Energy Efficiency in Network Communication Systems Through Bio-Inspired Optimization

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Abstract

Energy consumption is a critical issue for future wireless communication networks. Heterogeneous networks (HetNets) are considered a promising approach in fifth-generation (5G) cellular networks to meet the increasing data traffic demands. Expanding network coverage by adding more base stations significantly raises power costs. In a two-tier network setup, macrocell base stations (MBs) collaborate with small cell base stations (SBs) to provide broad coverage. However, light traffic loads at some SBs still result in excessive energy consumption. To address this, SBs can be switched off to reduce power usage and improve the overall energy efficiency (EE) of the network. This study presents a bio-inspired approach using Ant Colony Optimization (ACO) to optimize SB operation modes. SBs can operate in four power modes—On, Standby, Sleep, and Off—regulated by a bias factor to balance energy efficiency and coverage. The ACO-based Variant Power Mode Selection (ACO-VPMS) algorithm is proposed to select appropriate SB operation modes. Simulation results demonstrate that the proposed algorithm is able to achieve higher energy efficiency compared to existing methods.

Keywords: *Heterogeneous network (HetNets); Energy Efficiency (EE); bias Factor; Ant Colony Optimization (ACO).*

كفاءة الطاقة في أنظمة الاتصالات الشبكية من خلال تحسين مستوحى من الطبيعة

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الملخص
يُعد استهلاك الطاقة من القضايا المهمة لشبكات الاتصالات اللاسلكية المستقبلية. وتُعتبر الشبكات غير المتجانسة (HetNets) نهجًا واعدًا في شبكات الجيل الخامس (5G) لتلبية الطلبات المتزايدة على تدفق البيانات. يؤدي توسيع تغطية الشبكة عن طريق إضافة المزيد من محطات الارسال المتنوعة إلى زيادة كبيرة في تكاليف الطاقة. في إعداد شبكي مكوّن من مستويين، تتعاون محطات الارسال الكبرى (MBs) مع محطات الارسال الصغيرة (SBs) لتوفير تغطية واسعة. ومع ذلك، فإن الأحمال الخفيفة لحركة تدفق البيانات في بعض محطات الصغيرة تؤدي إلى استهلاك مفرط للطاقة. ولمعالجة هذا الأمر، يمكن إيقاف تشغيل محطات SBs لتقليل استهلاك الطاقة وتحسين كفاءة الطاقة (EE) العامة للشبكة. تقدم هذه الدراسة نهجًا مستوحى من الطبيعة باستخدام خوارزمية تحسين مستعمرة النمل (ACO) لتحسين أوضاع تشغيل هذه المحطات. حيث يمكن أن تعمل محطات SBs في أربعة أوضاع طاقة مختلفة التشغيل، مثل الوضع الاحتياطي، وضع النوم، والإيقاف وذلك تحت تنظيم عامل التحيز(bias factor) لتحقيق توازن بين كفاءة الطاقة والتغطية. تم اقتراح خوارزمية اختيار وضع الطاقة المتغير (ACO-VPMS) لاختيار أوضاع تشغيل محطات SBs المناسبة. تُظهر نتائج المحاكاة أن مخطط الخوارزمية المقترح يوفر كفاءة طاقة عالية.

الكلمات المفتاحية: *الشبكة غير المتجانسة(HetNets) ؛ كفاءة الطاقة(EE) ؛ عامل التحيز؛ خوارزمية تحسين مستعمرة النمل (ACO) .*

1. Introduction

The exponential growth in mobile data traffic, fueled by the proliferation of smart devices and bandwidth-intensive applications, demands advanced wireless communication solutions. Fifth-generation (5G) networks are expected to accommodate these demands by integrating diverse technologies, including heterogeneous networks (HetNets) [1]. HetNets leverage different types of base stations, such as macro base stations (MBs) for wide-area coverage and small cell base stations (SBs) for high-data-rate localized services [2].

Control Data Separation Architecture (CDSA) is a design paradigm in communication networks that separates the control plane from the data plane. It is a key enabler in modern network architectures, including software-defined networking (SDN) and some 5G network implementations [3].

Energy efficiency (EE) has become a key consideration in the design and operation of wireless communication systems. Base stations (BSs) account for a significant portion of network energy consumption, contributing to operational costs and environmental impact. Strategies such as dynamic BS operation, optimized network planning, and intelligent resource allocation are essential for addressing these challenges [4]. This study explores the application of Ant Colony Optimization (ACO), a bio-inspired algorithm, to optimize the power modes of SBs in a two-tier network. The proposed ACO-VPMS algorithm dynamically adjusts SB power modes to maximize energy efficiency while maintaining seamless network coverage and service quality.

2. Related Works

Research on energy-efficient HetNets has focused on various techniques to optimize network performance while minimizing power consumption. Prior studies have explored the benefits of SB density adjustments, cooperative base station switching, hybrid energy sources, and advanced sleep-mode techniques. For instance, stochastic geometry has been used to model and analyze network performance under different configurations, while bias factor have been applied to balance traffic loads and enhance energy efficiency [5]. Ant Colony Optimization (ACO) has been widely applied in fields such as routing, scheduling, and resource allocation. Inspired by the foraging behavior of ants, ACO uses a probabilistic framework to identify optimal solutions to complex problems. Its adaptability and robustness make it a suitable candidate for optimizing energy efficiency in two-tier wireless networks. Although existing studies have applied ACO to network optimization tasks, its application to SB power mode selection for enhancing energy efficiency in HetNets remains largely unexplored [6].

3. System Model

CDSA architecture assumed in this scenario. The proposed system model consists of a two-tier network comprising a macrocell base station (MB) and multiple small cell base stations (SBs). The MB, located at the network's center, manages the overall network operations, while SBs and user equipment (UEs) are distributed based on a Poisson point process (PPP). The MB is responsible for collecting critical network information, such as the received signal strength (RSS) of UEs, the signal-to-interference-plus-noise ratio (SINR) of communication links, and the geographic locations of SBs and UEs.

3.1 Channel Model

To model signal propagation, the network employs Rayleigh fading channels and considers a path loss exponent α greater than 2 [7]. SBs initially operate at maximum transmission power, P_s, which is subsequently adjusted based on the ACO-VPMS algorithm. Using Voronoi tessellation, the network is divided into regions, each serviced by a specific SB. The received signal strength indicator (RSSI) at a UE is calculated as a function of the transmission power, distance d_{su}, and path loss as follows:

$$RSSI = \frac{P_s}{h_{su} d_{su}^{-\alpha}} \quad (1)$$

Where h_{su}, represents the channel between particle UE u, and it's associated SB.

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

SINR is a critical metric for evaluating communication quality. The SINR for a UE serviced by an SB is calculated by considering the received signal power, interference from other SBs, and ambient noise. SINR values directly impact the achievable data rate and determine the quality of service (QoS) experienced by UEs and calculated as follows:

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

Where $P_s h_{su} d_{su}^{-\alpha}$, is the received power at specific UE.

3.3 Achievable Data Rate

The achievable data rate for a communication link between an SB and a UE is computed based on the SINR and the bandwidth allocated to the link. From Shannon formula the overall network data rate is the sum of individual data rates for all active UEs associated with SBs in the On mode.

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

Equal bandwidth allocation is assumed for simplicity W_{su}, Φ_{su} associated index variable and total data rate calculated as follows [8]:

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

3.4 Power Consumption

SBs operate in four different power modes: On, Standby, Sleep, and Off. Each mode consumes a different amount of energy based on the SB's functionality and load. A bias factor is applied to dynamically adjust power consumption across these modes. The total power consumption of the network is the sum of the power consumed by all SBs P_s^t and the MB P_m^t.

$$\begin{aligned} P_s^t &= \left[\sum_{s \in S_{on}} (P_s^s + P_s) \times \Phi_{su} \right] \\ &+ \left[\sum_{s \in S_{sby}} (P_s^s + P_s) \times 0.5 \times \Phi_{su} \right] \\ &+ \left[\sum_{s \in S_{slp}} (P_s^s + P_s) \times 0.15 \times \Phi_{su} \right] \\ &+ \left[\sum_{s \in S_{of}} (P_s^s + P_s) \times 0 \times \Phi_{su} \right] \qquad (5) \end{aligned}$$

Once the bias factor is applied, the power consumption for the four SB operation modes is determined 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} represent the groups of SBs operating in On, Standby, Sleep, and Off modes, respectively. The bias factor applied to the MB and SB sets (ξ_{on}^m, ξ_{on}^s, ξ_{sby}^s, and ξ_{slp}^s) independently regulates the energy consumption of each mode. Consequently, the total power consumption for the MB is given as follows:

$$P_m^t = (\rho_m^s + p_m) \quad (7)$$

Where ρ_m^s and p_m denote the transmission power and static power consumption of the MB, respectively. After applying the bias factor, the reduced power consumption of the MB can be calculated as follows:

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

Finally the total power consumption of a two-tier network is determined as:

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

3.5 Energy Efficiency

The primary objective of the study is to maximize EE, which is defined as the ratio of the total achievable data rate to the total power consumption of the network as below:

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

4. ACO-VPMS Algorithm

The ACO-VPMS algorithm simulates the behavior of ants in finding optimal paths. Each SB is represented as a node in a graph, with edges corresponding to power mode transitions. Ants traverse the graph, guided by pheromone trails and heuristic information, to identify the most energy-efficient configuration of SB power modes. The algorithm iteratively updates pheromone levels based on the quality of solutions, converging toward an optimal or near-optimal solution.

5. Problem Statement and Solution

The energy efficiency maximization problem is formulated with several constraints to ensure network stability and service continuity. These constraints include limiting bias factor values, maintaining adequate coverage, and preventing excessive SB inactivity. The ACO-VPMS algorithm addresses this problem by optimizing the power mode selection for each SB based on the network's real-time state and described as follows:

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

Subject to

$$0 \le \xi_{on}^{m} + \xi_{on}^{s} \le 0.9 \qquad (12)$$

$$0 \le \xi_{sby}^{s} + \xi_{slp}^{s} \le 0.1 \qquad (13)$$

$$\xi_{on}^{m} + \xi_{on}^{s} + \xi_{sby}^{s} + \xi_{slp}^{s} \le 1 \qquad (14)$$

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

$$\Phi_{su} \in \{0,1\}; \; \forall s \in U \qquad (16)$$

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

Constraint (12) restricts the bias factor value to a maximum of 90% of the total bias for both active MBs and active SBs. This ensures network stability by preventing excessive reductions in the power consumption of these components. Constraint (13) mandates that the bias factor for inactive SBs must not exceed 10% of the total bias value, focusing on minimizing their power usage. Constraint (14) specifies that the combined bias function values for the MB, active SBs, and inactive SBs must remain below 1. Constraint (15) enforces that each SB can only connect to a single UE. Constraint (16) defines as a binary variable (0 or 1) representing user association: a value of "1" indicates the UE is connected to an SB, while "0" indicates no connection. Finally, Constraint (17) ensures that the proportion of inactive SBs does not surpass the average inactivity ratio , thereby avoiding coverage gaps.

6. Simulation Results and Discussion

Simulations were conducted using MATLAB to evaluate the performance of the proposed ACO-VPMS algorithm. The network model includes 50 SBs and 200 UEs randomly deployed within a specified area. Key parameters such as transmission power, SINR, and data rates were dynamically adjusted based on the algorithm’s output. The simulation's network parameters are presented in Table 1.

TABLE 1. Simulation network parameters.

Simulation Parameter	Value	Unit
Number of MCB	1	-
Number of SCBs $\mathcal{S}$	50	-
Number of UEs $\mathcal{U}$	200	-
SCB radius	<100	m
$\mathcal{P}_m^s$	130	Watt
$\mathcal{P}_m$	20	Watt
$\mathcal{P}_s^s$	4.8	Watt
$\mathcal{P}_s$	0.75	Watt
B	100	MHz
r_{in}	500	m
$\mathcal{D}$	30	km
Number of Iterations	100	-
Upper bound ub_d	100	-
Lower bound lb_d	-100	-

At first, the MB and SBs' transmission powers are set to their highest possible levels. The optimal bias factor values ($\xi_{on}^{m^*}$, $\xi_{on}^{s^*}$, $\xi_{sby}^{s^*}$, and $\xi_{slp}^{s^*}$) after the ACO and VPMS algorithms are applied correspond to the MB (on) and SB (on, standby, and sleep) operation modes, respectively.

Results and Discussion

The simulation results with different values are shown in Table 2.

TABLE 2. Simulation Results and Values.

Operation Mode	MB/SBs Sets	Optimal Bias Function	Value
ON	MB	$\xi_{on}^{m^*}$	0.375
ON	S_{on}	$\xi_{on}^{s^*}$	0.362
Standby	S_{sby}	$\xi_{sby}^{s^*}$	0.071
Sleep	S_{slp}	$\xi_{slp}^{s^*}$	0.040
Off	S_{of}	$\xi_{of}^{s^*}$	-

The simulation results demonstrate the effectiveness of the ACO-VPMS algorithm in reducing power consumption and enhancing energy efficiency. the bias factor values $\xi_{on}^{m^*}$ and $\xi_{on}^{s^*}$, are reduced to 0.375 and 0.362, respectively, This is because the MC and active SCs handle all network operations. SCs in the 'on' mode consume more power than in inactive modes like standby, sleep, or off. 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). for the SCs in standby ($\xi_{sby}^{s^*}$ = 0.062) and sleep ($\xi_{slp}^{s^*}$ = 0.037) modes, reflecting the goal of minimizing power consumption in these inactive operation modes. According to (13), the total bias factor values cannot be greater than 10% of the total value. Compared to conventional sleep control, without sleep control, and random sleep (20%, 30%) configurations, the proposed method achieves significant energy savings as shown in figure 1 by 49.04%, 47.12%, 41.31%, and 35.3%, respectively. For instance, the ACO-VPMS algorithm reduces power consumption by over 50% compared to schemes without sleep control. Additionally, figure 2 and 3 demonstrate the algorithm outperforms traditional methods in terms of spectral efficiency, highlighting its ability to balance energy savings and data rate optimization.

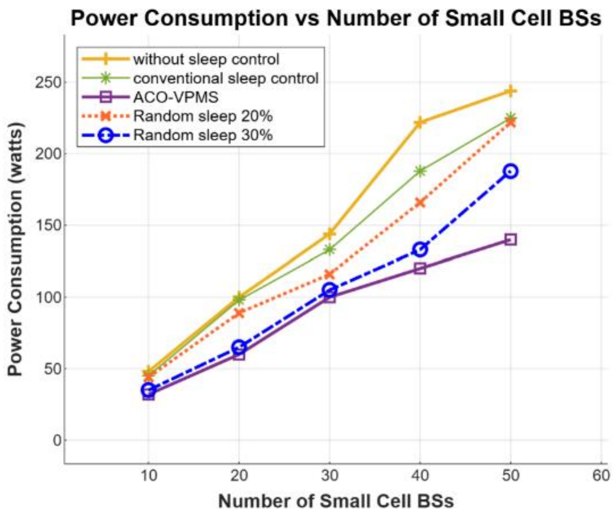

Figure 1.

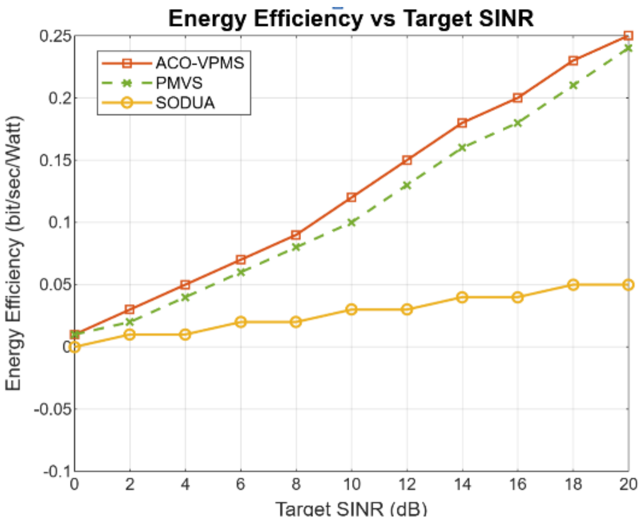

Figure 2.

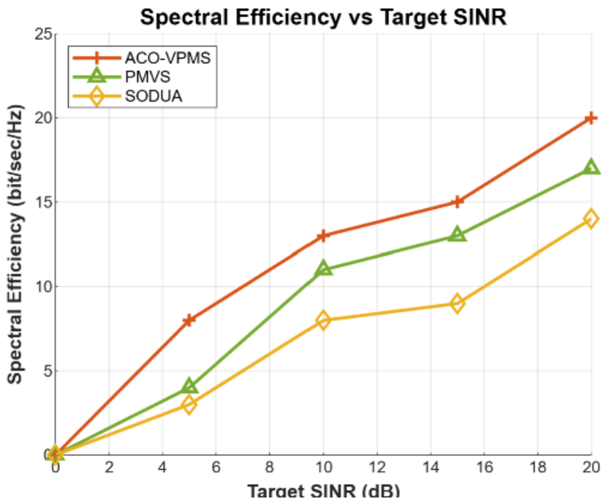

Figure 3.

The results underscore the potential of ACO for optimizing energy efficiency in two-tier wireless networks. By dynamically adjusting SB power modes based on network conditions, the ACO-VPMS algorithm ensures seamless coverage and high QoS. The algorithm's adaptability makes it well-suited for real-world scenarios with dynamic traffic patterns and user demands.

6. Conclusions

Energy consumption in mobile communication networks poses a significant challenge, particularly in the context of increasing data traffic and environmental concerns. This study introduces a bio-inspired approach using the Ant Colony Optimization (ACO) algorithm to optimize SB operation modes in two-tier networks. By leveraging the ACO-VPMS algorithm, the proposed method achieves substantial improvements in energy efficiency while maintaining network performance.

Simulation results validate the effectiveness of the ACO-VPMS algorithm in reducing power consumption and enhancing spectral efficiency. Future work will focus on extending the algorithm to multi-macrocell environments and exploring its application to user equipment (UE) energy optimization. These advancements will further enhance the energy efficiency of next-generation wireless communication networks.

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