Computer Networks and Communications
http://ojs.wiserpub.com/index.php/CNC/

UNIVERSAL WISER PUBLISHER

Research Article

Analyzing 5G Heterogeneous Cellular Networks: An Inclusive Examination of Throughput and Energy Efficiency

Maxwell Afriyie Oppong[1*], Emmanuel Ampoma Affum[2], Kwadwo Ntiamoah-Sarpong[1]

[1] Department of Electrical and Electronic Engineering, Kumasi Technical University, Kumasi, P. O. Box 854, Ghana
[2] Department of Telecommunication Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, 0000, Ghana
E-mail: maxwell.aoppong@kstu.edu.gh

Received: 1 April 2025; **Revised:** 30 May 2025; **Accepted:** 1 July 2025

Abstract: This paper presents an in-depth analysis of energy efficiency in Fifth Generation (5G) cellular networks, with a focus on Heterogeneous Network (HetNet) architectures. The user needs extensive network access in next-generation wireless networks, in addition to the overwhelming demand for high data rates and network capacity. The need for data services that are available anywhere, at any time, requires network operators to construct an increasing number of base stations, which ultimately results in excessive power usage. The 5G network proposes a heterogeneous wireless access network environment as a potential solution to this problem. The goal of green communication was realized with the rise of heterogeneous networks. A heterogeneous network consists of a combination of low-power nodes superimposed over a Macrocell to reduce traffic within the Macrocell and improve cell edge user quality of service. The goal of a heterogeneous network is to reduce energy consumption in mobile wireless networks while simultaneously improving Long-Term Evolution (LTE)-Advanced performance beyond its current limits. Specifically, Microcells, Picocells and Femtocells deployment under the auspices of Macrocell Base Stations (BS). Improved network coverage, increased network capacity, energy efficiency, increased data rates, and better Quality of Service (QoS) are all the outcomes of this networking approach. Two-tier, three-tier, and four-tier network architectures have been used in this article's energy efficiency analysis using stochastic geometry method. Our analysis considers a network configuration where microcells constitute 30%, picocells 20%, and femtocells 15% of the total deployed base stations, while macrocells remain dominant at 35%. Furthermore, While densification reduces macrocells interference, cross-tier interference increases by up to 20 dB. Multi-tier networks significantly enhance throughput and energy efficiency, but effective interference management is essential to maximize benefits.

***Keywords*:** Energy Efficiency (EE), 5G cellular networks, Heterogeneous Networks (HetNet)

Abbreviation

5G	Fifth Generation
LTE-A	Long-Term Evolution-Advanced
SCN	Small Cell Network
CO_2	Carbon Dioxide
MBS	Macro Base Station

DOI: https://doi.org/10.37256/cnc.3220256898

QoS	Quality of Service
HetNets	Heterogeneous Networks
IoT	Internet of Things
PPP	Poisson Point Processes
EE	Energy Efficiency
MS	Mobile Station
SBS	Small Base Stations
BS	Base Station
3G	Third Generation
ICT	Information and Communication Technology

1. Introduction

The mobile communications industry has grown rapidly in the last few decades. The need for mobile media and applications has grown as a result of smartphones. Therefore, Fifth Generation (5G) mobile communication technology must increase the current mobile capacity by approximately a thousand times to ensure proper communication in the intense traffic. However, several novel 5G approaches have been proposed. Regarded as a viable option that can meet current traffic demands, the hype-dense Small Cell Network (SCN) is one of the most significant aspects of 5G generation mobile communication technology [1]. The wireless sector is expanding rapidly to meet the demands of future communication needs, which will involve a wide range of devices with distinct characteristics, pervasive connection, and service requirements ranging from low latency to high speed restrictions [2]. Energy conservation has become a key consideration in the architecture and operation of wireless networks [3]. Cellular operators have spent the last several decades focusing primarily on maximizing other network performance measures, such as data latency, throughput, and coverage. However, because of its implications for the economy and environment, network energy efficiency has emerged as one of the most important elements in recent years. According to recent studies, the amount of carbon dioxide emissions caused by information and communication technology can exceed 4% [4]. Around 60% of all IoT-connected devices in 2020 came from the consumer segment, and this share is predicted to remain at this level over the next ten years. IoT devices are used in all types of industry verticals and consumer markets, and the number of devices worldwide is expected to nearly double from 15.1 billion in 2020 to more than 29 billion IoT devices in 2030 [5]. China will have the largest number of IoT devices in 2030, with about 8 billion consumer devices [6]. The rapid expansion of users and data volumes transferred has resulted in a rise in energy consumption inside mobile networks. One of 5G's goals is to dramatically increase energy efficiency to halt the generation-after-generation growth of the energy curve within networks. A new phase of development, known as the "green domain," is focused on deploying energy-efficient wireless networks to save the environment [7]. Approximately 80% of energy is used by radio networks, with base stations alone accounting for more than 50% of this total energy use [7]. Since multi-tier HetNets enable better coverage and quality of service in locations where high capacity is needed (such as sports events, retail malls, and downtown areas), they will remain a crucial technological element of 5G networks [8]. Once operators begin putting mmWave base stations within the coverage area of bigger high power macrocells, the optimization approaches currently used in 4G HetNets will also offer significant advantages in 5G systems [9]. Planning and designing such diverse networks, however, remain difficult tasks since service providers must strike a compromise between network implementation costs and performance. A typical HetNet is composed of several distinct cells. Based on the different coverage areas and application scenarios, network types might be divided into four classes [10].

1. Macrocell Networks: Like other cellular networks, a macrocell network uses a high-power Base Station (BS) to cover a wide area. The following traits apply to the macrocell network: The Macro Base station (MBS) is always located in a high location, like atop a mountain or skyscraper, from which it can offer a clear view of the surrounding structures and barriers, giving it a long transmission distance and a wide coverage area with a cell radius ranging from 1 km to 25 km. Multipath interference and shadow fading have a significant negative influence on the QoS of the cell-edge user.

2. Microcell Networks: A low power BS supports a microcell network in densely populated urban areas, including shopping malls. Compared to the macrocell network, this network's coverage area is much smaller (200 m to 1 km). The number of channels and traffic density decrease in tandem with the low-power BS's frequency reuse distance.

3. Picocell Networks: A picocell network (e.g., 100 m-200 m) spans a smaller area than a microcell network (e.g., compared to the network of microcells). Picocells are frequently seen indoors. There will be fewer locations where individuals can't communicate as a result.

4. Femtocell Networks: A small, low-power Base Station (BS) is intended to improve a femtocell network, also referred to as a House eNode, communication quality in a small business or residential setting. Indoor consumers' Quality of Service (QoS) is enhanced by using the home BS. However, compared to other cell types, femtocells are far easier and more profitable to install. Femtocells are perfect for cellular coverage since they can also bridge the gaps left by picocells and stop signal loss through structures. The main difference between the two technologies is that femtocells have a much smaller user base than picocells.

1.1 *Energy efficient network concerns*

1.2 *Operator's context*

As indicate in Figure 1, macro BS, which is often positioned in the cell's center to provide basic network coverage, is the major energy consumer in a wireless network. Increasing the number of Macro BS typically increases network capacity, however, this high energy consumption eventually results in increased electricity bills. Only BSs account for between 18 percent and 20 percent of Operating Expenditures (OpEx) [11].

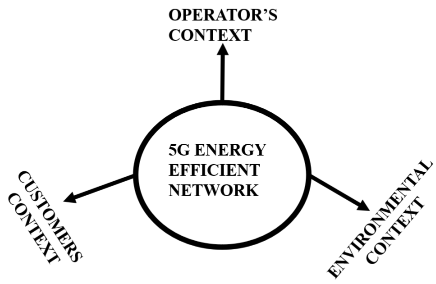

Figure 1. Issues related to energy efficient networks

1.3 *Customer's context*

One of the main issues with 3G data services from the standpoint of mobile users is the Energy Efficiency (EE) of cellular networks. When it comes to battery life, users' mobility becomes doubtful. According to a 2016 poll about smartphone user satisfaction, iPhones scored the lowest when it came to battery drainage. The same problem is also highlighted in the article [12], which also explores several possible solutions for One of the main issues with 3G data services from the standpoint of mobile users is the EE of cellular networks. If user battery life is not promptly addressed, it will become the largest barrier to high-speed or high-energy gadgets (such as multimedia, mobile TV, 3-D services, and video streaming).

1.4 *Environmental context*

Nowadays, Information and Communication Technology (ICT) is totally to blame for 10 percent of the world's energy use [13]. The number of cellular subscribers is growing, and this percentage is also rising. The fourth ICT sector will be wireless at the latest by 2020 [14], which highlights the need to cut ICT-related Carbon dioxide emissions as soon as feasible. The portion of energy used by ICT, telecommunication networks, cellular networks, and base stations is shown in detail in [11]. Given the significance of EE in today's cellular networks, the goal of this research is to examine the data throughput of an energy-aware heterogeneous network.

1.5 *Related works*

Optimization of the base station architecture for increased energy efficiency has been the subject of numerous studies. To improve energy usage, some studies have suggested resource allocation techniques for 5G ultra-dense networks and algorithms for task offloading in mobile edge computing networks. However, overuse of edge computing resources could lead to increased energy usage; therefore, it is necessary to find ways to reduce the energy usage of these resources [15].

In contrast, a tiny cell is a fully functional, low-power access node or base station that can function in both licensed and unlicensed frequencies. Small cell implementation increases cellular network energy efficiency and system throughput [16]. The fundamental goal is to provide high-quality service by shortening the path between an access node and the user it is serving. This can be accomplished by creating a dense network, consisting of a lot of tiny cells [17].

To address the growing demand for mobile data, Small Cell Networks (SCNs) are envisioned as a critical technology that allows the Fifth-Generation (5G) wireless communication system [18]. Given that the information and communication technology sector is expected to have a large increase in power consumption by 2030, green communications will be another important feature of 5G systems [19]. To improve multi-tier HetNet energy efficiency, numerous research initiatives have recently been carried out [20]. Therefore, in recent years, researchers have focused a great deal of effort on energy-efficient SCN design [21].

Furthermore, energy-efficient backhauling technologies are needed by service providers to facilitate the widespread deployment of dense small cells [22]. On the other hand, inter-tier interference and network energy consumption would rise dramatically with increasing SBS density. For a green 5G cellular network, it will be crucial to examine network energy efficiency through SBS density optimization [23].

In homogeneous networks, the optimization of the density of BS was studied by several researchers. Their primary focus was on single-tier networks, which consisted of just Macro-Base Stations (MBS). For example, the ideal BS density was examined in [24, 25] from the perspectives of power and energy efficiency. They did not, however, give any thought to multi-tiered heterogeneous networks. Unlike homogeneous networks, in this research, we establish tiny cell density optimization based on energy efficiency in heterogeneous multi-tier networks. The deployment approach was determined to minimize power consumption in a macro-femto type HetNet while maintaining a given area spectral efficiency [26]. In a macro-micro HetNet, Hossain et al. [27] assessed the impact of power consumption by adjusting the microcell density to achieve the necessary system-level performance.

1.5.1 *Motivation and contributions*

The previous study predominantly emphasizes energy efficiency as the primary metric for evaluating network performance for a maximum of three-tier HetNets. The other important factors such as interference, is not discussed extensively in energy efficiency optimization. To examine throughput and energy efficiency in 5G systems, a 4-tier Heterogeneous Cellular Network (HetNet) architecture with macro, micro, pico, and femto cells was used for this study. The rationale behind this decision stems from the increased complexity and variety of deployment scenarios in contemporary 5G networks, where a multi-tier structure is necessary to satisfy the expanding needs for energy, capacity, and coverage optimization.The reason why we choose these configurations are as follows:

1. Accurate Illustration of 5G Deployment Situations Real-world 5G network deployments, where operators use a mix of macro and small cells to combine wide-area coverage with localized capacity and energy savings, are reflected in the 4-tier structure.

2. Level of Detail in Network Performance Analysis The analysis can capture the subtle trade-offs between coverage, throughput, and energy efficiency across various spatial scales and user densities by combining macro, micro, pico, and femto cells.

3. Energy Efficiency Optimization Smaller cells, such as pico and femto, are frequently used in crowded urban or interior settings and run at lower power levels. Their presence makes it possible to thoroughly analyze energy-efficient load balancing and offloading tactics, both of which are essential to the design of green 5G networks.

4. Support for a Range of User Situations A thorough assessment of diverse traffic distribution and adaptive resource allocation is made possible by the distinct user types and traffic profiles that each tier supports (for example, femto cells for indoor residential access and macro cells for mobility users on highways).

Although the 4-tier architecture offers a comprehensive and accurate model, alternative HetNet configurations that are employed in both industry and literature include:

1. In a 2-Tier HetNet, only macro and micro or macro and femto cells are usually included. Although this more straightforward framework is helpful for fundamental coverage and capacity evaluations, it might not fully capture the variety of contemporary 5G scenarios.

2. Three-Tier HetNet: Usually uses femto, micro, and macro cells. Compared to 2-tier systems, this model is more realistic, but it does not have the ultra-dense deployment modeling that pico cells provide.

The 4-tier HetNet model that was selected provides the best possible balance between computational manageability, analytical richness, and real-world applicability. It offers a thorough enough framework to examine trade-offs between energy efficiency and throughput maximization without requiring the modeling complexity of more experimental architectures. In urban and suburban 5G deployment scenarios, where network densification and energy consumption are crucial considerations, this topology is especially well-suited.

The practical novelty of this study lies in its holistic approach to examining energy efficiency in different multitier network configurations. Unlike previous studies that often focus on a single tier or specific aspect of energy consumption, our analysis spans multiple tiers, offering a comprehensive view of energy dynamics in 5G networks.Providing detailed insights into the energy consumption patterns of 2-tier, 3-tier, and 4-tier network architectures. Providing practical recommendations that can be implemented by network operators to achieve significant energy savings. We create comprehensive models of energy usage for picocells, femtocells, macrocells, and microcells while taking operational situations, traffic load, and user density into account. In order to improve energy efficiency and throughput depending on the number of base stations, we proposed an energy efficient 5G heterogeneous network that consists of all types of base station, namely macrocells, microcells, picocells and femtocells. The key contributions of this study are summarized as follows:

1. We develop detailed energy consumption models for macrocells, microcells, picocells, and femtocells, considering factors such as traffic load, user density, and operational scenarios.

2. To propose an energy-efficient 5G heterogeneous network that includes all types of base stations, namely macrocells, microcells, picocells, and femtocells.

3. Introducing collaborative energy-saving techniques that leverage inter-tier communication and coordination, enhancing the overall energy efficiency of the network.

4. We analyzed a heterogeneous network configuration with macrocells, microcells, picocells, and femtocells, optimizing deployment for improved throughput and energy efficiency.

1.5.2 *Paper organization*

The remainder of this paper is organized as follows. In Section 2, the system model has been presented. Section 3 introduces energy efficiency in single-tier and multi-tier cellular environments. In Section 4 simulation scenario is briefly presented. In Section 5, results and analysis are presented through simulations, and conclusions are given in Section 6.

2. System model

2.1 *Network model*

The heterogeneous network that is examined in this work has four tiers: the macro, micro, pico and femto cell tiers, as seen in Figures 2-4. The densities, coverage, and sizes of the three layers vary. Poisson Point Processes (PPP) is used to locate each BS, which reflects a diverse network. In this study, a multi-tier network made up of three distinct network types has been examined. These network types are Macrocell only, Macrocell overlaid by Microcell, Macrocells overlaid by Micro and Pico cells, and Macrocell overlaid by Micro, Pico, and Femto cells The sizes, densities, and transmitting powers of each of these levels set them apart from one another. Stochastic geometry methods, which are commonly used for the design and analysis of heterogeneous networks, have been used for the modeling of networks. Every BS is placed by the Poisson Point Process (PPP). ρ_i denotes the density of the base station. P_t is the transmitting power of the base stations.

2.2 *Model of equations for power consumption*

2.2.1 *Model of a single-tier network*

The main components of a single-tier network are the macro-BS and MS. The majority of energy is used by macro-BS. The power amplifiers in macro-BS use between 70 and 80 percent of the energy. The following represents the power consumption of each macro-BS: $P_T = P_{\text{con}} + \beta P_{\text{trans}}$, P_T = total average power consumed by the macro base station and P_{trans} = transmitted power by the macro base station. P_{con} is the fixed power including miscellaneous power consumptions due to signal processing, cooling of the site, etc. The scaling factor for various radiated power losses, such as feeder losses, is denoted by β. It is assumed to be the same throughout the network for simplicity's sake.

2.2.2 *Model of multi-tier network*

A multi-tier network is further divided into three parts:
- 2-tier network: which consists of macro-BS under laid by micro-BS
- 3-tier network: which consists of macro-BS under laid by micro-BS and pico BS
- 4-tier network: which consists of macro-BS under laid by micro-BS, pico BS, and femto BS

The sizes, densities, and transmitting powers of each of these levels differentiate them from each other. Stochastic geometry methods, which are commonly used for the design and analysis of heterogeneous networks, have been used for the modeling of networks. The Poisson Point Process (PPP), which represents the density of the BSs, is used to arrange all of the BSs and P_{transmit} is the transmitting power of the BSs. Every tier's BSs share the same bandwidth. Any MS can connect to BS in i-th if its Γ is higher than that of the desired BS. γ_i is the representation of the threshold in i-th tier. The transmit power, density, and Γ threshold $\{\text{Pi}, \beta_i, \gamma_i\}$ can be used to define each tier. The mobile stations are randomly distributed according to the PPP distribution φ_m. Rayleigh serves as the channel between MS and BS. BS has an i.i.d. exponential distribution and is positioned at the center. Future research will take into account complex channels. At any moment P_i ith, the average received power P_i of MS is:

$$y_i = P_i h_{r_i} \|r_i\|^{-n} \tag{1}$$

where n ranges from 2 to 4, is the standard path loss exponent.

$$P_{\text{Small cells },i} = \alpha_i \left(P_{\text{con },i} + \beta_i P_{\text{trans }}\right) \tag{2}$$

where α_i, $P_{\text{constant }}$, i, β_i, and P_{transmit} are the density of the base station, fixed power consumption, the scaling factor of different losses, and the transmitted power output in the i^{th} tier, respectively.

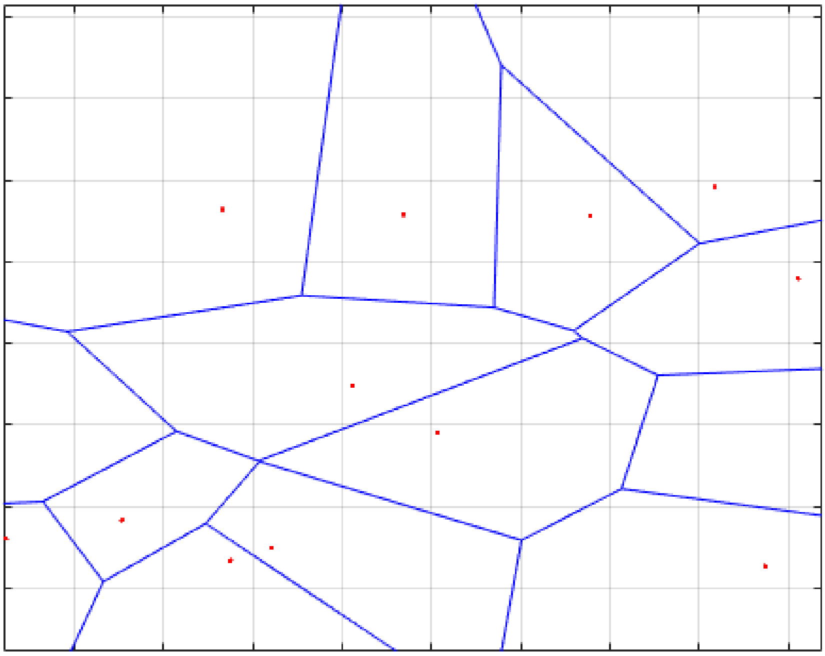

Figure 2. Single-tier network

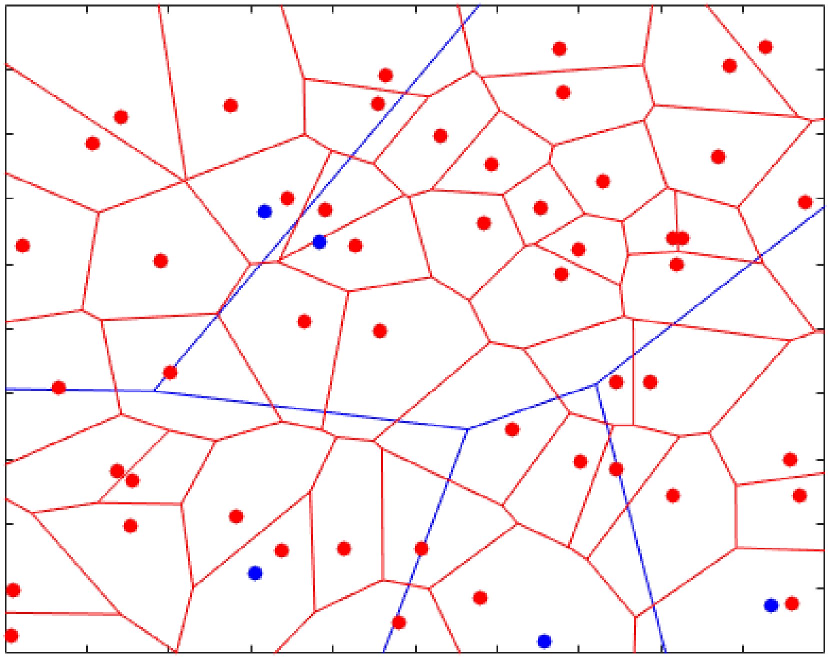

Figure 3. Two-tier heterogeneous network

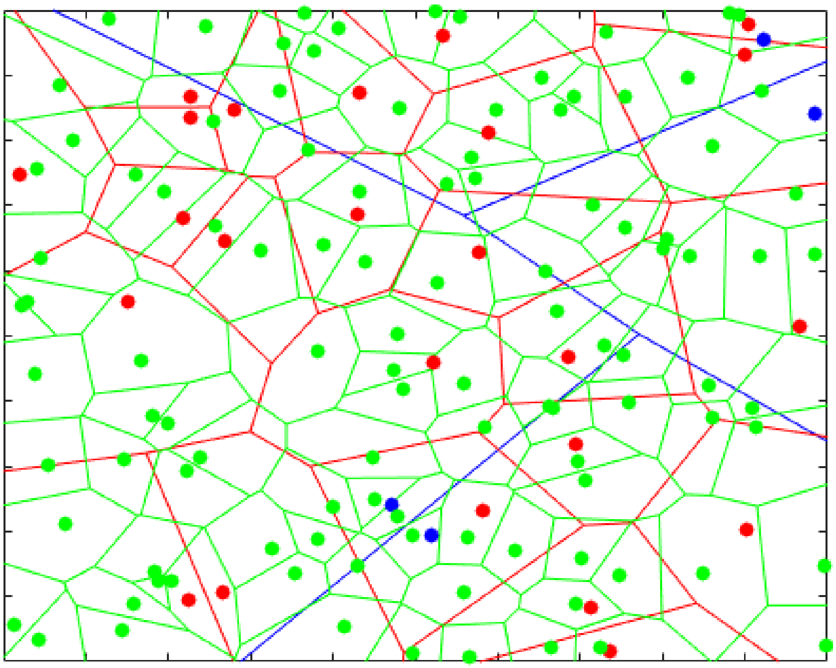

Figure 4. Three-tier heterogeneous network

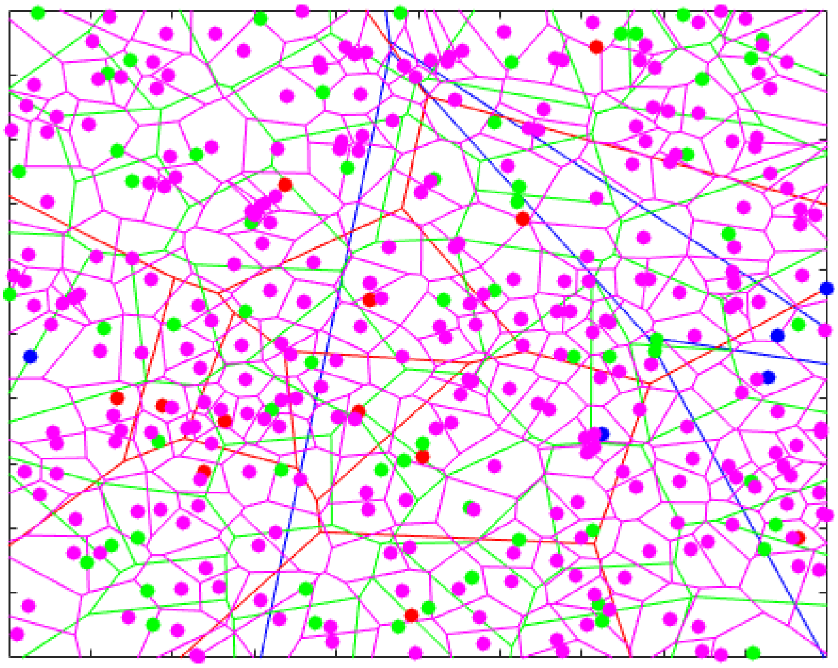

Figure 5. Four-tier heterogeneous hetwork

2.3 *Signal-to-interference and noise ratio* $(\Gamma/)$

In 5G Heterogeneous Networks (HetNets), interference is a critical issue due to the coexistence of different types of cells like macrocells, microcells, picocells, and femtocells. Each cell type introduces unique interference characteristics, which can significantly impact network performance and energy efficiency. This analysis will delve into the mathematical modeling of interference in different 5G HetNets architectures and examine how energy efficiency varies with interference levels.

2.3.1 *System model for interference analysis*

1. 1-Tier Architecture (Macrocells Only): In this scenario, we only have macrocells, and the interference primarily comes from neighboring macrocells. The interference power can be modeled as a sum of the received power from all other macrocells.

$$I_{\text{macro}} = \sum_{j \neq i} P_j G_j \left(\frac{d_{ij}}{d_0} \right)^{-\alpha} \tag{3}$$

where P_j is the transmission power of the interfering macrocells, G_j is the antenna gain, d_{ij} is the distance between the user and the interfering macrocells j, and α is the path loss exponent. Only nearby Macro Base Stations (MBS) can cause interference.

2. 2-Tier Architecture (Macrocells and Microcells): Here, we have both macrocells and microcells. The interference includes contributions from both macro and microcells.

$$I_{\text{total}} = I_{\text{macro}} + \sum_{k} P_k G_k \left(\frac{d_{ik}}{d_0} \right)^{-\alpha_{\text{micro}}} \tag{4}$$

where P_k is the transmission power of the microcells, G_k is the antenna gain for microcells, and α_{micro} is the path loss exponent for microcells.Denser deployment from microcells increases cross-tier interference.

3. 3-Tier Architecture (Macrocells, Microcells, and Picocells): The interference now also includes contributions from picocells.

$$I_{\text{total}} = I_{\text{macro}} + \sum_{k} I_{\text{micro}} + \sum_{l} P_l G_l \left(\frac{d_{il}}{d_0} \right)^{-\alpha_{\text{pico}}} \tag{5}$$

where P_l is the transmission power of the picocells, and α_{pico} is the path loss exponent for picocells.The possibility for interference increases with the density of cell deployment, particularly for small cells like pico.

4. 4-Tier Architecture (Macrocells, Microcells, Picocells, and Femtocells): This is the most complex scenario, where interference comes from all tiers.

$$I_{\text{total}} = I_{\text{macro}} + \sum_{k} I_{\text{micro}} + \sum_{l} I_{\text{pico}} + \sum_{m} P_m G_m \left(\frac{d_{im}}{d_0} \right)^{-\alpha_{\text{femto}}} \tag{6}$$

where P_m is the transmission power of the femtocell, and α_{femto} is the path loss exponent for femtocells.Femtocells produce a great deal of localized interference due to their low power and high density.

Assuming that every MS is linked to thei^{th} BS, the Γ for an individual MS will be:

$$\Gamma_{r_i} = \frac{P_i h_{r_i} \|r_i\|^{-n}}{I + {N_o}^2} \tag{7}$$

where N_o represents AWGN power in the i^{th} tier and I is the interference that r_i received.The equation provides the interference that results in Equation (5).

$$I = \sum_{j=1}^{M} \sum_{r\varepsilon_{\varphi i} \backslash r_i} \mathrm{P_i h}_{r_\mathrm{i}} \left\| r_\mathrm{i} \right\|^{-n} \tag{8}$$

As a result, the final Γ is provided by

$$\Gamma_{r_i} = \frac{\mathrm{P_i h}_{r_\mathrm{i}} \left\| r_i \right\|^{-n}}{\sum_{j=1}^{M} \sum_{x\in\Phi_i \backslash x_i} \mathrm{P_i h}_{r_\mathrm{i}} \left\| r_\mathrm{i} \right\|^{-n} + {N_o}^2} \tag{9}$$

To keep the rest of the paper simple, we will assume that $h_{ri} \sim \exp(1)$ Regardless of which BS has the strongest signal, MS can connect to it. An MS is considered to be in the coverage region if it is:

$$\max \Gamma(r) > \gamma_i \quad r \in \varphi_i \tag{10}$$

For simplicity, it is also assumed that γ_i has a threshold, $\gamma_i > 1$. This indicates that, throughout the network, a maximum of one BS can offer an γ greater than the threshold, enabling every MS to connect with a maximum of one BS simultaneously. In the simulated results, the interference effect is disregarded for simplicity's sake.

3. Energy Efficiency (EE)

The throughput of a network refers to its maximum feasible data rate. Throughput can be used to compute EE by just dividing it by the total power consumed.

$$\mathrm{EE} = \frac{\text{Total throughput}}{\text{Total Power consumption}} \tag{11}$$

EE is expressed in bits/joules as it is more widely known. A single tier's maximum throughput of kth user can be expressed in terms of Shannon's capacity C_k.

$$C_k = B_k \log_2 (1 + \Gamma_k) \tag{12}$$

where B_k is the assigned bandwidth of kth user. In the case of a multi-tier small cells network, this capacity will be scaled by a factor r_i, where r is the number of small BS in the i^{th} tier.

$$R_{m_i} = r_i B_m \log_2 (1 + \Gamma_m) \tag{13}$$

The average EE of one-tier i.e., macrocells is given as

$$\begin{gathered}\mathrm{EE}_{\text{one-tier}} = \frac{C_{\text{macro}}}{P_{\text{macro}}} \\ \mathrm{EE}_{\text{one-tier}} = \frac{B_M \log_2 (1 + \Gamma_M)}{(P_{\text{constant}} + \beta P_{\text{transmit}})}\end{gathered} \tag{14}$$

The average EE of two-tier i.e., macro under laid by microcells is given as

$$\begin{gathered}\mathrm{EE}_{\text{two-tier}} = \frac{C_{\text{macro}} + C_{\text{micro}}}{P_{\text{macro}} + P_{\text{micro}}} \\ \mathrm{EE}_{\text{two-tier}} = \frac{B_M \log_2 (1 + \Gamma_M) + m_i B_m \log_2 (1 + \Gamma_m)}{(P_{\text{constant}} + \beta P_{\text{transmit}}) + \alpha_i (P_{\text{constant},i} + \beta_i P_{\text{transmit}})}\end{gathered} \tag{15}$$

where C_{macro} and C_{micro} are the average throughput of macro re-transmitting stations respectively. $\mathrm{P}_{\text{macro}}$ and $\mathrm{P}_{\text{micro}}$ are transmitting powers of respective tiers. B_k, Γ_k, r_i, B_m, Γ_m represent bandwidth of macro base station, Signal-to-signal-to-interference noise Ratio of the macro base station, number of micro base stations, the bandwidth of the micro cell, and the signal-to-interference noise ratio of micro base stations respectively. In a similar vein, the three-tier network's EE can be determined as follows:

$$EE_{\text{three}-\text{tier}} = \frac{C_{\text{macro}} + C_{\text{micro}} + C_{\text{pico}}}{P_{\text{macro}} + P_{\text{micro}} + P_{\text{pico}}} = \frac{\Omega_{\text{three}-\text{tier}}}{\Psi_{\text{three}-\text{tier}}} \tag{16}$$

where

$$\Omega_{\text{three-tier}} = B_M \log_2 (1 + \Gamma_M) + m_i B_m \log_2 (1 + \Gamma_m) + p_i B_p \log_2 (1 + \Gamma_p) \tag{17}$$

$$\Psi_{\text{three-tier}} = (P_{\text{con}} + \beta P_{\text{trans}}) + \alpha_i (P_{\text{con},i} + \beta_i P_{\text{trans}}) + \alpha_i (P_{\text{con},i} + \beta_i P_{\text{trans}}). \tag{18}$$

where C_{pico} and P_{pico} represents the average throughput and average consumed power by pico base stations respectively.

Finally, the four-tier network's EE can be determined as follows:

$$EE_{\text{four - tier}} = \frac{C_{\text{macro}} + C_{\text{micro}} + C_{\text{pico}} + C_{\text{femto}}}{P_{\text{macro}} + P_{\text{micro}} + P_{\text{pico}} + P_{\text{femto}}} = \frac{\Omega_{\text{four - tier}}}{\Psi_{\text{four - tier}}} \tag{19}$$

where

$$\Omega_{\text{four-tier}} = B_M \log_2 (1 + \Gamma_M) + m_i B_m \log_2 (1 + \Gamma_m) + p_i B_p \log_2 (1 + \Gamma_p) + f_i B_f \log_2 \left(1 + \Gamma_f\right) \tag{20}$$

$$\Psi_{\text{four - tier}} = (P_{\text{con}} + \beta P_{\text{trans}}) + \alpha_i (P_{\text{con},i} + \beta_i P_{\text{trans}}) + \alpha_i (P_{\text{cons},i} + \beta_i P_{\text{trans}}) + \alpha_i (P_{\text{con},i} + \beta_i P_{\text{trans}}) \tag{21}$$

4. Simulation scenarios

This section examines the EE, throughput, and coverage tessellation of single-, two-, three-tier, and four-tier networks. In-depth analyses of data throughput and EE have been conducted for two-, three, and four-tier networks, with a particular emphasis on the effects of the base station and tier counts on EE and data throughput in multitier HetNets.

Table 1. Simulation parameters

Macrocell		Microcell		Picocell		Femtocell	
Frequency band	2.1 GHz (LTE Band 1)	Carrier Frequency	3.5 GHz	Frequency band	5.8 GHz	Frequency band	2.4 GHz
Channel Bandwidth	20 MHz	Bandwidth	100 MHz	Channel Bandwidth	80 MHz	Bandwidth	20 MHz
Transmit Power	40 dBm(10 W)	Cell radius	500 m	Transmit Power	20 dBm	Cell radius	2 m
Cellular layout	Hexagonal grid	User density	200 users/km square	Antenna gain	2 dBi	Transmit Power	15 dBm (30 mW)
Inter-site Distance	500 m	Antenna gain	14 dBi for base station	Minimum separation	2 m	Antenna gain	2 dBi
UE power class	23 dBm (200 mW)	Transmit power	30 dBm	Cell radius	50 m	Number of UE	50
UE distribution	70% inside building			Path Loss model	38 + 30 log 10 (R)		

The simulation settings used for the network under consideration are those found in Table 1 for 3GPP TR 36.931 version 9 and 3GPP TR 36.922 version 10 for only macro-BSs in a single-layer network. For single-tier networks, i-e macro-BSs only. In Figure 2, the coverage tessellation plot is shown. PPP is used to deploy macro Base Stations (BSs) throughout the network. In a similar vein, Figure 3 displays coverage tessellation for a two-tier network. Only the two-tier networks, Macro and micro, are shown in Figure 4. It consists only of macro cells (blue dots) with microcells (red dots) on top. Micro cells have twice the BS density of macro cells. Coverage tessellation for a three-tier network is shown in Figure 4. Figure 4 only shows the three-tier networks, macro, micro, and pico. It is composed solely of mega cells (blue dots), atop which are pico cells (green dots) and microcells (red dots). The BS density of pico cells is four times that of mega cells. Only the four-tier networks—the macro, micro, pico, and femtocells—are shown in Figure 5. It is made up entirely of microcells (blue dots), picocells (green dots), femtocells (magenta), and microcells (red dots) at the top. Femtocells have ten times the BS density of microcells.

5. Results and discussions

The presented results in Figures 6-11 indicate a strong impact due to the different 5G network architecture taking into account the heterogeneous nature. Detailed analysis of throughput and energy efficiency concerning signal-to-interference noise ratio and transmit power is considered. In this section, we provide a numerical demonstration of the proposed architectures. We perform a parameter analysis, varying different parameters, and visualize the resulting graphs to analyze their behaviors.

Figures 6-8 demonstrate the relationship between Signal-to-Interference-plus-Noise Ratio (Γ) and throughput in different cellular network configurations, highlighting the impact of cell types and their density on network performance. Figure 6, which is the two-tier architecture gives a positive correlation between $\Gamma$and throughput: Higher Γ leads to higher throughput due to clearer channels with less interference. Throughput increases with the number of microcells, but not proportionally. Too many microcells cause cochannel interference, reducing Γ and throughput. The optimal number of microcells depends on the traffic and layout of the network. Figure 7 is a three-tier architecture deploying picocells that increase overall network throughput, with the optimal number dependent on user traffic distribution and the desired balance between capacity and signal quality. Trade-off observed: More picocells can lead to increased interference, flattening, or slightly decreased throughput at high Γ values. Figure 8 gives Higher Γ directly correlated with higher throughput due to reduced interference and noise. Throughput increases with more femtocells, which offload traffic from macrocells and microcells. Excessive femtocells cause interference, degrading Γ and signal quality. The optimal femtocell number depends on traffic density, desired throughput, and acceptable signal quality.

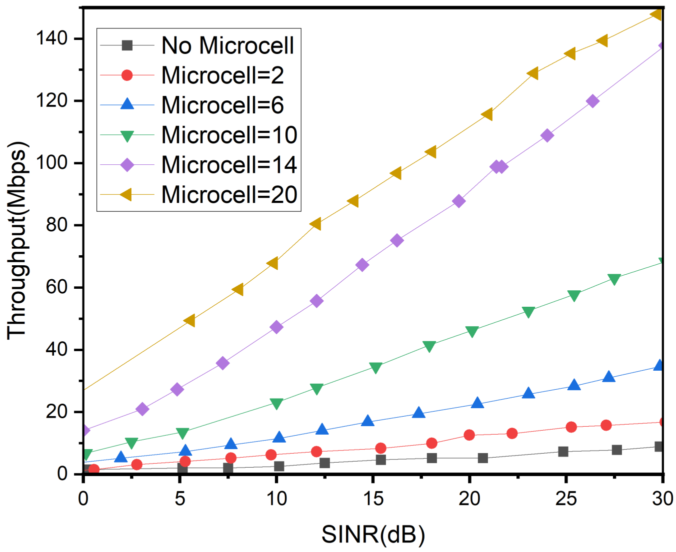

Figure 6. Throughput for two-tier HetNet

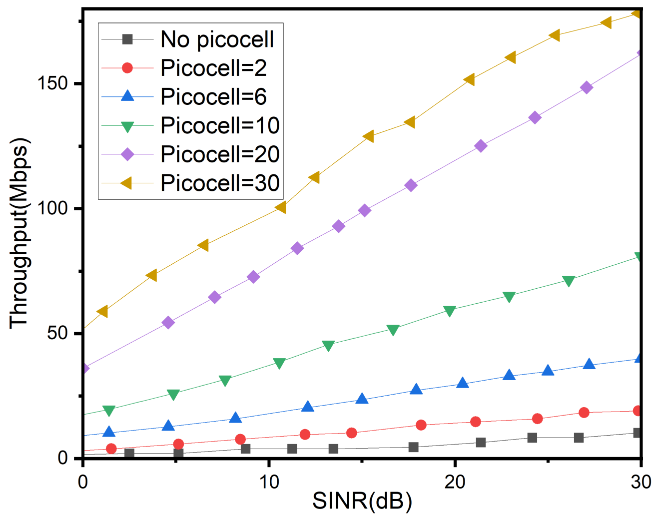

Figure 7. Throughput for three-tier HetNet

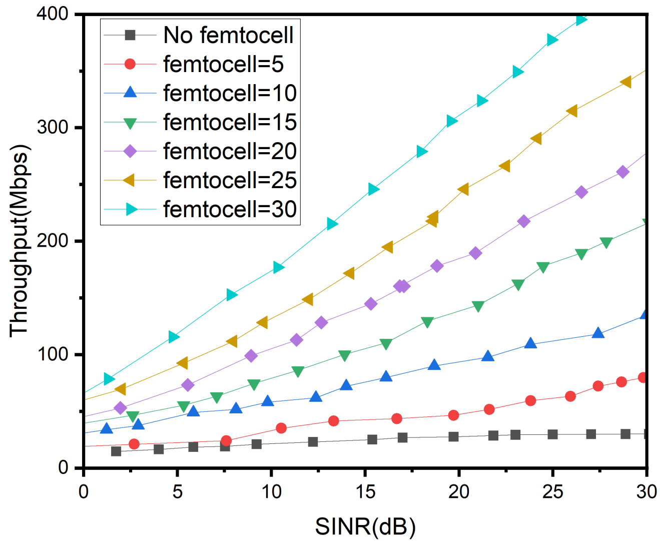

Figure 8. Throughput for four-tier HetNe

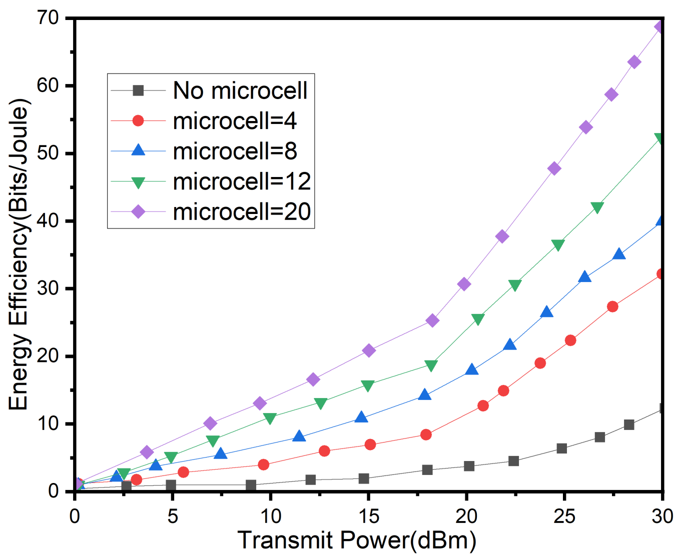

Figure 9. Energy efficiency for two-tier HetNet

Figure 9 shows the energy efficiency of a two-tier cellular network, which consists of macrocells and microcells, for different transmit powers. The presence of microcells has a significant impact on the energy efficiency of the network. As the number of microcells increases (from 4 to 20), the curves shift downwards, indicating better energy efficiency for a given transmit power level. This is because, with more microcells, there is more spatial reuse of resources, which reduces interference and allows lower transmit powers to be used. There is a trade-off between deploying more microcells and achieving better energy efficiency. While adding more microcells can improve energy efficiency, it also increases the complexity and cost of the network. Additionally, deploying a large number of microcells may lead to co-channel interference between themselves, which can negate the gains from spatial reuse.

Figure 10 shows the energy efficiency of a picocell cellular network, plotted against the transmit power. It includes macrocells and microcells to form a three-tier heterogeneous network. The lines also show that as the number of picocells increases, the energy efficiency improves. This is because picocells have a lower transmit power than macrocells and microcells, and they are used to cover smaller areas. Using picocells can reduce the overall transmit power in the network, which improves energy efficiency. In general, the graph shows that the use of picocells can improve the energy efficiency of a cellular network. This is because picocells have a lower transmit power than macrocells and microcells, and they are used to cover smaller areas.

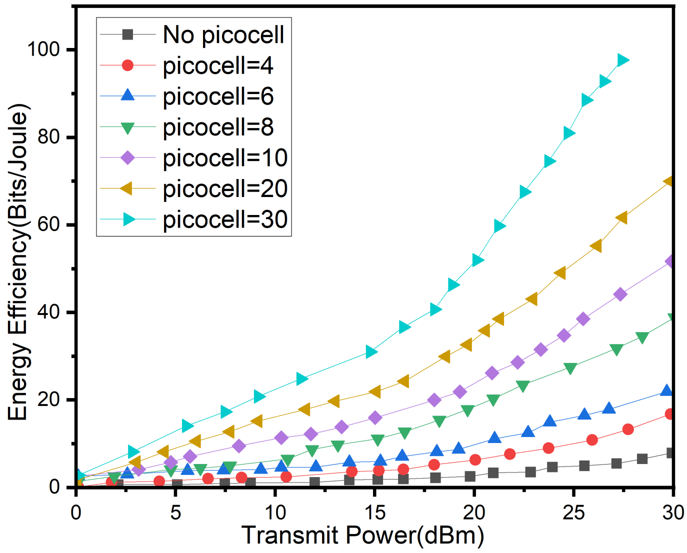

Figure 10. Energy efficiency for three-tier HetNet

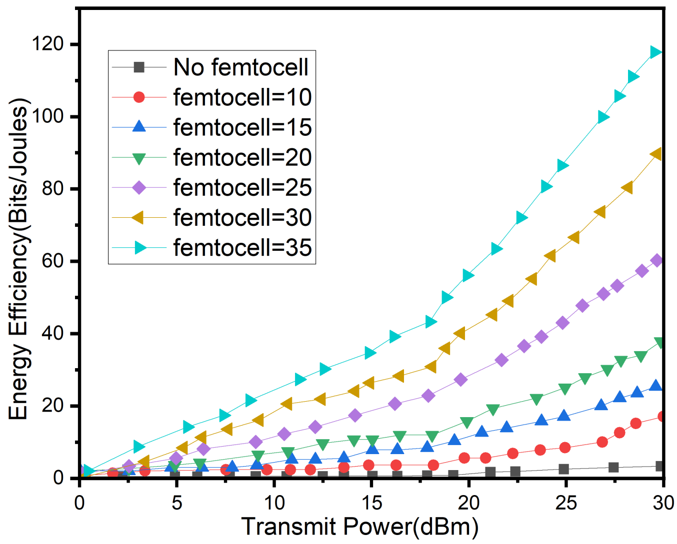

Figure 11. Energy efficiency for four-tier HetNet

Figure 11 shows a graph that shows the energy efficiency of a four-tier cellular network architecture, which consists of macrocells, microcells, picocells, and femtocells, plotted against the transmit power. The deployment of different tiers (macro, micro, pico, and femtocells) allows for a network to be optimized for both coverage and energy efficiency. Femtocells can be used to provide high-quality coverage in areas with low traffic where high-power macrocells would be inefficient. In conclusion, the graph depicts the trade-off between transmit power and energy efficiency in a four-tier cellular network architecture. Femtocells, because of their lower transmit powers, generally achieve higher energy efficiency than macrocells, microcells, and picocells. However, femtocells also have a smaller coverage area. The optimal network design will depend on the specific needs of the area being served.

6. Conclusions

This research paper investigates coverage tessellations, data throughput, and energy efficiency in multi-tier heterogeneous networks. The study focuses on three network architectures: two-tier (macro-micro), three-tier (macro, micro, and pico), and four-tier (macro, micro, pico, and femto). All these networks are modeled using stochastic geometry. The analysis examines the impact of the varying number of pico and femto base stations on data throughput and energy efficiency. Statistical and numerical results indicate that increasing the number of small base stations (pico and femtocells) significantly enhances 5G network throughput. Additionally, optimal deployment of base stations can lead to higher energy efficiency. The energy efficiency analysis is based on the power transmitted by base stations within each tier.Two-tier typically consist of macro cells and micro cells. Although they offer improved coverage and capacity over single-tier networks, they may not fully exploit the benefits of small cell densification for energy efficiency.Three-Tier Networks include macro, micro, and pico cells. They provide better coverage and capacity than two-tier networks but still may fall short in maximizing localized coverage and load balancing compared to a four-tier network. Four-tier networks introduce femto cells in addition to macro, micro, and pico cells. This architecture provides the highest level of granularity in network deployment, leading to significant improvements in energy efficiency through better load distribution, lower transmission power, and advanced power management techniques. The study suggests that further improvements in energy efficiency and data throughput could be achieved through optimal power transmission and adaptive power control strategies.

Acknowledgement

We acknowledge the contributions of all researchers and scholars whose work laid the foundation for this study. This research would not have been possible without their significant contributions to the field.

Disclosure

Regarding this research, the author or authors state that they have no conflicts of interest. The appropriate portion of this publication contains a proper acknowledgment. Additionally, all data, software, and procedures used in this work correspond to conventional research practices and ethical requirements.

Confilict of interest

The authors declare no competing financial interest.

References

[1] Y. Zhang, Y. Xu, Y. Sun, Q. Wu, and K. Yao, "Energy efficiency of small cell networks: Metrics, methods and market," *IEEE Access*, vol. 5, pp. 5965-5971, 2017.

[2] D. Marabissi, L. Mucchi, and S. Morosi, "User-cell association for security and energy efficiency in ultra-dense heterogeneous networks," *Sensors*, vol. 21, no. 2, p. 508, 2021.

[3] P. Gandotra and R. K. Jha, “Next generation cellular networks and green communication,” In Proc. 2018 10th International Conference on Communication Systems & Networks (COMSNETS), Bengaluru, India, Jan. 3-7, 2018, pp. 522-524.

[4] A. ARIF, N. ABAS, and M. HASSAN, “Small cells based call management for mobile network.” *Nonlinear Optics, Quantum Optics: Concepts in Modern Optics*, vol. 57, 2023.

[5] D. Chawla and P. S. Mehra, “A roadmap from classical cryptography to post-quantum resistant cryptography for 5g-enabled iot: Challenges, opportunities and solutions,” *Internet of Things*, p. 100950, 2023.

[6] G. Liu, Y. Huang, N. Li, J. Dong, J. Jin, Q. Wang, and N. Li, “Vision, requirements and network architecture of 6g mobile network beyond 2030,” *China Communications*, vol. 17, no. 9, pp. 92-104, 2020.

[7] M. Fall, Y. Balboul, M. Fattah, S. Mazer, M. El Bekkali, and A. D. Kora, “Towards sustainable 5g networks: A proposed coordination solution for macro and pico cells to optimize energy efficiency,” *IEEE Access*, vol. 11, pp. 50794-50804, 2023.

[8] B. Ji, Z. Chen, S. Mumtaz, C. Han, C. Li, H. Wen, and D. Wang, “A vision of iov in 5g hetnets: Architecture, key technologies, applications, challenges, and trends,” *IEEE Network*, vol. 36, no. 2, pp. 153-161, 2022.

[9] Y. Ullah, M. B. Roslee, S. M. Mitani, S. A. Khan, and M. H. Jusoh, “A survey on handover and mobility management in 5g hetnets: current state, challenges, and future directions,” *Sensors*, vol. 23, no. 11, p. 5081, 2023.

[10] V. Sathya, S. M. Kala, and K. Naidu, “Heterogenous networks: From small cells to 5g nr-u,” *Wireless Personal Communications*, vol. 128, no. 4, pp. 2779-2810, 2023.

[11] I. P. Chochliouros, M.-A. Kourtis, A. S. Spiliopoulou, P. Lazaridis, Z. Zaharis, C. Zarakovitis, and A. Kourtis, “Energy efficiency concerns and trends in future 5g network infrastructures,” *Energies*, vol. 14, no. 17, p. 5392, 2021.

[12] A. Khazali, D. Tarchi, M. G. Shayesteh, H. Kalbkhani, and A. Bozorgchenani, “Energy efficient uplink transmission in cooperative mmwave noma networks with wireless power transfer,” *IEEE Transactions on Vehicular Technology*, vol. 71, no. 1, pp. 391-405, 2021.

[13] M.-A. Karyotakis and N. Antonopoulos, “Web communication: A content analysis of green hosting companies,” *Sustainability*, vol. 13, no. 2, p. 495, 2021.

[14] M. Masoudi, M. G. Khafagy, A. Conte, A. El-Amine, B. Françoise, C. Nadjahi, F. E. Salem, W. Labidi, A. Süral, A. Gati *et al.*, “Green mobile networks for 5g and beyond,” *Ieee Access*, vol. 7, pp. 107270-107299, 2019.

[15] H. Fourati, R. Maaloul, L. Fourati, and M. Jmaiel, “An efficient energy-saving scheme using genetic algorithm for 5g heterogeneous networks,” *IEEE Systems Journal*, vol. 17, no. 1, pp. 589-600, 2022.

[16] S. Rajoria, A. Trivedi, and W. W. Godfrey, “A comprehensive survey: Small cell meets massive mimo,” *Physical communication*, vol. 26, pp. 40-49, 2018.

[17] J. Chen, X. Ge, and Q. Ni, “Coverage and handoff analysis of 5g fractal small cell networks,” *IEEE Transactions on Wireless Communications*, vol. 18, no. 2, pp. 1263-1276, 2019.

[18] M. Wen, Q. Li, K. J. Kim, D. López-Pérez, O. A. Dobre, H. V. Poor, P. Popovski, and T. A. Tsiftsis, “Private 5g networks: Concepts, architectures, and research landscape,” *IEEE Journal of Selected Topics in Signal Processing*, vol. 16, no. 1, pp. 7-25, 2021.

[19] B. Mao, F. Tang, Y. Kawamoto, and N. Kato, “Ai models for green communications towards 6g,” *IEEE Communications Surveys & Tutorials*, vol. 24, no. 1, pp. 210-247, 2021.

[20] M. H. Alsharif, R. Nordin, M. M. Shakir, and A. Mohd Ramly, “Small cells integration with the macro-cell under lte cellular networks and potential extension for 5g,” *Journal of Electrical Engineering & Technology*, vol. 14, pp. 2455-2465, 2019.

[21] X. Qi, S. Khattak, A. Zaib, and I. Khan, “Energy efficient resource allocation for 5g heterogeneous networks using genetic algorithm,” *IEEE Access*, vol. 9, pp. 160510-160520, 2021.

[22] M. M. Mowla, I. Ahmad, D. Habibi, and Q. V. Phung, “A green communication model for 5g systems,” *IEEE Transactions on Green Communications and Networking*, vol. 1, no. 3, pp. 264-280, 2017.

[23] R. K. Saha, “On maximizing energy and spectral efficiencies using small cells in 5g and beyond networks,” *Sensors*, vol. 20, no. 6, p. 1676, 2020.

[24] V. Poirot, M. Ericson, M. Nordberg, and K. Andersson, “Energy efficient multi-connectivity algorithms for ultra-dense 5g networks,” *Wireless Networks*, vol. 26, no. 3, pp. 2207-2222, 2020.

[25] A. Mughees, M. Tahir, M. A. Sheikh, and A. Ahad, “Energy-efficient ultra-dense 5g networks: recent advances, taxonomy and future research directions,” *IEEE Access*, vol. 9, pp. 147692-147716, 2021.

[26] H. Jiang, Z. Xiao, Z. Li, J. Xu, F. Zeng, and D. Wang, "An energy-efficient framework for internet of things underlaying heterogeneous small cell networks," *IEEE Transactions on Mobile Computing*, vol. 21, no. 1, pp. 31-43, 2020.
[27] M. S. Hossain, A. Jahid, K. Z. Islam, M. H. Alsharif, K. M. Rahman, M. F. Rahman, and M. F. Hossain, "Towards energy efficient load balancing for sustainable green wireless networks under optimal power supply," *IEEE Access*, vol. 8, pp. 200635-200654, 2020.