separate frequency bands and resources for the DL and UL channels, network operators can allocate resources more efficiently and reduce the risk of congestion. This can help to ensure that users receive the quality of service they expect, even during periods of high network demand. In conclusion, DUDe is a promising radio resource management technique that can provide significant benefits for both network operators and end-users. By decoupling the DL and UL channels, DUDe can reduce energy consumption, improve network performance and reliability, and allow for more efficient resource allocation.

## III. Mathematical Model Analysis

To determine the minimum distance between users and base station antennas, a mathematical model defined in TR 38.901 Section 7.4.1 is used [13]. The paper does not delve into a detailed analysis of this particular model, so we will 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.

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

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

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

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

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 user and the base station 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 antennas is determined, the next step is to compute the Signal-to-Noise Ratio (SNR) to find the antenna type that provides the best connection. Equation (4) represents the SNR as the ratio of the signal power to the noise power [14].

## IV. 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 cells (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|). We assume that the MBs are placed at high levels to provide continuous uninterrupted coverage to large cells. In addition, we assume that 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_cells
Micro_cells
Pico_cells
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_s
    cenarios
        // 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 30 dbm, keep value
    if transmit_power[i][-1] < 20 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
    else:
    coupled_power[i] = 20 or 30
    // 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

In our algorithm (Figure 3), we perform two different scenarios for distributing UE in a network: a DUCo scenario and a DUDe scenario. The algorithm starts by initializing some variables, including the number of Macro, Micro, and Pico cells, the number of UEs, and the number of snapshots used in the simulation. Then, for each UE and for each snapshot, the algorithm calculates the Signal-to-Noise Ratio (SNR) of each UE in the network. It stores these SNR values in a matrix.

Next, the algorithm calculates the standard SNR value for every UE in each snapshot by taking the average SNR value across all snapshots. It stores these values in a matrix called standard SNR. After calculating the standard SNR values, the algorithm calculates the transmit power for each UE in each snapshot. It stores these transmit power values in a matrix called transmit power. Next, the algorithm builds the DUCo and DUDe scenarios by distributing the UEs in the network.

For the DUCo scenario, the algorithm sets the transmit power of each UE to the last value in the transmit power matrix for that UE, unless that value is greater than a threshold (20 or 30 dBm in our simulations), in which case it sets the transmit power to the pre-selected threshold. For the DUCo scenario, the algorithm calculates the transmit power for each UE based on the typical SNR values and runs the scenarios for a number of snapshots (1000 in our simulations) in order to reduce the impact of random variations or uncertainties in the simulation outcomes.

## V. SIMULATION ENVIRONMENT

Specifically, we consider a 5G DUDe network consisting of 2 Macro cells, 4 Micro cells, and 8 Pico cells, each equipped with specific transmit power in dBm. Furthermore, it should be noted that the capacity of the Macro cells is 2000 users, the capacity of the Micro cells is 200 users, and the capacity of the Pico cells 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 antennas, including bandwidth and noise in the network, is also considered. For the implementation of our model and scenarios, we used MATLAB [15], 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 cell antennas are located at the center, surrounded by small cells that are distributed around them.

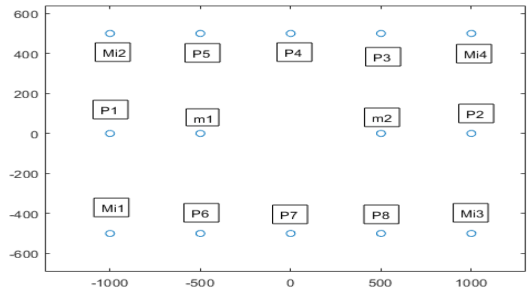


Figure 4. Topology of our network. (m) for Macro (mi) for Micro and (p) for Pico.

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 cell antennas. During UL processes, the user will connect to the small cell antennas, which can either be Micro or Pico cells. The selection of the appropriate small cell is based on the lowest path loss value, in addition to the transmission power.

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

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 Base Stations** | Macro cell = 2<br>Micro cell = 4<br>Pico cell = 8 |
| **Transmit power(dbm)** | UE = 20, 30<br>Macro cell = 45<br>Micro cell = 33<br>Pico cell = 24 |
| **BS height (m)** | Macro height = 30<br>Micro height = 10<br>Pico height = 5 |
| **Antenna gain (dbi)** | Macro cell = 21<br>Micro cell = 10<br>Pico cell = 5 |
| **bandwidth (MHz)** | 20 |
| **Environmental parameters** | UE1 = 100/UE2 = 500/UE3 = 1000<br>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 antenna (Macro, Micro, Pico) using the mathematical formula presented in Section III.

Next, the transmission power is calculated for different scenarios involving 500, 1000, and 2000 UEs for each antenna 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.

## VI. RESULTS EVALUATION AND ANALYSIS

Two scenarios, DUDe and DUCo, are implemented with transmit power of 20 dBm and 30 dBm. 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. However, any transmission power values exceeding 20 dBm and 30 dBm are limited to 20 dBm and 30 dBm, respectively, in both scenarios, as algorithm 1 suggests.

The limit for UE transmission power (20dbm, 30dbm) in our scenarios and in general in mobile telecommunications is set by the Mobile Broadband Standard Partnership Project (3GPP) [16].

Also, in the context of the provided diagrams, we initially determine the average SNR values 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, we take into consideration a threshold: if the calculated power exceeds 20 dBm or 30 dBm, we set the transmission power to those respective limits, regardless of the calculation outcome.

In the set of Figures 5 to 10, in both scenarios, 'x' represents the average transmission power of the UEs Upon analyzing these figures, we can draw the following conlsusions: 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 dB, the likelihood of DUDe correlation notably increases to over 50%. Also, with a stronger signal, which means a higher SNR value, we observe a steady increase in the DUDe correlation probability. Based on the insights gained from Figures 5 to 10 and the data presented, we can assert 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 antenna power consumption, more efficient user service, and a higher overall level of user satisfaction compared to the coupled scenario.

### A. *Evaluation and analysis of 1st scenario*

In this evaluation scenario, we compare DUDe and DUCo in terms of energy efficiency by setting the UE transmission power at 20dbm. The results of the evaluations are displayed from Figure 5 to 7. In the diagrams presented in these figures, the x axis is the average transmission power of the UEs in dB and the 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.

Based on Figures 5 to 7 provided, it is evident that the DUDe method has a higher likelihood of establishing successful connections compared to the DUCo (Downlink-Uplink Coordinated) method. For instance, considering a transmission with a UE transmit power of 10 dB, the DUDe method demonstrates a 50% chance of establishing a successful connection, while the DUCo method has a success rate of less than 40% across all three simulations involving 500, 1000, and 2000 users. Based on the information provided in the previous discussion, it can be inferred that the DUDe technology has been found to provide at least 20% more successful connections compared to DUCo technology. This higher success rate implies that the DUDe technology offers better reliability and improved connectivity for users in the wireless communication system. Figures 5 to 7 would demonstrate the higher probability of successful connections with DUDe technology, further supporting the claim of its superior performance. It is important to note that with more successful connections, the DUDe technology can contribute to reducing energy consumption compared to DUCo technology. This can be attributed to the fact that successful connections require fewer retransmissions and less energy-intensive signaling processes, resulting in overall lower energy consumption. Therefore, the combination of higher success rates and lower energy consumption makes DUDe technology a more efficient and preferable choice compared to DUCo technology, as indicated by the probability diagrams and the research findings.

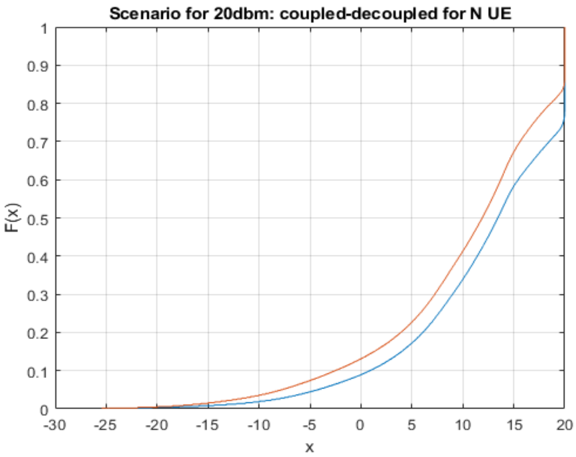


Figure 5. DUDe/DUCo comparison with 20dbm UE limit for N=500.

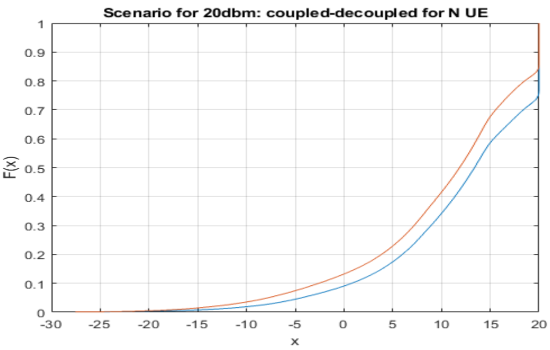


Figure 6. DUDe comparison with 20dbm UE limit for N=1000.

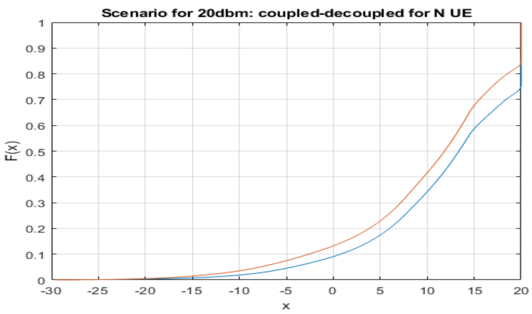


Figure 7. DUDe comparison with 20dbm UE limit for N=2000.

Similarly, when considering an SNR of 15 dB, Figures 5 to 7 illustrate that the probability of achieving low consumption with the DUDe method is 80%, whereas the primary DUCo technology only reaches 62%. The difference between the two technologies in this case is approximately 29%, further strengthening the initial hypothesis that the DUDe technology achieves lower power consumption for the same performance level.

These findings provide evidence supporting the notion that the DUDe method is more energy-efficient than the DUCo method. The research establishes a significant advantage of DUDe in terms of reduced power consumption, thereby reinforcing its potential for implementation in practical scenarios and aligning with the objective of developing sustainable and environmentally friendly 5G networks.

### B. *Evaluation and analysis of 2nd scenario*

In this evaluation scenario, we compare DUDe and DUCo in terms of energy efficiency by setting the UE transmission power at 30dbm. The results of the evaluations are displayed on Figure 8 to 10. In the diagrams presented in these figures, x axis is the average transmission power of the UEs in dB and the F(x) axis is the possibility of successful DUDe or DUCo scenario. In this second scenario, it is worth noting that there is a limit of 30 decibels per milliwatt (30dbm) imposed by 3GPP, the Mobile Broadband Standard Partnership Project. This limit sets a cap on the maximum amount of transmit power that can be used to transmit signals in our scenario.

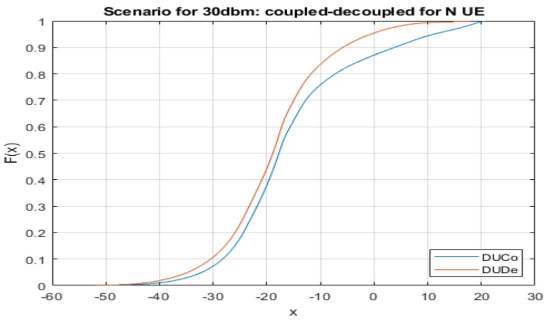


Figure 8. DUDe comparison with 30dbm UE limit for N=500.

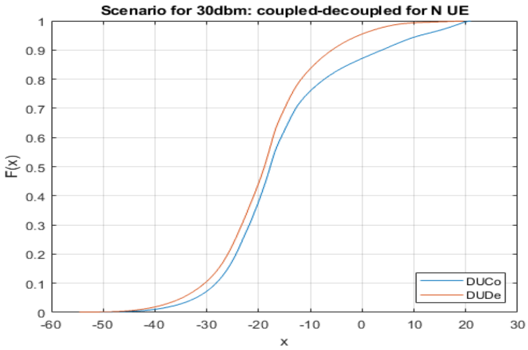


Figure 9. DUDe comparison with 30dbm UE limit for N=1000.

Despite this limit, our findings remain consistent with those of the first scenario. We have determined that the DUDe method for implementing a heterogeneous 5G network is more environmentally friendly than the DUCo method. This conclusion holds true even with the 30dbm limit in place. It is worth mentioning that the difference in energy consumption between the DUDe and DUCo methods is smaller in the second scenario than in the first. However, this does not change our overall conclusion that the DUDe method is more energy-efficient and will have a positive impact on the environment and society. To summarize, although the 30dbm limit is a factor to consider when implementing a 5G network, it does not change our conclusion that the DUDe method is the better choice for a more environmentally friendly network.

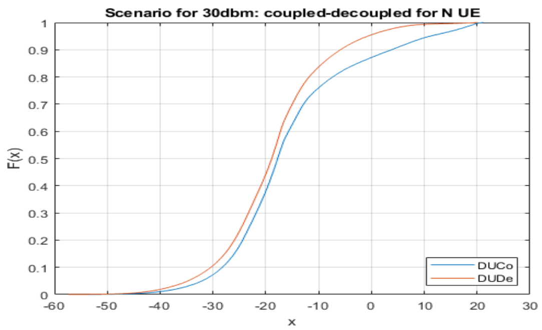

Figure 10. DUDe comparison with 30dbm UE limit for N=2000.

As diagrams in Figure 8 to 10 show and according to the data, it appears that increasing the transmission power of a UE results in a greater probability of DUDe association. When the transmission power is 2dbm or higher, there is a 70% and higher likelihood of a DUDe connection. These findings suggest that the algorithm designed for DUDe communication requires less transmission power to achieve similar results compared to the DUCo scenarios.

## VII. Conclusions And Future Work

In this paper, we have compared the energy efficiency of DUCo and DUDe in a HetNet 5G network. Our analysis shows that DUDe is a more energy-efficient method for the same task, as it requires less energy consumption.

The results of our study suggest that DUDe can be a promising method to reduce energy consumption in 5G networks. By separating the DL and UL transmissions, we can optimize the use of resources and minimize energy consumption, while still providing high-quality network performance. This approach can have significant benefits for both mobile network operators and end-users, by reducing costs and improving overall user experience.

Furthermore, we believe that future work in this area could focus on optimizing bandwidth allocation using DUDe. By carefully allocating bandwidth to each cell, we can further improve energy efficiency, minimize interference, and maximize throughput. This approach could have significant benefits for large-scale 5G networks, where bandwidth allocation is critical to achieving optimal network performance. Also, the experiments yield consistent results, indicating that the findings remain unchanged regardless of the network's user population, whether it is extensive or limited in size. In other words, the number of users in the network has minimal impact on the conclusions drawn from our experiments.

Overall, our findings highlight the importance of adopting energy-efficient techniques in mobile networks to reduce the environmental impact of high-speed data transfer. We encourage further research in this area to explore new ways of optimizing network performance while minimizing energy consumption. By identifying new opportunities for sustainable innovation in mobile communications, we can create a more efficient and sustainable future for the industry.

## Acknowledgment

This research has been co-financed by the Hellenic Foundation for Research & Innovation (H.F.R.I) through the H.F.R.I.'s Research Projects to Support Faculty Members & Researchers (project code: 02440).

## References

[1] S. Ruiza et al., "5G and beyond networks" in ScienceDirect, Inclusive Radio Communications for 5G and Beyond, 2021, pp. 141-186.

[2] H. Elshaer, F. Boccardi, M. Dohler, and R. Irmer, "Downlink and Uplink Decoupling: A disruptive architectural design for 5G networks", 2014 IEEE Global Communications Conference, Austin, TX, USA, 2014, pp. 1798-1803.

[3] H. Khan, M. Ali, I. Rashid, A. Ghafoor and M. Naeem, "Cell Association for Energy Efficient Resource Allocation in Decoupled 5G Heterogeneous Networks", 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), Antwerp, Belgium, 2020, pp. 1-5.

[4] N. Garg, "Downlink and Uplink User Association in Dense Next-Generation Wireless Networks", Ph.D dissertation, University of Texas at Austin 2015 [Online]. Availabe : http://hdl.handle.net/2152/30074.

[5] Y. Hu, R. MacKenzie and M. Hao, "Expected Q-learning for Self-Organizing Resource Allocation in LTE-U with DL-UL Decoupling", European Wireless 2017; 23th European Wireless Conference, pp. 1-6, 2017.

[6] J. Guo, Y. Zhang, B. Guo, Z. Fan, and H. Song, "5G UL Coverage Enhancement Based on Coordinating NR TDD and NR FDD", In: Sun, Signal and Information Processing, Networking and Computers. Lecture Notes in Electrical Engineering, vol. 917, 2023, Springer, Singapore. https://doi.org/10.1007/978-981-19-3387-5_168.

[7] H. Elshaer, F. Boccardi, M. Dohler and R. Irmer, "Load & backhaul aware DUDe DL/UL access in 5G systems," 2015 IEEE International Conference on Communications (ICC), 2015, pp. 5380-5385, doi: 10.1109/ICC.2015.7249179.

[8] T. Konstantinos et al., "On the Optimization of User Allocation in Heterogeneous 5G Networks Using DUDe Techniques", ICUFN 2023, in press.

[9] A. J. Muhammed, Z. Ma, Z. Zhang, P. Fan and E. G. Larsson, "Energy-Efficient Resource Allocation for NOMA Based Small Cell Networks With Wireless Backhauls", in IEEE Transactions on Communications, vol. 68, no. 6, pp. 3766-3781, June 2020.

[10] Y. Shi, E. Alsusa, and M. W. Baidas, "A survey on downlink–uplink decoupled access: Advances, challenges, and open problems" In ScienceDirect, Computer Networks, vol. 213, 2022.

[11] H. Z. Khan et al., "Resource allocation and throughput maximization in decoupled 5G" 2020 IEEE wireless communications and networking conference (WCNC). IEEE, 2020.

[12] 3GPP, TR 38.901 Section 7.4.1 "Study on channel model for frequencies from 0.5 to 100 GHz", release 17, March 2022.

[13] F. A. Niasar and A. Reza, "A novel approach to fairness-aware energy efficiency in green heterogeneous cellular networks," Momen Wireless Networks, vol. 28, pp. 2651–2667, 2022.

[14] B. Błaszczyszyn and H. P. Keeler, "Studying the SINR Process of the Typical User in Poisson Networks Using Its Factorial Moment Measures", in IEEE Transactions on Information Theory, vol. 61, no. 12, pp. 6774-6794, Dec. 2015.

[15] MathWorks, 2023. 5G Toolbox [Software]. Information retrieved 20/10/2024 from https://www.mathworks.com/products/5g.html.

[16] 3rd Generation Partnership Project (3GPP). (n.d.). 3GPP References Search. Information retrieved 20/10/2024 from 3GPP website: https://portal.3gpp.org/3gppreferences/SearchReferences.aspx.