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RESEARCH ARTICLE

Optimizing the stochastic deployment of small base stations in an interleave division multiple access-based heterogeneous cellular networks

Etinosa Noma-Osaghae[1] | **Sanjay Misra**[2] | **Murat Koyuncu**[3]

[1]Department of Electrical and Information Engineering, Covenant University, Ota, Nigeria

[2]Department of Computer Science and Communication, Østfold University College, Halden, Norway

[3]Department of Information System Engineering, Atilim University, Ankara, Turkey

Correspondence
Sanjay Misra, Department of Computer Science and Communication, Østfold University College, Halden, Norway.
Email: sanjay.misra@hiof.no

Summary

The use of small base stations (SBSs) to improve the throughput of cellular networks gave rise to the advent of heterogeneous cellular networks (HCNs). Still, the interleave division multiple access (IDMA) performance in sleep mode active HCNs has not been studied in the existing literature. This research examines the 24-h throughput, spectral efficiency (SE), and energy efficiency (EE) of an IDMA-based HCN and compares the result with orthogonal frequency division multiple access (OFDMA). An energy-spectral-efficiency (ESE) model of a two-tier HCN was developed. A weighted sum modified particle swarm optimization (PSO) algorithm simultaneously maximized the SE and EE of the IDMA-based HCN. The result obtained showed that the IDMA performs at least 68% better than the OFDMA on the throughput metric. The result also showed that the particle swarm optimization algorithm produced the Pareto optimal front at moderate traffic levels for all varied network parameters of SINR threshold, SBS density, and sleep mode technique. The IDMA-based HCN can improve the throughput, SE, and EE via sleep mode techniques. Still, the combination of network parameters that simultaneously maximize the SE and EE is interference limited. In sleep mode, the performance of the HCN is better if the SBSs can adapt to spatial and temporal variations in network traffic.

KEYWORDS
energy efficiency, heterogeneous cellular network, nonorthogonal multiple access, optimization, orthogonal multiple access, spectral efficiency

1 | INTRODUCTION

The interleave division multiple access (IDMA) is already used as a hybrid with orthogonal frequency division multiple access (OFDMA). More research is being carried out to understand the nature of the IDMA in various aspects of communication engineering, including heterogeneous cellular networks (HCNs).[1] The drive to adopt the IDMA as a communication standard for future networks is gradually gaining momentum as more researchers explore IDMA as a multiple access technique.[2] It has also been submitted that IDMA as a NOMA technique can perform very well, especially when power becomes a constraint in the design of the communication system. This submission warrants more investigation to determine the gains in power conservation from the use of IDMA in future networks of which HCNs are a part.[3] Some researchers confirmed that research endeavors in nonorthogonal multiple access (NOMA) focused excessively on the power domain nonorthogonal multiple access (PD-NOMA). There is a need to explore other NOMA techniques to provide more versatility and better spectral efficiencies.[4] The IDMA provides spectral efficiency (SE) when applied in multiple input multiple output (MIMO) systems as part of the overall HCN design. The IDMA is also valuable for massive machine communication.[5]

Frameworks for balancing SE and energy efficiency (EE) in HCNs with quality of service (QoS) consideration emphasize cooperation among the various heterogeneous network technologies. The tradeoff between SE and EE in HCNs is primarily examined for the downlink or the Broadcast Channel (BC). The tradeoff can be analyzed using a distributed joint power allocation technique that is cooperative and dynamic. EE-SE tradeoff models use various priorities and fairness parameters to develop algorithms that enable flexible tradeoffs between EE and SE.[6] User fairness, QoS, and throughput are typical constraints used to provide optimal solutions to the EE-SE tradeoff problem in HCNs.

There is a tradeoff between network performance and energy-saving when base station sleeping mode is implemented. In a study,[7] the measured call blocking probability was used to estimate the tradeoff between network performance and energy savings in sleep mode capable cellular networks. The researchers proposed an information exchange surrogate approximation for cellular networks to extensively approximate the tradeoff between network performance and energy savings in cellular networks.

Mobile traffic demands are nonuniform when considered in large-scale connectivity scenarios. Thus, at various instances in time, radio resources are grossly underutilized to the point of negatively affecting energy-spectral-efficiency (ESE) in HCNs. The varying large-scale temporal user traffic, base station density per tier, load migration factor, and geographic traffic intensity all contribute to the overall energy-SE of HCNs.

The existing literature provides very little regarding the performance of an IDMA-based HCN in terms of its SE and EE. To the best of the authors' knowledge, no information in the existing literature deals with the simultaneous maximization of the SE and EE of IDMA-based HCNs. This identified gap in the current literature leads to the following research questions:

1. Given a 24-h traffic profile and a sleep-mode activated HCN, what would the nature of the network's throughput, SE, and EE be if the multiple access technique is IDMA?
2. What would be the behavior of an IDMA-based HCN when the SE and EE of the network are simultaneously maximized?

This research study was carried out to shed light on the network performance of an IDMA-based HCN and provide a look at the behavior of the HCN when SE and EE are simultaneously maximized. The following are the contributions of this research study to the existing body of knowledge:

1. A model to characterize the SE and EE of an IDMA-based HCN.
2. A detailed analysis of the throughput, SE, and EE of an IDMA-based HCN.
3. An algorithm that simultaneously maximizes the SE and EE of an IDMA-based HCN.

The remaining part of the article is organized in this format. Section 2 considers related works. Section 3 discusses the collective energy and SE outlook in IDMA-based HCNs and the proposed algorithm to maximize the SE and EE. In Section 4, the simulation results are discussed. The article is then concluded, and references are provided.

2 | RELATED WORKS

Results have consistently shown that the SE of HCNs improves with any increase in the density of small base stations within the macro area. Still, this improvement comes at the expense of increased energy consumption or deteriorating EE. In a related study, the area SE and EE were jointly optimized using the firefly algorithm in a two-tier HCN to derive the optimal system parameters for any weight of area SE and EE. The joint power allocation and user association were investigated for the downlink of a PD-NOMA based network. Although the EE was not explicitly investigated, the network's SE was investigated using particle swarm optimization and salp swarm algorithm for power allocation to superimpose users on dedicated physical resource blocks. The power allocation and user allocation optimization problem was formulated to maximize the minimum achievable user rate of the network.[8]

In situations where the focus is on the EE of the HCN, UEs are assigned to base stations within power and SINR constraints. The SINR constraint is taken at each UE within the HCN. The problem formulated for EE optimization within HCNs is resolved by changing the resulting complex problem into a tractable form and solving iteratively. In some cases, a coalition game and a two-sided scalable function have been used to solve EE-focused optimization problems in HCN.[9] In general, the EE optimization study reveals the impact of small cell density on the performance of HCNs. In Table 1, a summary is made of some HCN EE-SE problems that have been solved in the existing literature and the utilized multiple access techniques.

TABLE 1 HCN EE-SE problems and proposed solutions

Author	Multiple access technique	EE-SE problem	Proposed solutions
Han et al.[10]	OFDMA	Quasi-concave problem	An interference mitigating solution that optimizes EE through SE selection
Xiong et al.[11]	OFDMA	Quasi-concave problem	Fairness index used to achieve balanced resource allocation
Hadi and Ghazizadeh[12]	PD-NOMA	EE-SE in the presence of imperfect and perfect knowledge of the channel state information	A probability-based model that approximates network unpredictability
Fadoul[13]	OFDMA	The rate/coverage of a k-tier heterogeneous cellular network	Stochastic geometry used to model the base stations and deployed antennas in the HCN
Wang et al.[14]	OFDMA	The rate/coverage of a k-tier heterogeneous cellular network	A biased cell association scheme that controls the power and subchannel allocation to UE
Zhao et al.[6]	OFDMA	Large-scale user behavior	Joint optimization
Lu et al.[15]	OFDMA	A quadratic programming problem	Joint optimization
Han et al.[16]	OFDMA	A multiperson bargaining problem using stochastic processes in a study	An online dynamic control algorithm that made the HCN consume the least energy without the required user rate shortfall
Ghariani and Jouaber[17]	OFDMA	EE-SE metrics combination to determine user base station association	A green topological potential approach
Qian et al.[18]	OFDMA	Non-convex and combinatorial	Simulated annealing framework, coalition formation game theory, and primal decomposition theory.
Alavi et al.[19]	PD-NOMA	A non-convex power minimization problem	The Taylor series approximation and semi-definite relaxation approaches
Elbamby et al.[20]	OFDMA/PD-NOMA	A pairwise stable matching problem	Concave-convex techniques

Abbreviations: OFDMA, orthogonal frequency multiple access; PD-NOMA, power domain nonorthogonal multiple access.

TABLE 2 Proposed EE-SE optimization algorithms for HCNs in the existing literature

Author	Proposed EE-SE optimization algorithm
Luo et al.[22]	A Fire-fly inspired algorithm
Alostad[7]	A deactivation algorithm
Alsharif et al.[23]	Particle swarm optimization
Nie et al.[24]	An iterative algorithm
Nguyen et al.[25]	A path-following algorithm
Saimler and Ergen[26]	A heuristic algorithm
Zhang et al.[27]	A time-sharing technique and a gradient assisted binary search algorithm
Jiang Zhou et al.[28]	A two-tier iterative algorithm

Linear programming (LP) is a common technique used to solve EE and SE optimization problems in broadcast and multiple access channels. The use of LP provides a nearly monotonic variation between spectral and EE. In LP, the power allocation, subchannel assignment, rate selection, and transmission scheduling problems are jointly considered with the view of maximizing EE in a PD-NOMA-based HCN. The formulated optimization problem is fractional, and the UE's highest and lowest throughput ratio is used as constraints. The fractional optimization problem is resolved by turning it into a LP problem. The NOMA-HCN joint scheduling and resource management assignment has a better performance than its OMA counterpart. A subgradient algorithm was proposed to solve the LP problem iteratively.[21] After a series of tests, the algorithm gave a suboptimal solution. In numerical terms, the EE improved by 23%, and power consumption decreased by 20%. The proposed iterative algorithm used to solve the LP problem came close to becoming practically implementable in NOMA-HCN systems.

Several researchers have proposed different EE-SE optimization algorithms in the existing literature, and some of the most prominent ones are highlighted in Table 2.

Resource efficiency is also used in the existing literature to study the tradeoff between SE and EE in HCNs. Resource efficiency helps to balance SE and EE in HCNs.[29] The resource efficiency of any typical HCN is derived by formulating an optimization problem that seeks to maximize resource efficiency with power allocation as a constraint.

3 | METHODOLOGY

A mathematical model that characterizes the energy and SE of a two-tier IDMA-based HCN was developed. The nature of the signal at the transmitter and receiver for the IDMA-based HCN was derived. The network traffic-aware and sleep-mode HCN was optimized using a weighted sum modified particle swarm optimization algorithm to maximize the SE and EE of the HCN simultaneously.

3.1 | Mathematical notations

u—Probability SBS is awake.
d_N—MBS density.
ρ—SINR threshold.
b—Subchannel.
d_j —SBS density.
W—Bandwidth.
P_c—Coverage probability.
R—Throughput.

P_{sleep}—Power consumed by BS when it is asleep.
βP_N—Static power of MBS.
βP_j—Static power of SBS.
Δ_j—Slope of load dependent power consumption of SBS.
Δ_N—Slope of load dependent power consumption of MBS.
λ_N—Coefficient of power allocated to subchannel in macro cell.
λ_j—Coefficient of power allocated to subchannel in small cell.
g_N—Gain of channel users in macro cell.
g_j—Gain of channel users in small cell.
δ—Noise density.
R—Coding rate.
E—Mathematical statistical expectation.
C—Average power consumption.

3.2 | The IDMA SINR model

The signal from the transmitter has interleaved and superimposed chips and can be expressed mathematically, as shown in Equation (1).

$$Y_i = \sum_{j=1}^{J} g_i x_i + n \tag{1}$$

$\sum_{j=1}^{J} g_i x_i$ are the superimposed chips of J users at the transmitter, and n is the additive white Gaussian noise with zero mean and variance σ^2. In IDMA, the amount of information bit that can be reliably transmitted per chip for J users with coding rate R is expressed as the signal-plus-interference-to-noise ratio. The *SINR* can be derived as written in Equation (2).

$$SINR_{new} = \frac{P_i g_i}{\sum_{i' \neq i} P_i g_i . R + N_o W} \forall i \in J \tag{2}$$

where $R = 1/n$. $n \in \{2, 4, \ldots, n, n+2\}$ is usually even depending on the modulation technique used to encode the information bits of the user.

3.2.1 | IDMA SINR for small cell users

Every subchannel b_j allocated by BS j is occupied by two users with $g_{i,j}^{b_j} < g_{2,j}^{b_j}$. The coding rate for each user is determined by the modulation technique, and thus, the *SINR* of the two users within the coverage area of SBS j becomes as shown in Equations (3) and (4).

$$SINR_{s1,j}^{IM,b_j} = \frac{\left(1 - \lambda_j^{b_j}\right) P_j^{b_j} g_{1,j}^{b_j}}{r.N_o b_j} \tag{3}$$

$$SINR_{s2,j}^{IM,b_j} = \frac{\lambda_j^{b_j} P_j^{b_j} g_{2,j}^{b_j}}{r.\left(N_o b_j + \left(1 - \lambda_j^{b_j}\right) P_j^{b_j} g_{1,j}^{b_j}\right)} \tag{4}$$

$SINR_{s1,j}^{IM,b_j}$ and $SINR_{s2,j}^{IM,b_j}$ are the signal-plus-interference-to-noise ratios of UE_1 and UE_2.

Sharing the same subchannel $b_j \in W_J$ in small cell j.

3.2.2 | IDMA SINR for macro cell users

Every subchannel b_n allocated by the MBS N is occupied by two users with $g_{i,N}^{b_n} < g_{2,N}^{b_n}$. Therefore, the *SINR* of the two users within the coverage of the MBS N becomes as shown in Equations (5) and (6).

$$SINR_{s1,N}^{IM,b_n} = \frac{\left(1-\lambda_N^{b_n}\right) P_N^{b_n} g_{1,N}^{b_n}}{r.N_o b_N} \tag{5}$$

$$SINR_{s2,N}^{IM,b_n} = \frac{\lambda_N^{b_n} P_N^{b_n} g_{2,N}^{b_n}}{r.\left(N_o b_n + \left(1-\lambda_N^{b_n}\right) P_N^{b_n} g_{1,N}^{b_n}\right)} \tag{6}$$

$SINR_{s1,N}^{IM,b_n}$ and $SINR_{s2,N}^{IM,b_n}$ are the signal-plus-interference-to-noise ratios of UE_1 and UE_2 sharing the same subchannel $b_n \in W_N$ in macrocell N.

3.3 | The ESE of IDMA-based HCN

The SE of the IDMA-based HCN is given, as shown in Equation (7).

$$SE_{IM} = \frac{R_T^{IM}}{W} \tag{7}$$

where R_T^{IM} is the throughput of the two-tier HCN when IDMA is used as the multiple access technique.

The EE of the IDMA-based HCN for random sleep mode is given as shown in Equation (8).

$$EE_{ran}^{IM} = \frac{R_T^{IM}}{\left[d_j u\left(P_{r,j} + \Delta_j \beta P_j\right) + d_j (1-u) P_{sleep}\right] + \left(P_{s,N} + \beta \Delta_N P_N\right)} \tag{8}$$

The EE of the IDMA-based HCN for strategic sleep mode is given as shown in Equation (9):

$$EE_{stra}^{IM} = \frac{R_T^{IM}}{\left[d_j E\{I\}\left(P_{s,j} + \Delta_j \beta P_j\right) + d_j (1-E\{I\}) P_{sleep}\right] + \left(P_{s,N} + \beta \Delta_N P_N\right)} \tag{9}$$

Therefore, the ESE for the IDMA-based HCN in random sleep mode becomes as shown in Equation (10).

$$ESE_{ran}^{IM} = SE_{IM} \frac{W}{\left[d_j u\left(P_{r,j} + \Delta_j \beta P_j\right) + d_j (1-u) P_{sleep}\right] + \left(P_{s,N} + \beta \Delta_N P_N\right)} \tag{10}$$

The ESE for the IDMA-based HCN in strategic sleep mode becomes as shown in Equation (11).

$$ESE_{stra}^{IM} = SE_{IM} \frac{W}{\left[d_j E\{I\}\left(P_{s,j} + \Delta_j \beta P_j\right) + d_j (1-E\{I\}) P_{sleep}\right] + \left(P_{s,N} + \beta \Delta_N P_N\right)} \tag{11}$$

3.4 | The optimisation algorithm

The SBS in the HCN is put to sleep using normalized traffic data to achieve an overall average power consumption that matches the required coverage probability.

```
Algorithm 1: Sleep Mode Algorithm
Input: Normalized traffic profile, time(hourly), SBS density($d_j$), MBS density ($d_N$),
network simulation parameters.
Output: Coverage probability($P_c$ ) throughput ($R$), Spectral Efficiency ($SE$), Energy
efficiency (EE) and the Pareto-optimal front for energy and spectral efficiency
maximization
for hourly values of normalized traffic $Y \in t_1, t_2, t_3, \dots, t_{24}$ do
    Set probability of SBS awake $= u$
    Calculate Bernoulli trial:
    SBS operates with probability $= u$, independently
    SBS sleeps with probability $= 1 - u$, independently
    Set SBS operating probability based on activity level $(x)$ of small cell
    SBS operates with probability $= I(x)$, independently
    SBS operates with probability $= 1 - I(x)$, independently
    for random sleep mode, do
        Compute the average power consumption, $C_R$
        Determine the random sleep mode coverage probability, $P_{c,ran}$
        Determine the random mode spectral efficiency ($SE_{IM}$)
        Determine the strategic sleep mode energy efficiency ($EE_{ran}^{IM}$)
        Plot the Pareto-optimal front for energy and spectral efficiency maximization
        for strategic sleep mode, do
            Compute the average power consumption, $C_S$
            Determine the strategic sleep mode coverage probability, $P_{c,stra}$
            Determine the random mode spectral efficiency ($SE_{IM}$)
            Determine the strategic sleep mode energy efficiency ($EE_{stra}^{IM}$)
            Plot the Pareto-optimal front for energy and spectral efficiency maximization
        end for
    end for
    Display average power consumption and coverage probability for random and strategic
    sleep modes
end for
```

Algorithm 1 was used to track the critical metrics of coverage probability, network throughput, SE, EE, and the simultaneous maximization of the SE and EE tradeoff when the HCN is in sleep mode.

4 | RESULTS AND DISCUSSION

In this section, the performance of the two-tier IDMA-based HCN is evaluated through numerical simulations in MATLAB2018b. The obtained results are thoroughly discussed.

The simulation of the 24-h throughput of the IDMA-based HCN was done using Algorithm 1. The result is shown in Figure 1. The IDMA achieved the highest throughput of 1.7×10^{11} *bps* at $22:00$ *hours* when traffic was at its peak and when all SBSs were kept awake. The result obtained from simulating the throughput of the HCN shows that the IDMA outperforms the OFDMA by at least 68% at peak traffic levels.

The throughput simulation with varying small cell densities was done using Algorithm 1. The result is shown in Figure 2. The throughput achieved in the no-sleep mode was the highest, reaching 1.72×10^{11} *bps* for IDMA and 7.85×10^{10} *bps* for OFDMA when the SBS density d_j was at its peak. The improvement in throughput with an increase in SBS density d_j was caused by the offloading of more traffic from the MBS to nearby SBSs. UEs can connect to closeby SBSs instead of the MBS and get improved SINR, thus causing the HCN to achieve higher throughput. The lower throughput

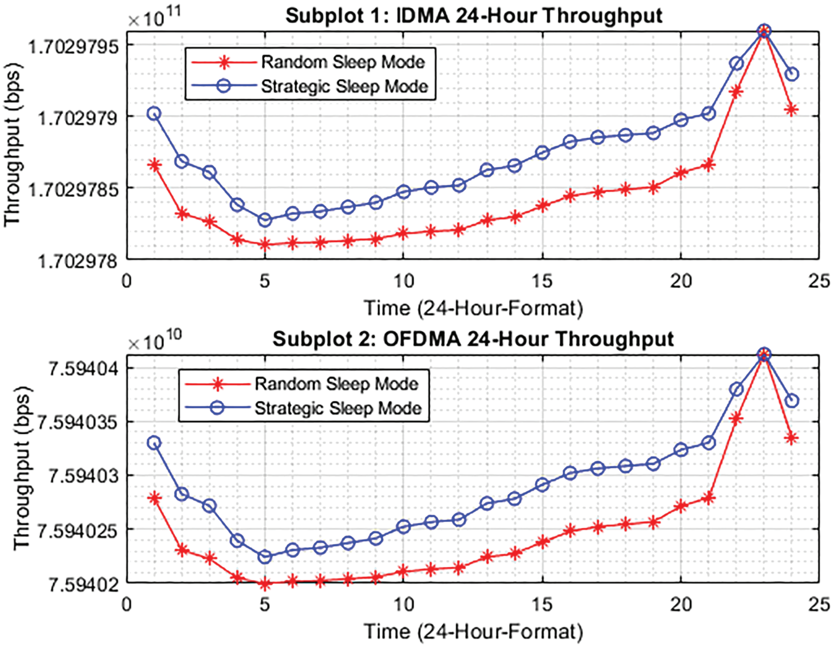

FIGURE 1 24-h throughput using sleeping techniques

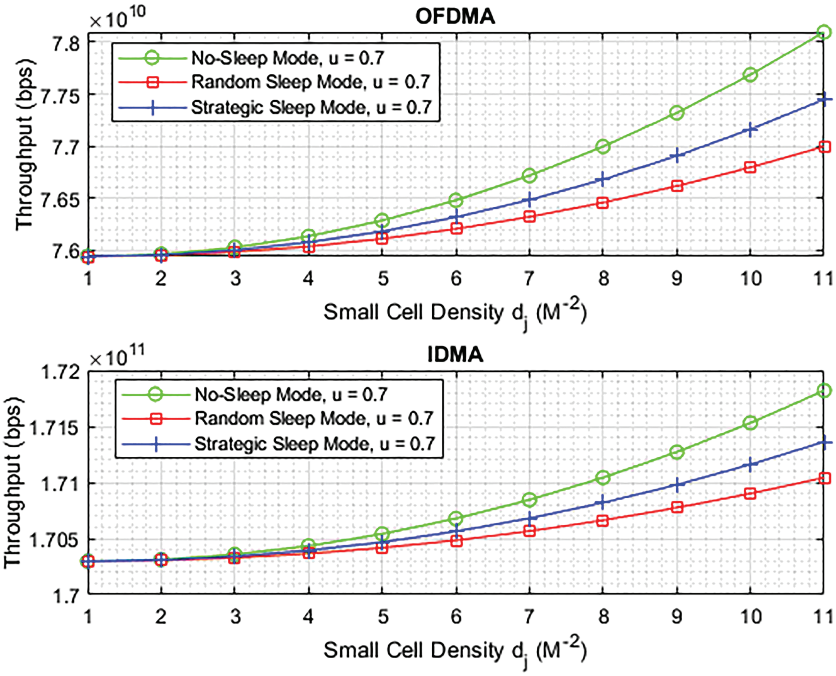

FIGURE 2 Throughput with varying small cell density

in random and strategic sleep modes across was caused by limited SBSs availability due to the sleep-mode policy in operation.

The throughput simulation with a varying fraction of SBS awake was done using Algorithm 1. The result is shown in Figure 3. The throughput shows an upward trend with every increase in the SBS fraction kept awake for both IDMA and OFDMA. The random sleep mode shows a "knee" in its plots across all multiple access techniques because it only responds to temporal variations in traffic levels and randomly puts SBSs to sleep in the HCN. When the fraction of SBSs kept awake is low, the random sleep-mode technique causes the HCN to experience a decline in coverage probability due to its inability to adapt to the spatial variation of traffic.

The IDMA was able to achieve a maximum throughput of 1.7×10^{11} *bps* when all SBS are kept awake, and the OFDMA had a lower throughput of 7.59×10^{10} *bps* when all SBSs in the HCN is kept awake.

The simulation of the throughput of the two-tier HCN with varying SINR thresholds was done using Algorithm 1. The result is shown in Figure 4. The throughput dropped with every increase in the SINR threshold across all multiple access techniques. The drop in throughput with increasing SINR threshold was caused by the higher transmit power of all SBSs trying to achieve the set SINR threshold leading to intra-tier interference in the HCN.

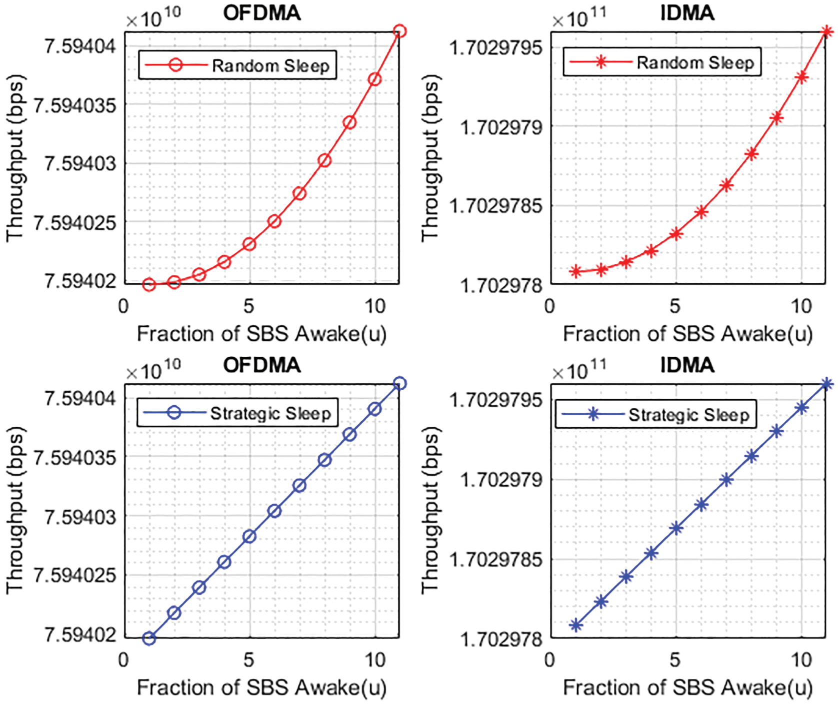

FIGURE 3 Throughput with varying fraction of SBS awake

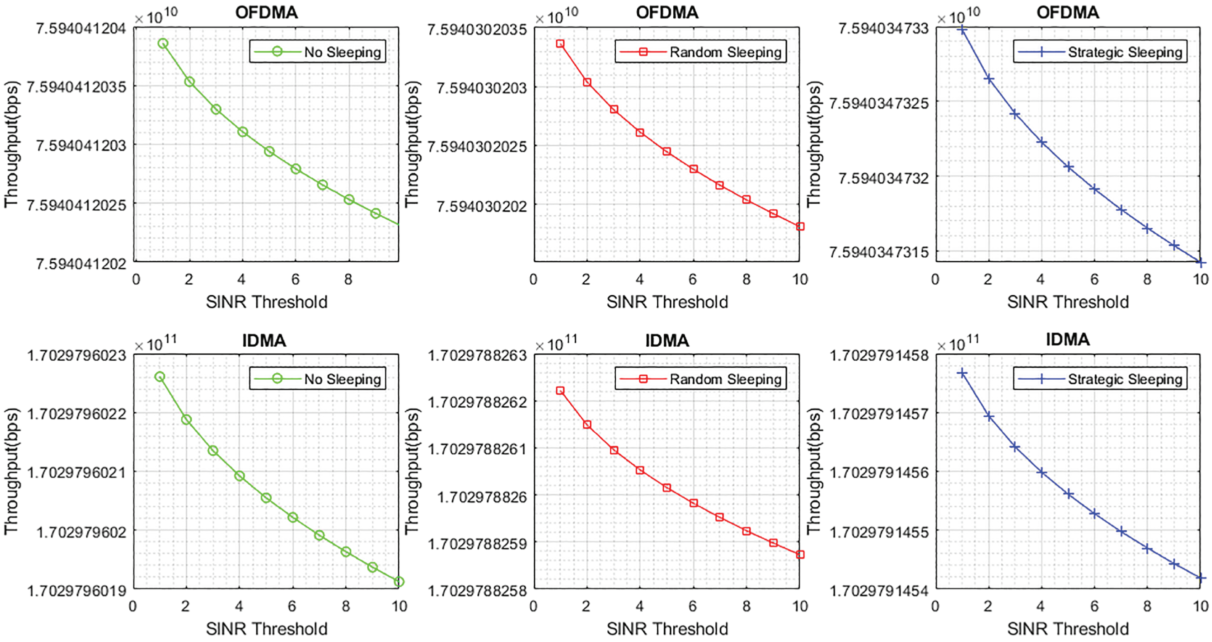

FIGURE 4 Throughput with varying SINR threshold

The simulation of the SE of the HCN was done using Algorithm 1. The result is shown in Figure 5. The no-sleep mode showed no variation in the hourly traffic load because all SBSs remain active throughout the day. In the no-sleep mode, the SE is highest throughout the day regardless of the hourly traffic levels. All UEs in the HCN experience excellent throughput at low traffic levels, although the entire available bandwidth is underutilized. The OFDMA's SE remains low at $2.531348 \times 10^5\, bps/hz$ in comparison to the SE attained by the IDMA $(5.67 \times 10^5\, bps/Hz)$. The IDMA achieves the highest efficiency in spectrum utilization, probably because of its interleavers used to separate users that share the same spectrum, thus achieving spectral efficiencies limited by the number of users per channel and the coding rate.

Over the 24 h, the SE attained using strategic sleep mode outperforms the SE achieved using random sleep mode. Compared with the case of the 24-h EE presented in Figure 9, where the difference in energy savings over the 24 h was only marginal, the SE for the strategic sleep-mode and random sleep mode in Figure 5 also shows a marginal difference.

The simulation of SE with a varying fraction of SBS awake was done using Algorithm 1. The result of the simulation is shown in Figure 6. The SE showed drastic improvements with every increase in the fraction of SBS kept awake (u) across all multiple access techniques. The curve for random sleep mode showed a slight bend close to the point at which the fraction of SBS kept awake is half. The curve appears because random sleep mode performs suboptimally in SE when fewer SBSs are awake.

The SE of the HCN thus shows the ineffectiveness of the random sleep mode at low traffic levels. The random sleep mode eventually picks up and improves the overall SE of the HCN across all multiple access techniques when the fraction of SBS awake (u) increases beyond the halfway mark. In the case of strategic sleep mode, the plot of SE against the fraction of SBS awake (u) is linear and shows a good distribution of SBSs when the fraction of SBSs awake is low. In strategic sleep mode, the SBSs are distributed according to temporal and spatial variations in traffic.

The simulation of SE with varying SBS density was done using Algorithm 1. The result is shown in Figure 7. In no-sleep mode, the SE achieved was more than that of the random and strategic sleep-modes because all SBSs are kept

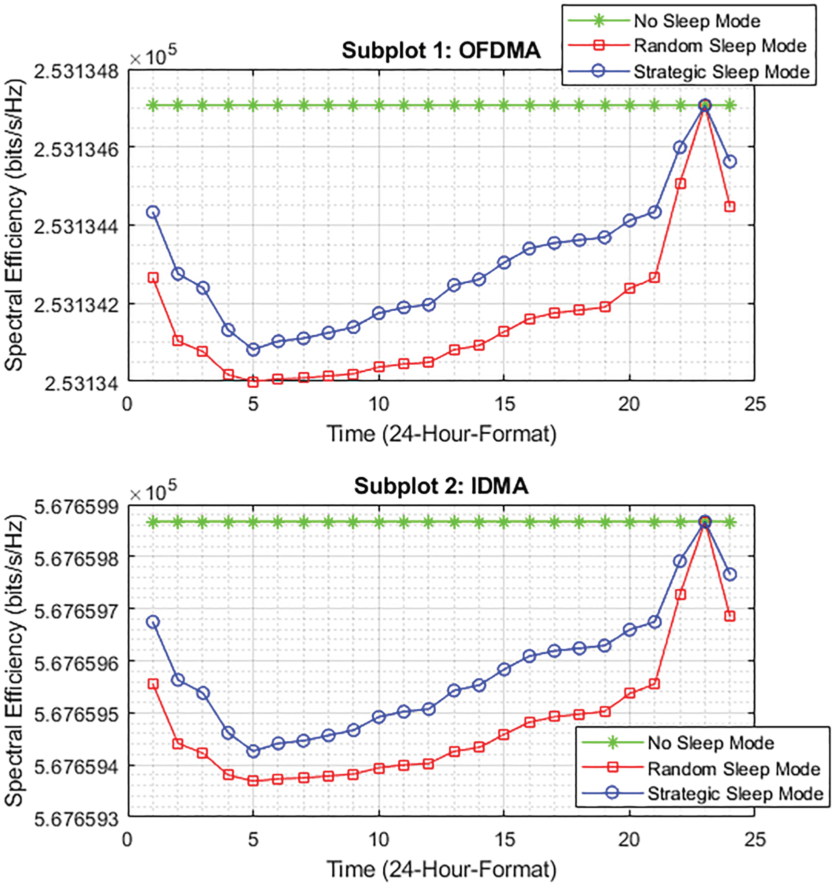

FIGURE 5 24-h spectral efficiency using sleeping techniques

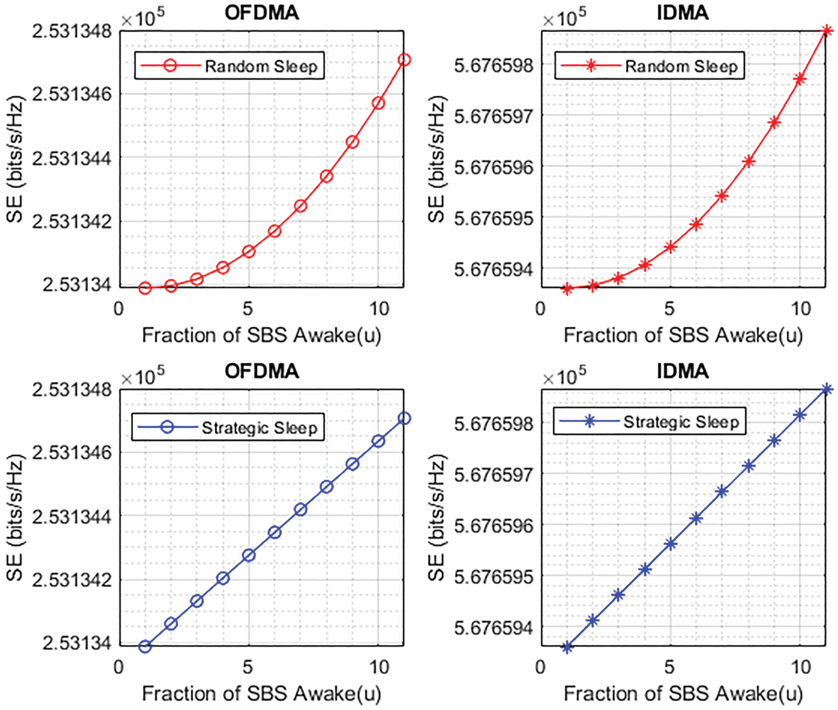

FIGURE 6 Spectral efficiency with varying fraction of SBS awake

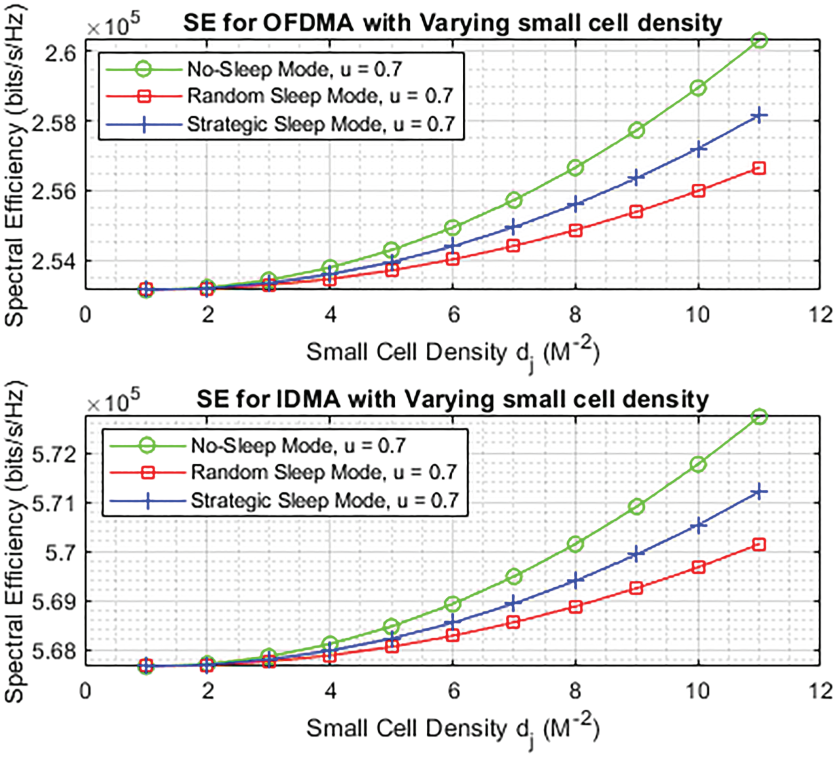

FIGURE 7 Spectral efficiency with varying SBS density

awake at all traffic levels. The no-sleep mode of operation represents the upper limit of the SE the HCN can achieve across all multiple access techniques. The random sleep mode is the least performing mode of operating the HCN and represents the lower limit of the SE the HCN can achieve across all multiple access techniques.

The OFDMA is the least performing multiple access technique, reaching a SE of about $2.7 \times 10^5\ bps/Hz$ at an SBS density of $0.01m^{-2}$ in comparison to a SE of $5.7 \times 10^5\ bps/Hz$ reached by the IDMA technique.

The simulation of SE with varying SINR thresholds was done using Algorithm 1. The result is shown in Figure 8. The SE shows a decline for every increase in the required SINR threshold across all multiple access techniques. The decrease in the SE with increasing SINR threshold values was caused by a deterioration in the coverage probability of the HCN. An increase in the SINR threshold means all SBSs in the HCN would have to transmit at a high power level to lower the noise floor of the HCN further.

The increase in transmit power inevitably leads to more intra-tier interference in the HCN and eventual deterioration of the SE of the HCN. The gains in SE across all multiple access techniques are only visible at more realistic SINR threshold levels where the interference within the HCN is kept at manageable levels. Regardless of the sleep mode utilized, the SE of the HCN deteriorated at high SINR threshold values.

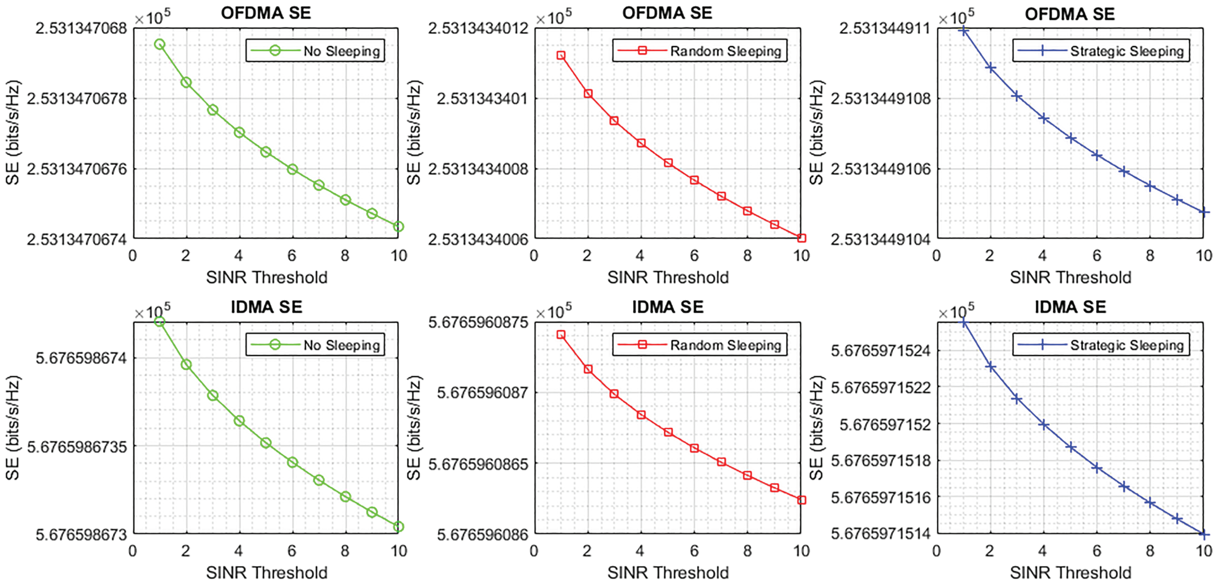

FIGURE 8 Spectral efficiency with varying SINR threshold

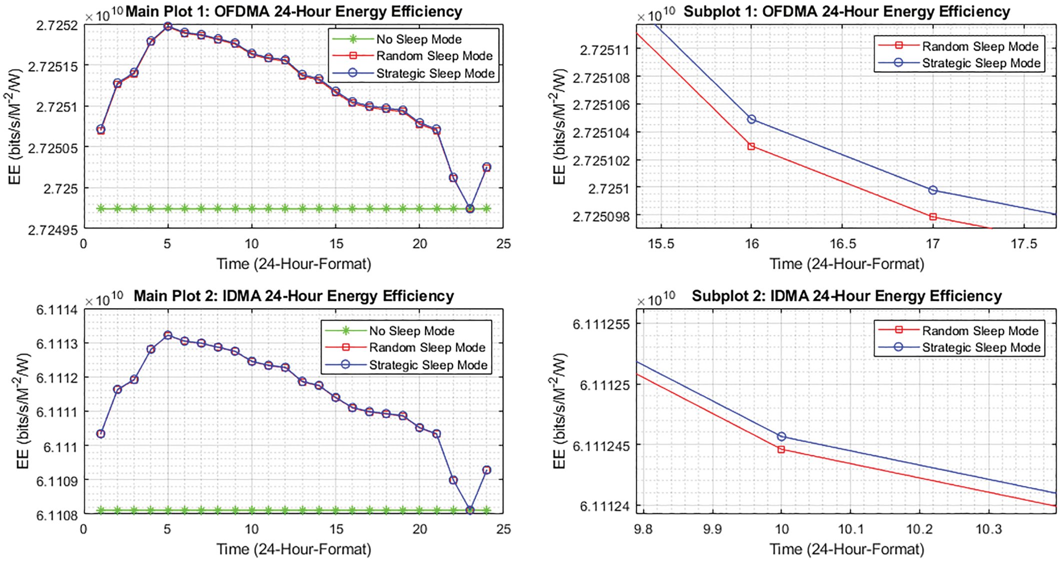

FIGURE 9 24-h energy efficiency using sleeping techniques

The 24-h EE of the two-tier HCN was simulated using Algorithm 1. The result is shown in Figure 9. Random and strategic sleep-mode strategies were employed and compared with the no-sleep scenario to determine the EE of the two-tier HCN. The no-sleep mode had the least performance in terms of EE as the gains from increased network throughput are not matched by any corresponding decrease in energy consumption. The poor performance of the no-sleep mode is due to the continuous operation of all SBSs in the HCN, even when the network traffic is low.

The poor performance of the no-sleep mode can also be seen across all the multiple access techniques employed in the HCN. However, the multiple access technique used determines the HCN's efficiency in terms of its energy utilization. The OFDMA was the least performing multiple access technique in terms of EE ($2.725 \times 10^{10}\ bits/s/m^2/W$) in no-sleep mode due to its orthogonal means of allocating the available radio resources to UEs. The IDMA had the best performance in terms of EE in no-sleep mode, reaching an EE value of $6.1108 \times 10^{10} bits/s/m^2/W$.

The subplots of Figure 9 show an interesting result about the performance of the random and strategic sleep modes. Across all multiple access techniques, the strategic sleep mode helps the HCN attain a marginally better (about 0.0004% for the OFDMA case) level of EE than the random sleep mode.

The EE simulation with a varying fraction of SBS awake was done using Algorithm 1. The result of the simulation is shown in Figure 10. Across all multiple access techniques, the EE has an inverse relationship with the fraction of SBS kept awake. Ideally, the network throughput increases slower than the amount of energy utilized to attain the desired throughput in the HCN. Thus, at high traffic levels, more energy is expended at the SBS to meet the throughput requirement of the HCN. In addition, there are more intra-tier and cross-tier interferences in the network when a higher fraction of SBSs are awake, thus leading to even greater energy consumption as the transmit power of all SBSs is increased to overcome interferences in the network. The reverse is when fewer SBSs are kept awake at low traffic levels. Ideally, the network throughput rises faster than the energy needed to sustain the required throughput.

The EE simulation of all multiple access modes with varying SBS density was done using Algorithm 1. The result of the simulation is shown in Figure 11. The no-sleep mode had the least performance in terms of EE as the density d_j of SBSs increases. The cross-tier and intra-tier interferences at high SBS densities are more pronounced when there is no sleeping technique to manage interference at high traffic levels and wastage of energy at low traffic levels. The no-sleep mode shows a faster decline in EE with increasing SBS density because all SBSs are kept awake at both low and high traffic periods. On the contrary, strategic sleep mode offers better performance than both no-sleep mode and random sleep mode at all traffic levels.

The QoS within the HCN is directly related to the signal-to-interference-plus-noise ratio. The QoS is improved in the presence of a high SINR ratio. The EE simulation with varying SINR thresholds was done using Algorithm 1. The result of the simulation is shown in Figure 12. The HCN utilizes more energy to sustain the required SINR threshold across multiple access techniques. The EE drops with every increase in the required SINR. Regardless of the sleeping

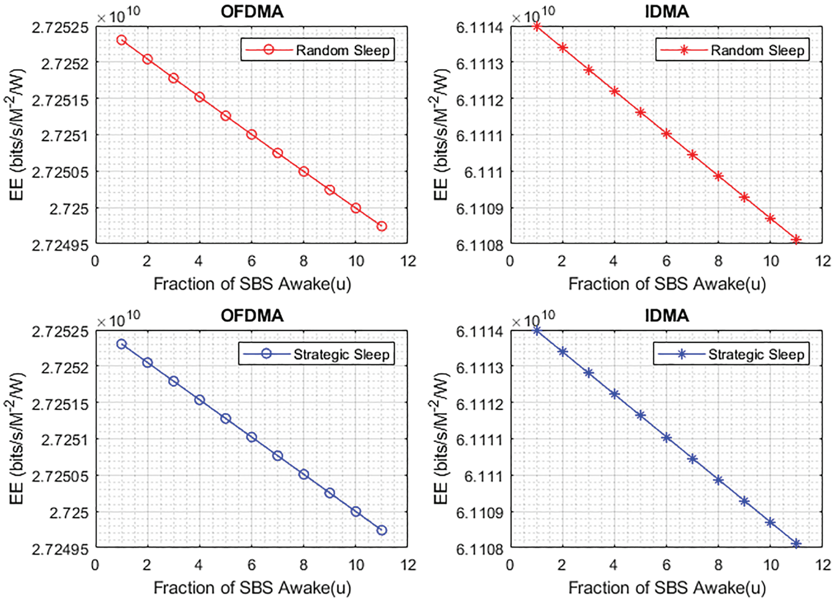

FIGURE 10 Energy efficiency with varying fraction of SBS awake

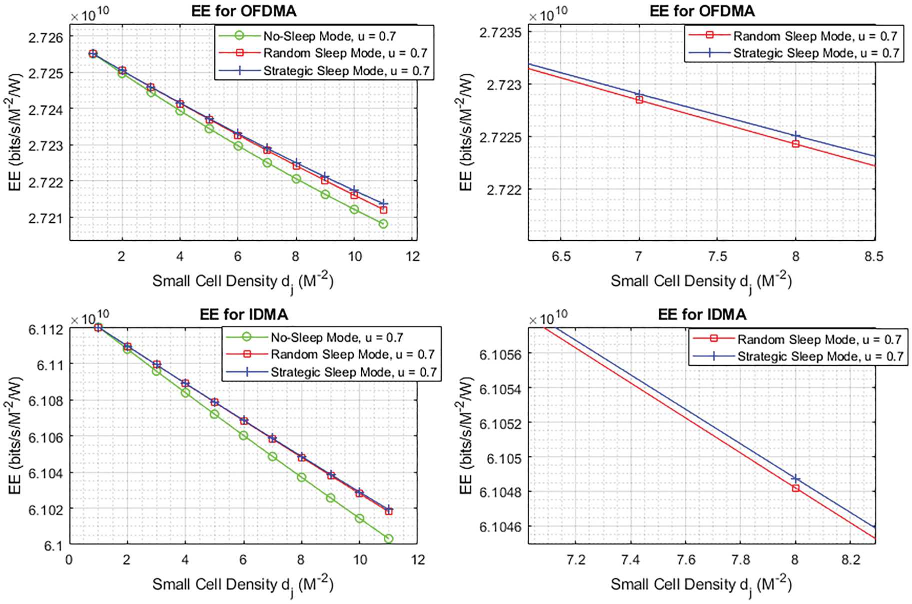

FIGURE 11 Energy efficiency with varying SBS density

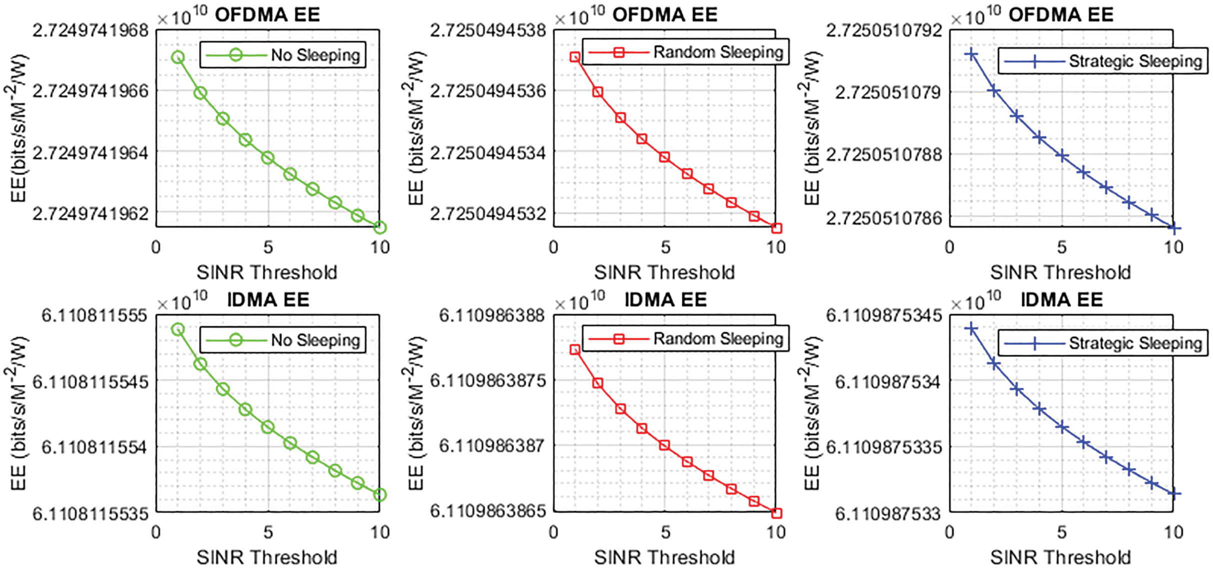

FIGURE 12 Energy efficiency with varying SINR threshold

technique used, the result obtained followed the same pattern. A high SINR threshold requirement means more SBSs in the HCN would have to be kept awake, thus lowering the EE of the network. At lower SINR levels and in either random or strategic sleep mode, the SBSs in the HCN utilize lower amounts of SBSs, and the EE of the network improves.

The simulation of the tradeoff between energy and SE under varying traffic conditions was done using Algorithm 1. The result is shown in Figure 13. Figure 13 confirms the tradeoff that exists between EE and SE. The best utilization of the available spectrum is matched by a corresponding decrease in the efficiency of energy utilization. Across all multiple access techniques, the marginal improvement in spectral and EE made possible by deploying SBSs within a cell is subject to the level of efficiency desired by network operators. Strategic sleep mode provides better EE and SE tradeoff performance at high traffic levels than random sleep mode across multiple access techniques. Strategic sleep mode offers better energy and SE at low traffic levels than random sleep mode across all multiple access techniques. The better performance of strategic sleep mode is due to its ability to adapt to temporal and spatial variations in traffic.

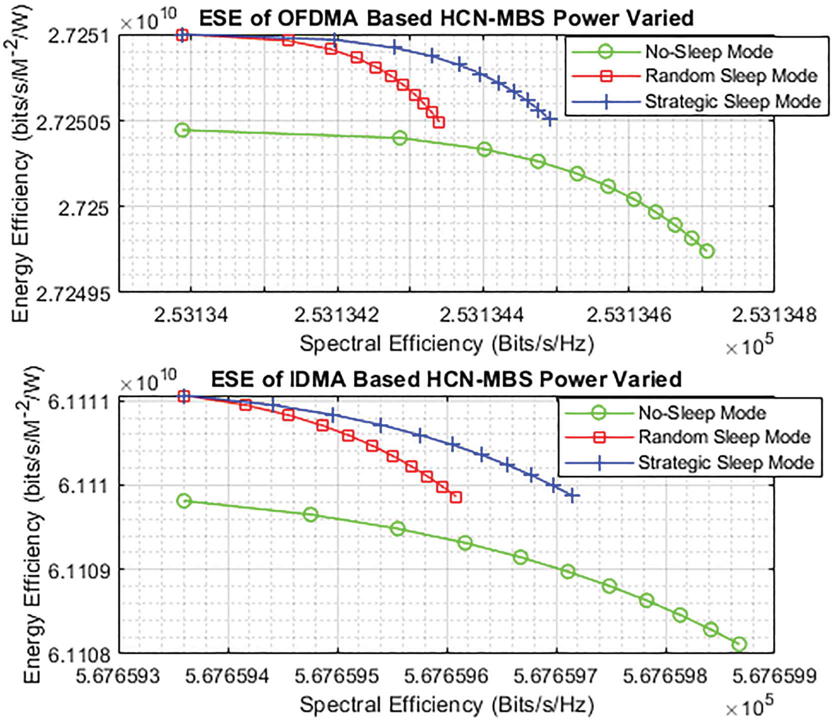

FIGURE 13 Energy spectral efficiency (ESE) with varying traffic levels

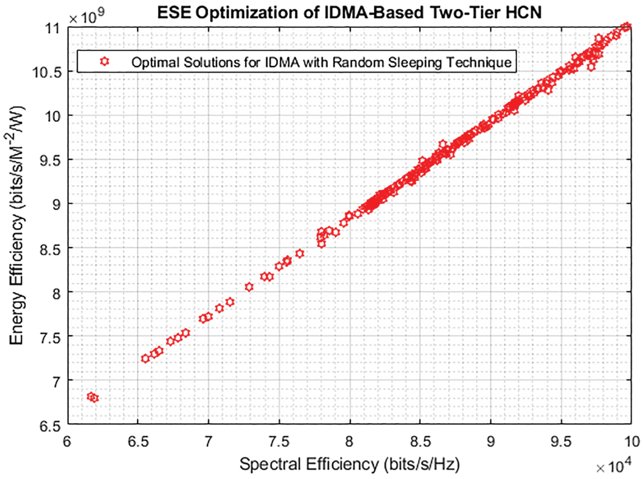

FIGURE 14 Random sleep mode ESE optimization of IDMA-based HCN at moderate traffic levels with all constraints varied

The highest efficiency in utilizing the available spectrum is reached for all multiple access techniques at high traffic levels. The highest efficiency in using the available energy is achieved for all multiple access techniques at low traffic levels. The IDMA is the better performing multiple access technique in ESE tradeoff.

The energy and SE of the IDMA-based HCN were simulated using Algorithm 1. The simulation results for both random and strategic sleep modes are shown in Figures 14 and 15. The traffic level was set to moderate, and all constraints were varied according to the data in Table 1. The Pareto-optimal front was non-convex and showed that EE and SE were maximized simultaneously. The Pareto-optimal front for Figures 14 and 15, which represents the ESE optimization for the random and strategic sleep modes for IDMA-based HCN, is lighter because, with more constraints, the optimization algorithm found fewer optimal solutions. The fewer solutions are also caused by the diversity gains of NOMA techniques and limited by the additional constraints that must be taken into account to produce optimal solutions. For example, the SINR threshold is a limitation that makes the optimization algorithm carefully consider power allocation.

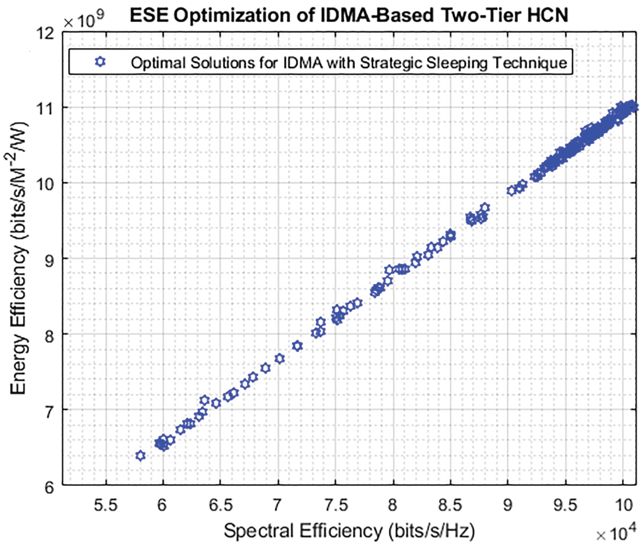

FIGURE 15 Strategic sleep mode ESE optimization of IDMA-based HCN at moderate traffic levels with all constraints varied

TABLE 3 ESE optimization for all access modes with all constraints varied

Constraints			
MBS transmit power $(\beta P_N) = 31$ Watts SBS transmit power $(\beta P_j) = 0.03$–0.1 Watts Traffic level = *low*: 0.1–0.15; *high*: 0.8–0.85; *moderate*: 0.4–0.5 SBS density $(d_j) = 0.01 - 0.09\ (m^{-2})$ MBS density $(d_N) = 10^{-2}(m^{-2})$ SINR threshold $(\rho) = 3 - 9$			
Multiple access mode and sleep policy		***Spectral efficiency*** $(\mathbf{bps/Hz})$	***Energy efficiency bits*** $/\mathbf{s}/\mathbf{m^2}/\mathbf{W}$
IDMA	Random sleep mode	10.99×10^9	9.95×10^4
	Strategic sleep mode	11.02×10^9	10.08×10^4

The algorithm would want to ensure that the interference caused by imperfect decoding at the receiver is not made worse by an ineffective power allocation scheme.

4.1 | The O-complexity and time complexity of the proposed optimization algorithm

The bulk of the computation involves the proposed weighted-sum modified particle swarm optimization algorithm, which has a computational complexity of $O(XD)$, where X is the population size and D is the dimensionality. The other part of the proposed algorithm involves the implementation of the IDMA at the user equipment and its decoding at the base station. The computational complexity of IDMA implementation is given as $O(n)$, where n represents the number of UEs accessing each radio resource per time. The value of $n = 2$ in this paper. Thus, the complexity of the entire algorithm is given as $O(XD + O(n))$ which leaves the complexity of the algorithm as $O(XD)$. The time complexity of the proposed algorithm was approximately 35 s after using the $tic - toc$ feature in MATLAB® (Table 3).

5 | LIMITATIONS OF THE PROPOSED ALGORITHM

The limitation of the proposed EE and SE optimization algorithm is its non-leverage of the direct impact of the technique used to implement the interleavers on the SE and EE of the IDMA-based HCN. The algorithm also considers the case of only two interleaved users, but the IDMA can accommodate more interleaved users per resource. The proposed optimization algorithm gives only suboptimal solutions. The proposed algorithm may not satisfactorily use the information provided by the objective function and its constraints due to its use of only the individual and swarm optimal positions/velocity.

5.1 | Threat to validity

This research study did not consider actual real-time base stations to arrive at the results obtained.

6 | CONCLUSION

This research study sought to examine the behavior of IDMA-based HCNs with the stochastic deployment of SBSs that are sleep-mode enabled. The throughput, SE and EE of the IDMA-based HCN were studied. It was discovered that the SINR, SBS density, and the sleep mode technique used had a substantial effect on the SE and EE performance of the HCN. The IDMA-based HCN showed a superior throughput, SE, and EE than the OFDMA. The SE of the IDMA-based HCN improves with an increase in the density of small base stations and the fraction of small base stations kept awake. The EE of the HCN improves with a reduction in the density of small base stations and the fraction of small base stations kept awake. Thus, the study confirmed the inverse relationship between the EE and SE in an IDMA-based HCN and the need to ensure that the conflicting objectives do not deteriorate the network's QoS. Therefore, the research study proposed using a weighted-sum modified particle swarm optimization algorithm that can simultaneously maximize the SE and EE of the IDMA-based HCN.

The following are some recommendations for further studies:

1. The traffic-aware optimization algorithm may be further refined for implementation on actual base stations.
2. Higher tier orders of HCNs may be considered where the deployed SBSs are not under the direct control of the network operator.

DATA AVAILABILITY STATEMENT

We have not used any data instead used parameters and mathematical derivations from various papers (all those references are duly cited) and perform simulations.

REFERENCES

1. Oyerinde OO. An overview of channel estimation schemes based on regularized adaptive algorithms for OFDM-IDMA systems. *Digit Signal Process*. 2018;75:168-183. doi:10.1016/j.dsp.2018.01.009
2. Rouijel A, Hadmi A, El Ghazi H, Mohammadi Z. Tensor-based approach for blind separation of interleave-NOMA 5G system. *Sci African*. 2021;14:e00956. doi:10.1016/j.sciaf.2021.e00956
3. Shukla A. Comparative analysis of various code domain NOMA schemes for future communication networks. *Mater Today Proc*. 2021;46:5797-5800. doi:10.1016/j.matpr.2021.02.718
4. Patel A, Shukla A. On the performance of modulo based Deci power interleaver in code domain NOMA system. *Mater Today Proc*. 2021;46:5785-5790. doi:10.1016/j.matpr.2021.02.716
5. El Dyasti SK, Hagras EAA, El-Hennawy H. QSM-IDM—a novel quadrature spatial modulation based on interleaving division multiplexing for multiple antenna system. *Digit Commun Networks*. 2019;5(3):183-188. doi:10.1016/j.dcan.2018.02.002
6. Zhao G, Chen S, Zhao L, Hanzo L. Energy-spectral-efficiency analysis and optimization of heterogeneous cellular networks: a large-scale user-behavior perspective. *IEEE Trans Veh Technol*. 2018;67(5):4098-4112. doi:10.1109/TVT.2018.2789498
7. Alostad JM. Design of power and resource management in OFDMA networks using sleep mode selection technique. *Comput Netw*. 2020;180:107411. doi:10.1016/j.comnet.2020.107411
8. Goudos SK. Joint power allocation and user association in nonorthogonal multiple access networks: An evolutionary approach. *Phys Commun*. 2019;37:100841. doi:10.1016/j.phycom.2019.100841
9. Zhou T, Zhao J, Qin D, Li X, Li C, Yang L. Green base station assignment for NOMA-enabled HCNs. *IEEE Access*. 2019;7:53018-53031. doi:10.1109/ACCESS.2019.2912633
10. Han S, Chih-Lin I, Xu Z, Sun Q. Energy efficiency and spectrum efficiency co-design: From NOMA to network NOMA. *IEEE COMSOC MMTC E-Letter*. 2014;9(5):21-24.

11. Xiong C, Li GY, Zhang S, Chen Y, Xu S. Energy-and spectral-efficiency tradeoff in downlink OFDMA networks. *IEEE Trans Wirel Commun*. 2011;10(11):3874-3886. doi:10.1109/TWC.2011.091411.110249
12. Hadi M, Ghazizadeh R. Sub-channel assignment and power allocation in OFDMA-NOMA based heterogeneous cellular networks. *AEU-International J Electron Commun*. 2020;120:153195. doi:10.1016/j.aeue.2020.153195
13. Fadoul MM. Rate and coverage analysis in multi-tier heterogeneous network using stochastic geometry approach. *Ad Hoc Netw*. 2020; 98:102038. doi:10.1016/j.adhoc.2019.102038
14. Wang H, Leung S-H, Song R. Uplink area spectral efficiency analysis for multichannel heterogeneous cellular networks with interference coordination. *IEEE Access*. 2018;6:14485-14497. doi:10.1109/ACCESS.2018.2811387
15. Lu F, Hu J, Yang LT, et al. Energy-efficient traffic offloading for mobile users in two-tier heterogeneous wireless networks. *Futur Gener Comput Syst*. 2020;105:855-863. doi:10.1016/j.future.2017.08.008
16. Han Q, Yang B, Song N, Li Y, Wei P. Green resource allocation and energy management in heterogeneous small cell networks powered by hybrid energy. *Comput Commun*. 2020;160:204-214. doi:10.1016/j.comcom.2020.06.002
17. Ghariani T, Jouaber B. Green topological potential-based optimization for power and spectral efficiency tradeoff in LTE HetNets. *2017 27th International Telecommunication Networks and Applications Conference (ITNAC)*. 2017:1-6.
18. Qian LP, Wu Y, Zhou H, Shen X. Joint uplink base station association and power control for small-cell networks with nonorthogonal multiple access. *IEEE Trans Wirel Commun*. 2017;16(9):5567-5582. doi:10.1109/TWC.2017.2664832
19. Alavi F, Cumanan K, Ding Z, Burr AG. Beamforming techniques for nonorthogonal multiple access in 5G cellular networks. *IEEE Trans Veh Technol*. 2018;67(10):9474-9487. doi:10.1109/TVT.2018.2856375
20. Elbamby MS, Bennis M, Saad W, Debbah M, Latva-Aho M. Resource optimization and power allocation in in-band full duplex-enabled nonorthogonal multiple access networks. *IEEE J Sel Areas Commun*. 2017;35(12):2860-2873. doi:10.1109/JSAC.2017.2726218
21. Uddin MF. Energy efficiency maximization by joint transmission scheduling and resource allocation in downlink NOMA cellular networks. *Comput Netw*. 2019;159:37-50. doi:10.1016/j.comnet.2019.05.002
22. Luo Y, Shi Z, Li Y, Li Y. Analysis of area spectral efficiency and energy efficiency in heterogeneous ultra-dense networks. *2017 IEEE 17th International Conference on Communication Technology (ICCT)*. 2017:446-451.
23. Alsharif MH, Kelechi AH, Kim J, Kim JH. Energy efficiency and coverage tradeoff in 5G for eco-friendly and sustainable cellular networks. *Symmetry (Basel)*. 2019;11(3):408. doi:10.3390/sym11030408
24. Nie X, Wang Y, Ding L, Zhang J. Joint optimization of FeICIC and spectrum allocation for spectral and energy efficient heterogeneous networks. *IEICE Trans Commun*. 2017;E101.B(6):1462-1475. doi:10.1587/transcom.2017EBP3175
25. Nguyen V-D, Tuan HD, Duong TQ, Poor HV, Shin O-S. Convex quadratic programming for maximizing sum throughput in MIMO-NOMA multicell networks. *GLOBECOM 2017-2017 IEEE Global Communications Conference*. 2017:1-6.
26. Saimler M, Ergen SC. Uplink/downlink decoupled energy efficient user association in heterogeneous cloud radio access networks. *Ad Hoc Netw*. 2020;97:102016. doi:10.1016/j.adhoc.2019.102016
27. Zhang H, Fang F, Cheng J, Long K, Wang W, Leung VCM. Energy-efficient resource allocation in NOMA heterogeneous networks. *IEEE Wirel Commun*. 2018;25(2):48-53. doi:10.1109/MWC.2018.1700074
28. Jiang Y, Zou Y, Guo H, et al. Joint power and bandwidth allocation for energy-efficient heterogeneous cellular networks. *IEEE Trans Commun*. 2019;67(9):6168-6178. doi:10.1109/TCOMM.2019.2921022
29. Shoukat M, Khan BS, Jangsher S, Habib A, Bhatti FA. Iterative resource efficient power allocation in small cell network. *Phys Commun*. 2018;30:68-75. doi:10.1016/j.phycom.2018.07.014

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