http://www.doi.org/10.62341/enoa1007

Received	2024/12/11	تم استلام الورقة العلمية في
Accepted	2025/01/13	تم قبول الورقة العلمية في
Published	2025/01/16	تم نشر الورقة العلمية في

Energy Optimization for Two-Tier Wireless Communication Networks: A Particle Swarm Optimization (PSO) Algorithm-Based Approach

Ashraf Sherif
Higher Institute of Occupational Safety and Health Technology Espia, Libya
dr_ashraf@aol.com

Abstract
One of the most challenges for future wireless communication networks is energy consumption. Heterogeneous networks, which are built to handle the increasing need for high data traffic, are one of the most promising strategies to address these challenge in future cellular networks. Network coverage may be increased by adding more base stations, but this comes with a high power cost. In the two-tier network concept, small cells (SCs) work along with main cell stations (MCs) to provide wider coverage. Some SCs experience low traffic rates due to user equipment's (UEs) mobility, yet they still consume a considerable amount of energy. To save energy and increase energy efficiency (EE), some SCs must be turned off. This study extends the operation modes for BSs and introduces a bio-inspired mechanism to select the optimal operation mode for each SC. A bias factor is used to regulate power consumption, with SCs operating in one of four modes: On, Standby, Sleep, or Off. The EE maximization problem is defined under a set of limitations and a Variant Power Mode Selection (PSO-VPMS) based on Particle Swarm Optimization Algorithm is proposed in this study. The simulation findings show that the suggested algorithm scheme offers a high EE.

Keywords: two-tier network; energy efficiency (EE); bias factor; Particle Swarm Optimization (PSO).

http://www.doi.org/10.62341/enoa1007

تحسين الطاقة لشبكات الاتصال اللاسلكي ذات الطبقتين: نهج قائم على خوارزمية تحسين سرب الجسيمات(PSO)

أشرف عبد الله الشريف
المعهد العالي لتقنيات السلامة والصحة المهنية، إسبيعة، ليبيا
dr_ashraf@aol.com

الملخص

من أبرز التحديات التي تواجه شبكات الاتصال اللاسلكي المستقبلية استهلاك الطاقة. من بين الأساليب الواعدة لمعالجة هذه المشكلة في شبكات الجيل الخامس (5G) هي الشبكات غير المتجانسة، التي تم تصميمها لتلبية الطلب المتزايد على حركة البيانات الكبيرة. يمكن زيادة تغطية الشبكة من خلال إضافة المزيد من محطات الارسال، ولكن هذا يأتي بتكلفة طاقة مرتفعة. تتعاون محطات الارسال الصغيرة (SCs) مع المحطات الكبرى (MCs) لتوفير تغطية أوسع ضمن مفهوم الشبكة ذات الطبقتين. حركة أجهزة المستخدمين (UEs) تخلق أحمال مرور خفيفة لبعض المحطات الصغيرة، إلا أن هذه المحطات لا تزال تستهلك كمية كبيرة من الطاقة. وبناءً عليه، يجب إيقاف بعض المحطات الصغيرة لتقليل استهلاك الطاقة وزيادة الكفاءة الإجمالية للطاقة (EE) في الشبكة ذات الطبقتين. تم تمديد أوضاع التشغيل لمحطات الإرسال في هذه الدراسة، وتم تقديم آلية تعتمد على السلوك المستوحى من الطبيعة لاختيار وضع التشغيل المناسب لكل محطة صغيرة. يتم استخدام دالة انحياز لتنظيم استهلاك الطاقة، مع وضع المحطات الصغيرة في أحد الأوضاع الأربعة: التشغيل، الاستعداد، النوم، أو الإيقاف. تم صياغة معادلة زيادة كفاءة الطاقة تحت مجموعة من القيود، وتم اقتراح اختيار وضع الطاقة المتغيرة استناداً إلى خوارزمية تحسين سرب الجسيمات(PSO-VPMS) في هذه الدراسة. تظهر نتائج المحاكاة أن الخوارزمية المقترحة توفر كفاءة عالية للطاقة.

الكلمات المفتاحية: الشبكة ذات الطبقتين، الكفاءة الطاقة (EE)، خوارزمية دالة انحياز تحسين سرب الجسيمات(PSO).

1. Introduction

The study discusses the anticipated growth in mobile subscriptions and data traffic, highlighting the need for more efficient wireless networks. Fifth-generation (5G) networks are expected to handle significantly more data than fourth-generation (4G) networks. To

http://www.doi.org/10.62341/enoa1007

meet this demand, various technologies, such as heterogeneous networks (HetNets) with different types of base stations (BSs), have been developed. Main base stations (MCs) provide wider coverage, whereas small cells (SCs) provide higher rates of data.The study emphasizes the importance of energy efficiency (EE) in wireless communication systems, highlighting the significant energy consumption of base stations (BSs), which contributes considerably to operational costs and CO_2emissions. Several strategies to improve EE, such as on-off BS operation, network planning, and resource allocation, are taken into the account. The study introduces a bio-inspired Particle Swarm Optimization Algorithm (PSO) to optimize the power modes of SCs (On, Standby, Sleep, Off) to maximize EE in two-tier networks.The proposed PSO-based Variant Power Mode Selection (VPMS) algorithm aims to select the appropriate power mode for each SC, ensuring network coverage and avoiding coverage gaps. The study ends by analyzing the results and providing recommendations for future research.

2. Related Works

Researchs on HetNets has focused on optimizing energy efficiency (EE) and coverage by leveraging techniques like SC density adjustments, hybrid energy sources, cooperative BS switching, and sleep modes, achieving up to 56% energy savings [1]. Methods such as stochastic geometry and bias factors have enhanced performance while balancing network load [2],[3].

Control Data Separation Architecture (CDSA) architecture and reinforcement learning have been explored to reduce power consumption and improve responsiveness [4],[5]. PSO algorithms have been applied successfully to various optimization problems, but their use in maximizing EE for two-tier networks remains unexplored well. This work utilizes PSO to optimize power consumption and enhance EE in such networks e.g. two tire networks.

3. System Model

The proposed system model considers a two-tier network with a single main base station (MC) and multiple small cell stations (SCs). The MC is positioned at the origin, while the SCs and user equipment (UEs) are distributed according to an independent Poisson point process (PPP). The MC holds all necessary information about the UEs and SCs, including the received signal

International Science and Technology Journal
المجلة الدولية للعلوم والتقنية
Volume 36 العدد
Part 1 المجلد
المجلة الدولية للعلوم والتقنية
International Science and Technology Journal
ISTJ
http://www.doi.org/10.62341/enoa1007

strength (RSS) at each UE, the signal-to-interference-plus-noise ratio (SINR) of each communication link, and their respective locations. It manages and associates each UE with the appropriate SC based on its RSS value.

3.1. Channel Model

Due to the varying transmission powers of the SCs, Voronoi tessellation was employed to divide them.At the start of the simulation, the transmission power of the MC, P_m, and SCs, P_s, are considered to be at its maximum; the suggested method will then adjust this value.A Rayleigh fading channel $h \sim exp(1)$ assumed between u UEs and their corresponding SCs.The path loss exponent parameter, α, is assumed > 2. Given the distance between the UE and the SC that was donated as d_{su}, the received signal strength indicator ($RSSI$) is computed as follows:

$$RSSI = \frac{P_s}{h_{su} d_{su}^{-\alpha}} \tag{1}$$

3.2. Signal-to-Interference-Plus-Noise Ratio (SINR)

Since other SCs have a different bandwidth than MCs in the CDSA scheme, the communication connection of UEs, u, serviced by a certain SC, only encounters interference in this case [0]. The received power at a specific user can be defined as $P_s h_{su} d_{su}^{-\alpha}$. Then the SINR can be computed as follows.

$$SINR_{su} = \frac{P_s h_{su} d_{su}^{-\alpha}}{\sum_{i \in S} P_i h_{iu} d_{iu}^{-\alpha} + N_0} \tag{2}$$

3.3. Achievable Data Rate

For every communication link between u, UEs that is offered by a SC, the achievable data rate is specified as:

$$R_{su} = W_{su} log_2\big(1 + (\Phi_{su} . SINR_{su})\big), \forall s \in S, u \in U \tag{3}$$

WhereW_{su}, is the frequency bandwidth of each s SC and u, UE link, and Φ_{su}, is the user association index variable. Each mobile users share equal bandwidth [0]. If UEs are active and connected to SCs that are only in "On" mode, the overall data rate they can achieve is calculated as below:

http://www.doi.org/10.62341/enoa1007

$$R_{total} = \left[\xi_{on}^{s} \times \sum_{s \in S_{on}} \sum_{u \in U} R_{su} \right] \quad (4)$$

3.4. Calculation of Power Consumption

SCs are categorized into four operational groups: On, Standby, Sleep, and Off, based on their functionality. Each group consumes energy based on the number of SCs and their operational states. Consequently, the power consumption of SCs is modeled as defined in Equation (5):

$$P_s^t = \left[\sum_{s \in S_{on}} (P_s^s + P_s) \times \Phi_{su} \right] + \left[\sum_{s \in S_{sby}} (P_s^s + P_s) \times 0.5 \times \Phi_{su} \right] + \left[\sum_{s \in S_{Slp}} (P_s^s + P_s) \times 0.15 \times \Phi_{su} \right] + \left[\sum_{s \in S_{Of}} (P_s^s + P_s) \times 0 \times \Phi_{su} \right] \quad (5)$$

After a bias factor applied, the power consumption of the four SC operation modes calculated as follows:

$$P_s^{t^*} = \left[\xi_{on}^{s} \times \sum_{s \in S_{on}} (\rho_s^s + p_s) \times \Phi_{su} \right] + \left[\xi_{sby}^{s} \times \sum_{s \in S_{sby}} (\rho_s^s + p_s) \times 0.5 \times \Phi_{su} \right] + \left[\xi_{slp}^{s} \times \sum_{s \in S_{Slp}} (\rho_s^s + p_s) \times 0.15 \times \Phi_{su} \right] + \left[\xi_{slp}^{s} \times \sum_{s \in S_{Of}} (\rho_s^s + p_s) \times 0 \times \Phi_{su} \right] \quad (6)$$

Where S_{on}, S_{sby}, S_{slp}, and S_{of} stand for groups of SCs for On, Standby, Sleep, and Off, respectively. The bias factor of the MC and each set of SCs (ξ_{on}^{m}, ξ_{on}^{s}, ξ_{sby}^{s}, and ξ_{slp}^{s}) independently regulates

http://www.doi.org/10.62341/enoa1007

the power consumption of each mode. The total power consumption of the MC is given as follows:

$$P_m^t = (\rho_m^s + p_m) \tag{7}$$

Where: p_m, is a transmit power and ρ_m^s represent the MC's static power consumption. Once the bias factor value is applied, the MC's reduced power consumption can be calculated as follows:

$$P_m^{t^*} = \xi_{on}^m \times (\rho_m^s + p_m) \tag{8}$$

The total power consumption of the network is calculated as:

$$P_{m,s}^t = P_m^{t^*} + P_s^{t^*} \tag{9}$$

3.5. Calculation of Energy Efficiency

The aim of this study is to achieve energy-efficient communication. Therefore, the Energy Efficiency (η EE), of the two-tier network is defined as the ratio of the total power consumption of the MC and SCs to the total possible data rate of active SCs. The equation is derived as follows from (4) and (9):

$$\eta\ EE = \frac{R_{total}}{P_{m,s}^t} \tag{10}$$

4. Problem Statement and Solution

The problem formulation and limitations for the suggested PSO-VPMS algorithm are described as follows:

$$\underbrace{max}_{\xi_{on}^m, \xi_{on}^s, \xi_{sby}^s, \xi_{slp}^s} = \eta\ EE \tag{11}$$

Subject to

$$0 \le \xi_{on}^m + \xi_{on}^s \le 0.9 \tag{12}$$

$$0 \le \xi_{sby}^s + \xi_{slp}^s \le 0.1 \tag{13}$$

$$\xi_{on}^m + \xi_{on}^s + \xi_{sby}^s + \xi_{slp}^s \le 1 \tag{14}$$

$$\sum_{s \in S} \Phi_{su} \le 1\ ;\ \forall u \in U \tag{15}$$

$$\Phi_{su} \in \{0, 1\};\ \forall s \in U \tag{16}$$

http://www.doi.org/10.62341/enoa1007

$$count\left(\sum_{u\in U}\Phi_{su}\neq 1\right)\leq\bar{\Psi};\ \forall s\ \notin\ S \qquad (17)$$

Constraint (12) limits the bias factor value to no more than 90% of the total bias for both active MC and active SCs. This ensures the stability of the two-tier network by preventing excessive power reductions in the MC and active SCs.Constraint (13) ensures that the bias factors of inactive SCs do not exceed 10% of the total bias factor value, aiming to limit their power usage. Constraint (14) requires the MC and active and inactive SCbias factor sums to be smaller than 1. Constraint (15) limits SC connections to one UE. Constraint (16) definesΦ_{su}as a binary variable (0 or 1) indicating user association: "1" means the UE is connected to an SCB, while "0" means it is not. Constraint (17) ensures that the number of SCs in inactive mode does not exceed the average inactive ratio$\bar{\Psi}$, preventing coverage holes.

4.1. PSO-Based Variant Power Mode Selection Algorithm (PSO-VPMS)

This section explains how the PSO and VPMS algorithms work together to maximize energy efficiency (EE) in a two-tier network. Its goal is to optimize bias factor values (ξ_{on}^{m}, ξ_{on}^{s}, ξ_{sby}^{s}, ξ_{slp}^{s}) to adjust BS power consumption and enhance EE. Figure 1, shows the proposed logic flow diagram.

http://www.doi.org/10.62341/enoa1007

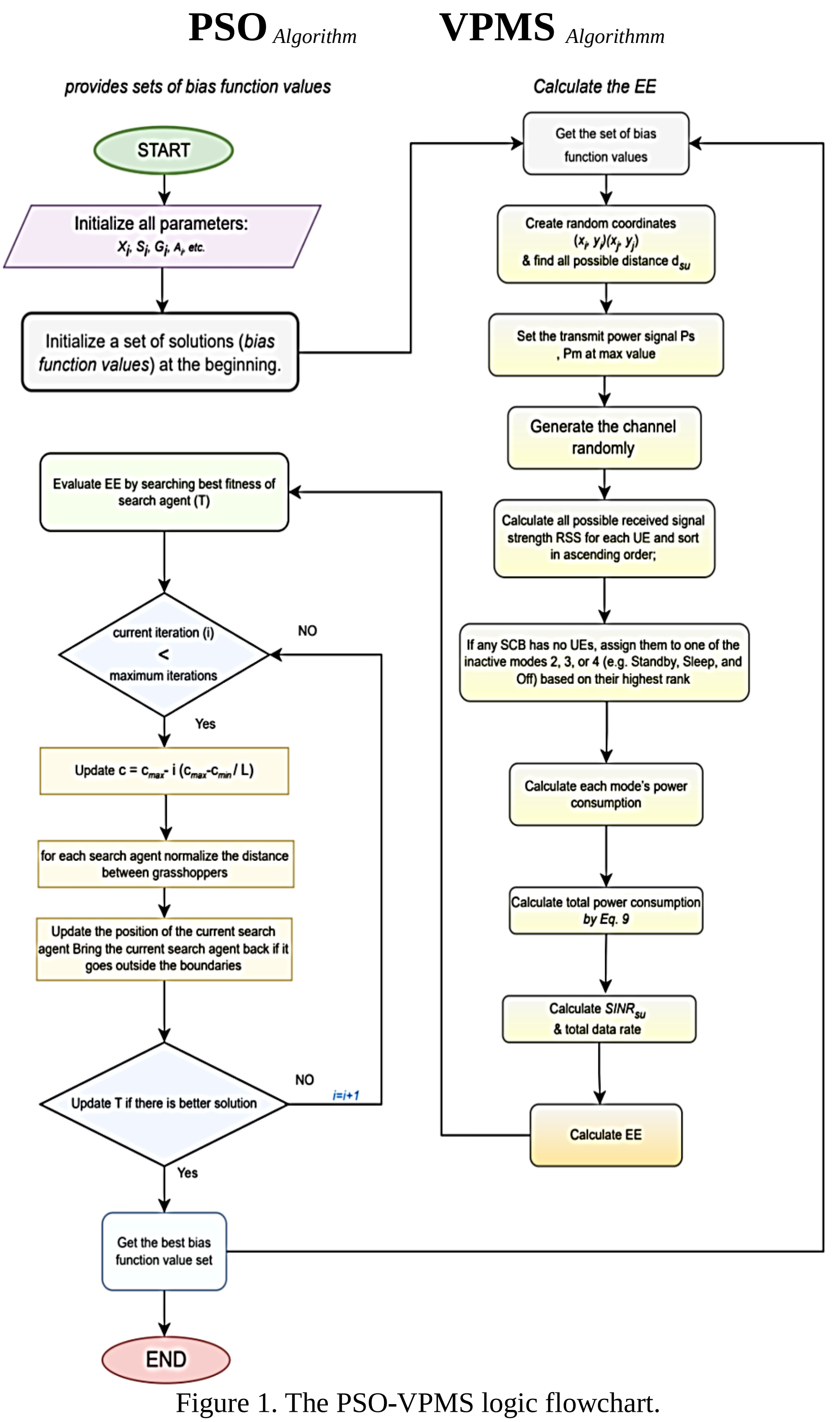

Figure 1. The PSO-VPMS logic flowchart.

http://www.doi.org/10.62341/enoa1007

5. Simulation Results and Discussion

The simulation and analysis of the proposed VPMS, based on the PSO algorithm, were conducted using MATLAB 2021a on Windows 11. The network consists of 50 SCs (S) and 200 UEs (U), both randomly deployed according to a Poisson point process (PPP) within the specified area. The instantaneous SINR values for users, as given by Equation (2), may vary based on dynamic channel conditions and UE location [7]. Simulation results are presented to demonstrate the proposed method for determining SC operating patterns. The network parameters used in the simulation are listed in Table 1.

TABLE 1. Simulation network parameters.

SimulationParameter	Value	Unit
Number of **MC**	1	-
Number of SCs$\boldsymbol{S}$	50	-
Number of UEs $\boldsymbol{U}$	200	-
SC radius	< 100	m
Static Power Consumption of MC$\boldsymbol{P_m^s}$	130	watt
Transmission Power of SC$\boldsymbol{p_m}$	20	watt
Static Power Consumption of SC$\boldsymbol{P_s^s}$	4.8	watt
Transmission Power of SC$\boldsymbol{p_s}$	0.75	watt
Band width$\boldsymbol{B}$	100	MHz
Inactive radius$\boldsymbol{r_{in}}$	500	meter
Coverage of MC$\boldsymbol{D}$	30	km
Number of Iterations	100	-

The main goal is to maximize EE across the two-tier network by optimizing the power consumption of all BSs. Initially, the transmission power of the MC and SCs is set to their maximum values. After applying the PSO and VPMS algorithms, the optimal bias factor values ($\xi_{on}^{m^*}$, $\xi_{on}^{s^*}$, $\xi_{sby}^{s^*}$, and $\xi_{slp}^{s^*}$) correspond to the MC (on) and SC (on, standby, and sleep) operation modes respectively. Table 2 presents the simulation results with various values, which will be analyzed in this section to evaluate the performance of the PSO-VPMS algorithms.

TABLE 2. Simulation Results and Values.

Operation Mode	MC/SCs Sets	Optimal Bias factor	Value
ON	MC	$\xi_{on}^{m^*}$	0.485
ON	S_{on}	$\xi_{on}^{s^*}$	0.395

http://www.doi.org/10.62341/enoa1007

Standby	S_{sby}	$\xi_{sby}^{s^*}$	0.071
Sleep	S_{slp}	$\xi_{slp}^{s^*}$	0.040
Off	S_{of}	$\xi_{of}^{s^*}$	-

The results show that the bias factor values, $\xi_{on}^{m^*}$ and $\xi_{on}^{s^*}$, are reduced to 0.485 and 0.395, respectively, which are higher than the values for SCs in inactive modes (e.g., $\xi_{sby}^{s^*}$ and $\xi_{slp}^{s^*}$). This is because the MC and active SCs handle all network operations and UE services. SCs in the 'on' mode consume more power than in inactive modes like standby, sleep, or off. However, the bias factor values for both the MC and active SCs do not exceed 90% of the total bias factor value, as constrained by Equation (13). Table 2 also shows that the lowest bias factor values were obtained for the SCs in standby ($\xi_{sby}^{s^*}$ = 0.071) and sleep ($\xi_{slp}^{s^*}$ = 0.040) modes, reflecting the goal of minimizing power consumption in these inactive operation modes. The total bias factor values do not exceed 10% of the overall value, as constrained by (13). Figure 2, compares the PSO-VPMS scheme with conventional sleep control, no sleep control, random sleep 20%, and random sleep 30%. The simulation, based on [8], shows that power consumption increases proportionally with the number of SCs across all schemes.

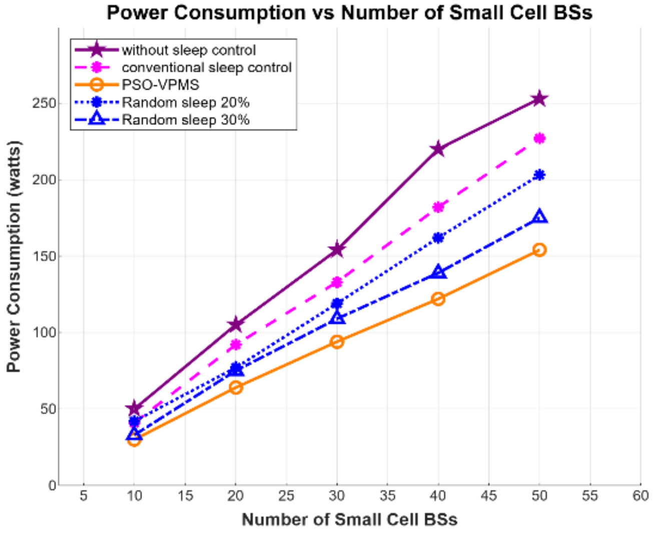

Figure 2.

http://www.doi.org/10.62341/enoa1007

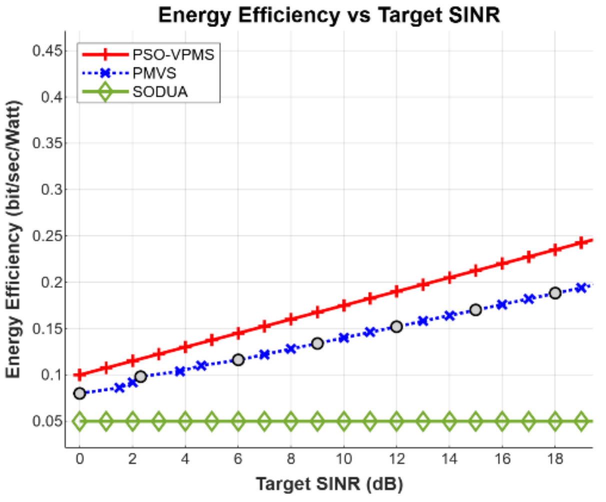

Figure 3.

Figure 4.

The scheme without sleep control significantly increases power consumption, as all SCs remain active. The conventional sleep control reduces power usage, while random sleep 20% consumes slightly more than random sleep 30% and the conventional method. However, the proposed PSO-VPMS outperforms these schemes by 53.04%, 51.12%, 43.32%, and 39.1%, respectively. Additionally, PSO-VPMS is compared to the SODUA and PMVS algorithms in terms of energy efficiency (EE) and spectral efficiency (SE), as shown in Figures 3 and 4. The proposed PSO-VPMS algorithm outperforms SODUA and PMVS, improving EE by 59.3% and 7.4% and SE by 18.01% and 13.09%, respectively. Its flexibility in

http://www.doi.org/10.62341/enoa1007

utilizing four operation modes (on, standby, sleep, and off) surpasses SODUA's single switched-off mode and outperforms other algorithms, including the Genetic Algorithm (GA) [9].

6. Conclusions

Energy consumption in mobile communication networks is a significant challenge in the context of global warming, representing a substantial proportion of overall Information and Communication Technology (ICT) energy usage. In this paper, a bio-inspired, behavior-based mechanism proposed to optimize the operation modes of Small cell stations (SCs), selecting between "on," "standby," "sleep," and "off" states. The approach leverages a bias factor to manage power consumption effectively across these modes. The calculations incorporated metrics such as signal-to-interference-plus-noise ratio (SINR), user-SC association index, power consumption, and energy efficiency (EE). By employing the VPMS-PSO algorithm, substantial improvements in network performance were achieved, with simulation results indicating a significant reduction in power consumption compared to existing schemes. Specifically, it achieved reductions of 53.04%, 51.12%, 43.32%, and 39.1%, over algorithms without sleep control, conventional sleep control, random sleep at 20%, and random sleep at 30%, respectively. The method outperformed the SODUA and PMVS algorithms in terms of EE, with gains of 59.3% and 7.4% respectively, also improved spectral efficiency (SE) by 18.01% and 13.09%, respectively. This scenario presents additional challenges due to the typically higher energy demands of communication with main cell base stations (MCs), which are often located farther from UEs than nearby SCs. Overcoming these challenges will lead to significant advancements in the energy efficiency of mobile communication networks, contributing to more sustainable and effective system performance.

References

[1]. Li, Y.; Celebi, H.; Daneshmand, M.; Wang, C.; Zhao, W. Energy-efficient femtocell networks: Challenges and opportunities. IEEE Wirel. Commun. 2013, 20, 99–105.
[2]. Zhu, Y.; Zeng, Z.; Zhang, T.; An, L.; Xiao, L. An energy efficient user association scheme based on cell sleeping in LTE heterogeneous networks. In Proceedings of the 2014 International Symposium on Wireless Personal Multimedia Communications (WPMC), Sydney, Australia, 7–10

http://www.doi.org/10.62341/enoa1007

September 2014; pp. 75–79.
[3]. Yang, B.; Yang, X.; Ge, X.; Li, Q. Coverage and handover analysis of ultra-dense millimeter-wave networks with control and user plane separation architecture. IEEE Access 2018, 6, 54739–54750.
[4]. Ghosh, J.; Gupta, A.; Haci, H.; Jako, Z. User association, power control and channel access schemes for two-tier main-femto networks: CDF of SINR analysis. IETE Tech. Rev. 2020, 39, 219–230.
[5]. Liu, Q.; Wu, G.; Guo, Y.; Zhang, Y.; Hu, S. Energy Efficient Resource Allocation for Control Data Separated Heterogeneous-CRAN. In Proceedings of the 2016 IEEE Global Communications Conference (GLOBECOM), Washington, DC, USA, 4–8 December 2016; pp. 1–6.
[6]. Mirza, J.; Aljohani, A.J.; Raza, A.; Iqbal, S.; Ghafoor, S. A multi-hop free space optical link based on a regenerative relay. Alex. Eng. J. 2022, 61, 1459–1467.
[7]. Ghosh, J.; Gupta, A.; Haci, H.; Jako, Z. User association, power control and channel access schemes for two-tier main-femtonetworks: CDF of SINR analysis. IETE Tech. Rev. 2020, 39, 219–230.
[8]. Natarajan, J. Cell throughput contribution rate based sleep control algorithm for energy efficiency in 5G heterogeneous networks.
[9].Sherif, Ashraf, and Huseyin Haci. "A novel bio-inspired energy optimization for two-tier wireless communication networks: A grasshopper optimization algorithm (GOA)-based approach." Electronics 12.5 (2023): 1216.