International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 10 Issue 4, Jul-Aug 2026 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

Comprehensive Energy Consumption Modeling for 5G and Beyond Radio Access Networks Under Dynamic Traffic Conditions

Vinod Kumar Sharma, Dr. Mohd. Ilyas

Department of Electrical & Electronics Engineering, Al-Falah University, Dhouj, Haryana, India

ABSTRACT

The rapid growth of mobile traffic and heterogeneous services in 5G and beyond Radio Access Networks (RANs) has created significant challenges in reducing network energy consumption while maintaining adequate service performance. This paper proposes a comprehensive traffic- and user-density-aware energy consumption model for 5G and beyond RANs under dynamic traffic conditions. The proposed framework is implemented in MATLAB and considers a 24-hour operating period with 15-minute time intervals. Dynamic traffic is first generated and used to estimate active-user density and Physical Resource Block (PRB) utilization. Based on the instantaneous traffic and resource utilization, base stations (BSs) are dynamically assigned to sleep, low-load, medium-load, or high-load states, enabling unnecessary BSs to be deactivated during low-demand periods. The model incorporates static, dynamic, sleep-state, and auxiliary power components to estimate hourly and daily RAN energy consumption. In addition, throughput, energy efficiency, energy consumption per bit, and energy-saving potential are evaluated to establish the relationship between traffic demand, resource utilization, BS activity, and power consumption. Simulation results show that the proposed dynamic BS operation consumes 64.84 kWh/day, compared with 91.72 kWh/day for continuous BS operation, achieving an energy reduction of approximately 26.88 kWh/day or 29.28%. The network achieves 3,547,502.97 bit/J energy efficiency with an energy consumption of 2.8189×10^{-7} J/bit. The results demonstrate that traffic-aware dynamic BS activation provides an effective and practical approach for improving energy efficiency in 5G and beyond RANs.

How to cite this paper: Vinod Kumar Sharma | Dr. Mohd. Ilyas "Comprehensive Energy Consumption Modeling for 5G and Beyond Radio Access Networks Under Dynamic Traffic Conditions" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-10 | Issue-4, August 2026, pp.1202-1215, URL: www.ijtsrd.com/papers/ijtsrd142150.pdf

IJTSRD142150

KEYWORDS: *5G RAN; Beyond-5G Networks; Energy Consumption; Energy Efficiency; Dynamic Traffic; User Density; PRB Utilization; Base-Station Sleep; Dynamic BS Activation.*

I. INTRODUCTION

The rapid growth of mobile data traffic, connected devices, and high-capacity wireless services has made energy efficiency an important design objective for 5G and beyond radio access networks (RANs). Although 5G provides higher capacity, lower latency, and improved connectivity, these capabilities increase the complexity and energy requirements of the RAN. The RAN represents a major contributor to overall mobile-network energy consumption, making energy-aware network operation an important requirement for sustainable future networks [1]. The energy consumption of a RAN is strongly influenced by the operating conditions of its base stations (BSs). In conventional operation, BSs may remain active even during periods of low traffic, resulting in unnecessary energy consumption. Recent studies have therefore focused on energy-saving mechanisms that dynamically adapt network operation according to traffic conditions. Kundu *et al.* discussed recent 3GPP and O-RAN developments for improving RAN energy efficiency and highlighted network-level approaches for reducing unnecessary energy consumption [2]. Accurate modelling of BS power consumption is also essential for evaluating energy-saving strategies. Piovesan *et al.* developed analytical and machine-learning-based models for characterizing the power consumption of 5G BSs and demonstrated that BS power varies according to operating conditions and can be modelled to evaluate energy-saving mechanisms [3]. Their subsequent work further investigated power-consumption modelling for multi-carrier 5G active antenna units, demonstrating the importance of considering the characteristics of modern 5G BS architectures when estimating energy consumption [4]. In addition to BS power characteristics, traffic load, user density, and radio-resource utilization are important factors affecting RAN energy consumption. As traffic increases, more physical resource blocks (PRBs) are required to serve users, which increases the dynamic power component of BS operation. Similarly, high user density can require additional BSs to remain active to maintain network capacity. Therefore, an energy model that jointly considers traffic variation, user density, PRB utilization, and BS activity can provide a more representative description of real network operating conditions. The energy-efficiency challenge becomes even more significant for beyond-5G and 6G networks because future systems are expected to support highly heterogeneous services, dense deployments, and increasingly intelligent network functions. Recent research on green 6G RANs emphasizes multi-domain energy-saving mechanisms and the need for intelligent adaptation of network resources to changing traffic conditions [5]. However, many existing studies focus on specific energy-saving techniques or detailed BS power models. There is still a need for a simple, integrated, and practical energy-consumption framework that links traffic demand with user density, PRB utilization, BS operating states, power consumption, throughput, and energy efficiency. Motivated by this requirement, this paper proposes a Comprehensive Energy Consumption Model for 5G and Beyond RANs Under Dynamic Traffic Conditions. The proposed model generates a 24-h dynamic traffic profile and uses it to estimate active users and PRB utilization. Based on the instantaneous traffic level, BSs are assigned to sleep, low-load, medium-load, or high-load states, and the corresponding static, dynamic, sleep, and auxiliary power components are calculated. The model subsequently evaluates total energy consumption, throughput, energy efficiency, energy consumption per bit, and energy-saving potential.

II. LITERATURE REVIEW

Recent research has increasingly focused on energy-efficient operation of 5G and beyond RANs because the increasing number of connected users and growing traffic demand can significantly increase network power consumption. Larsen *et al.* [6] presented a comprehensive survey of green 5G and beyond RANs and examined architectural and operational approaches for reducing energy consumption. Their study reported that appropriate energy-saving technologies and architectures can substantially reduce overall mobile-network energy consumption, highlighting the importance of RAN-level energy management. Piovesan *et al.* [7] investigated analytical and machine-learning-based approaches for modelling the power consumption of 5G base stations. Their work demonstrated that BS power consumption depends on operational characteristics and that accurate power models are important for evaluating energy-saving mechanisms. This provides a basis for developing traffic-dependent models in which BS power changes according to network load. In another study, Piovesan *et al.* [8] developed a machine-learning-based power-consumption model for multi-carrier 5G base stations. The study considered the complexity of active antenna units and different operating conditions and demonstrated that power consumption varies with BS configuration and resource utilization. Chen *et al.* [9] proposed a 5G energy-consumption modelling approach using real-world BS data. Their method incorporated the individual characteristics of base stations through a BS identifier and achieved substantially improved prediction accuracy compared with existing approaches. The study highlights the importance of considering BS-specific characteristics when developing accurate energy-consumption models.) Kundu *et al.* [10] investigated energy-efficient RAN operation from the perspective of industry standards and practical implementation. Their work discussed energy-saving mechanisms associated with modern RAN architectures and emphasized the importance of integrating energy efficiency into operational network management. A recent review presented in *IEEE Access* [11] classified 5G RAN energy-efficiency techniques into hardware improvements, MIMO and antenna technologies, network architecture, sleep modes, optimization methods, and renewable-energy-based approaches. The study also emphasized the importance of practical power measurements and identified several open research challenges in implementing energy-efficient RANs. More recently, de Araujo *et al.* [12] proposed a flexible energy model for 5G RANs that considers the computational energy associated with the physical layer and baseband processing. Their work demonstrated the need for more granular energy models capable of representing different applications and implementation conditions.

III. PROPOSED METHODOLOGY

The proposed methodology develops a dynamic traffic- and user-density-based energy consumption model for 5G and beyond RANs. The model is implemented in MATLAB and evaluates the relationship between network traffic, user density, PRB utilization, base-station activity, power consumption, throughput, and energy efficiency over a 24-hour operating period. The overall methodology consists of traffic generation, user-density estimation, PRB utilization calculation, BS-state determination, dynamic BS activation, power calculation, energy and throughput estimation, and energy-saving evaluation.

A. Network and Simulation Configuration

The simulation considers a RAN consisting of 10 base stations operating over a 100-MHz bandwidth with 273 available PRBs. The maximum supported user density is assumed to be 100 users per cell. The simulation duration is 24 h with a time interval of **15 min**, resulting in 96 simulation points. The BS power model includes static power, maximum dynamic power, sleep-state power, and auxiliary power. The parameters used in the proposed model are summarized in Table I.

B. Dynamic Traffic Generation

A time-varying traffic profile is generated to represent realistic daily network demand. The 24-h period is divided into low-traffic, morning, daytime, evening-peak, and night periods. A normalized traffic value T(t), ranging from 0 to 1, is generated for every 15-min interval. Random variation is introduced within each traffic period to avoid an unrealistically constant traffic pattern.

$0 \leq T(t) \leq 1$

The traffic profile represents the primary input to the proposed energy model because changes in traffic directly affect user density, PRB utilization, BS activity, and power consumption.

C. User Density Estimation

The total number of active users is estimated from the traffic level as

$$U(t) = U_{max} N_{BS} T(t)$$

where Umax is the maximum number of users per cell and NBS is the total number of base stations. The average number of users per active cell is then calculated as

$$U_{BS}(t) = \frac{U(t)}{N_{BS}}$$

Thus, higher traffic conditions produce higher user density and consequently increase the radio-resource requirements of the network.

D. PRB Utilization Model

PRB utilization is estimated using both traffic load and user density. The proposed relationship is

$$\rho PRB(t) = T(t)\left[0.6 + 0.4\,\frac{U_{BS}(t)}{U_{max}}\right]$$

The resulting utilization is restricted to the range .0 $\leq \rho PRB \leq 1$ The number of utilized PRBs is obtained from

$$PRB_{used}(t) = PRB_{used}\,\rho PRB(t)$$

This step links network demand and user density with actual radio-resource utilization.

E. Dynamic Base-Station State Selection

Based on the instantaneous traffic level, each simulation interval is assigned to one of four BS operating states:

- State 0: Sleep, T(t)<0.20
- State 1: Low load, 0.20≤T(t)<0.45
- State 2: Medium load, 0.45≤T(t)<0.75
- State 3: High load, T(t)≥0.75

The number of active BSs is dynamically adjusted according to the selected state. Approximately 30%, 60%, 80%, and 100% of the available BSs are activated for States 0–3, respectively. This mechanism allows unnecessary BSs to enter a low-power state during periods of low network demand.

F. Base-Station Power Consumption

For the sleep state, the dynamic power is calculated using

$$P_{dynamic}(t) = N_{active}(t)\, P_{sleep}$$

For active states, the power of an individual BS is calculated as

$$P_{BS}(t) = P_{static}(t) + (P_{max} - P_{static})\,\rho PRB(t)$$

The total dynamic BS power is then

$$P_{dynamic}(t) = N_{active}(t)\, N_{BS}(t)$$

Auxiliary power is included as

$P_{aux}(t) = N_{active}(t)\, P_{aux}$ and the total RAN power becomes

$$P_{total}(t) = N_{dynamic}(t) + P_{aux}(t)$$

This formulation captures both the fixed and load-dependent components of RAN power consumption.

G. Energy Consumption and Throughput

The energy consumed during each 15-min interval is calculated as

$$E(t) = P_{total}(t)\Delta t$$

where Δt=0.25 h. Total daily energy consumption is obtained by

$$E_{day} = \sum_{1}^{N} E(t)$$

The instantaneous throughput is estimated from the maximum network capacity as

R(t)=R_{max}T(t),

where Rmax=20 Gbps. The total transmitted data is subsequently calculated over the complete simulation period.

H. Energy-Efficiency Evaluation

Energy efficiency is evaluated using the total transmitted data and total energy consumption:

$$EE = \frac{E_{total}}{D_{total}}$$

where D_{total} is the total transmitted data in bits and E_{total} is the total consumed energy in joules. Energy consumption per transmitted bit is also calculated as

$$E_{bit} - \frac{D_{total}}{E_{total}}$$

These metrics provide a direct assessment of how efficiently the proposed RAN configuration utilizes electrical energy for data delivery.

I. Energy-Saving Evaluation

To quantify the benefit of dynamic BS operation, a reference case is considered in which all 10 BSs remain continuously active. The reference energy consumption is calculated using the same traffic-dependent power model but without BS deactivation. The energy-saving percentage is then obtained as

$$ES(\%) - \frac{E_{reference} - E_{proposed}}{E_{raference}} * 100$$

This comparison directly determines the energy benefit achieved through traffic-aware dynamic BS operation. Finally, the proposed model evaluates total energy consumption, average power, maximum power, minimum power, total transmitted data, energy efficiency, energy per bit, and energy-saving percentage. MATLAB is also used to generate power-versus-time, traffic-versus-time, user-density-versus-time, PRB-utilization-versus-time, and active-BS-versus-time plots. Scatter plots between traffic/users and power are used to investigate the underlying relationships. The complete methodology therefore provides a quantitative framework for assessing how dynamic traffic and user density influence 5G RAN energy consumption and the potential for energy savings.

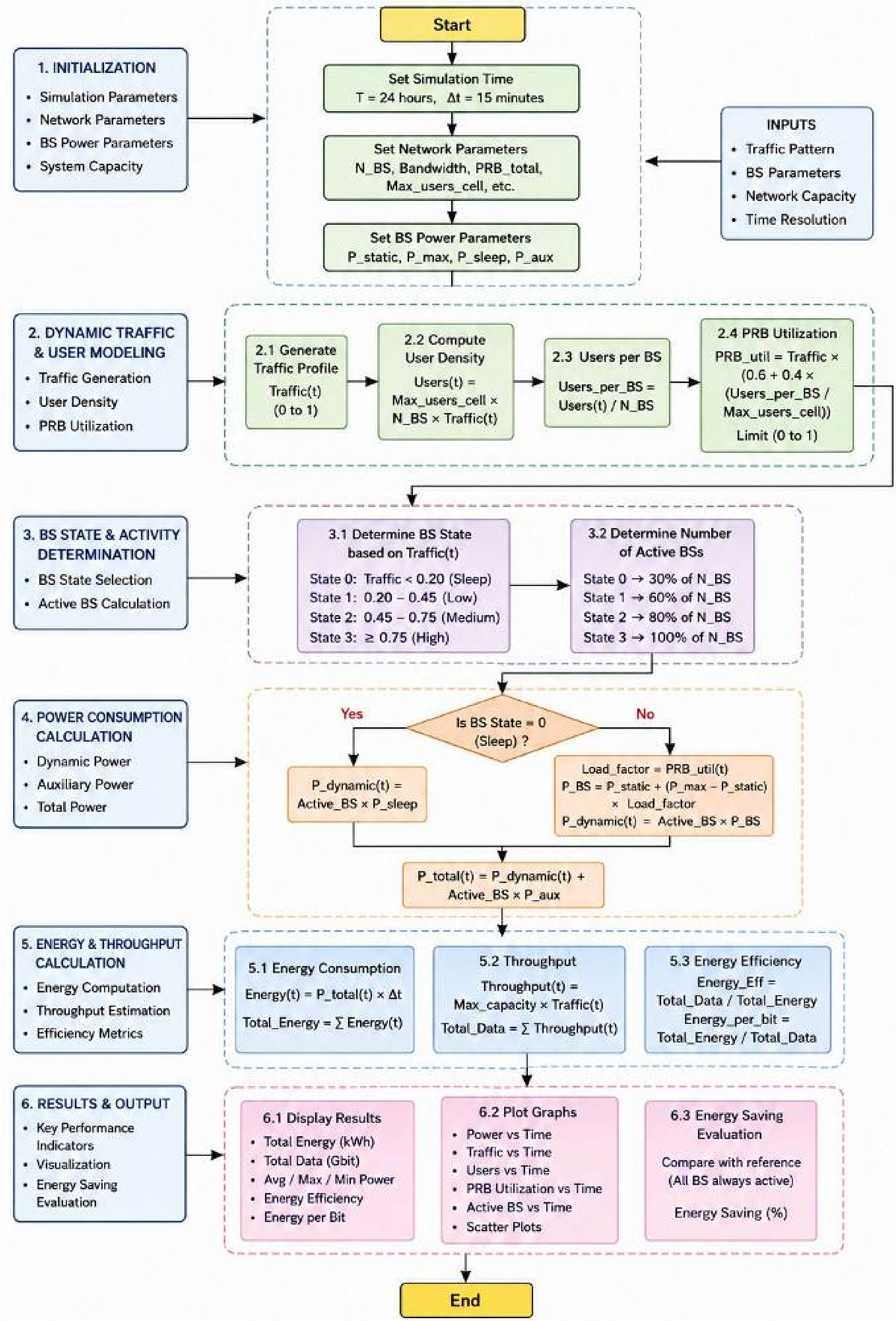

Figure 1. Working Flow Chart of the Proposed 5G RAN Energy Consumption Model

Figure 1 illustrates the complete workflow of the proposed 5G RAN energy consumption model. The process begins with the initialization of simulation, network, and base-station power parameters. A dynamic traffic profile is then generated for the 24-hour simulation period. Based on the traffic level, the number of active users, users per base station, and PRB utilization are calculated. The traffic and resource utilization are subsequently used to determine the BS operating state and the corresponding number of active base stations. Depending on whether the BS is in sleep or active mode, dynamic and auxiliary power consumption are calculated. Finally, total energy consumption, throughput, energy efficiency, energy per bit, and energy-saving performance are evaluated. The model also generates power, traffic, user-density, PRB-utilization, and BS-activity plots for detailed analysis.

Table 1. Simulation Parameters of the 5G RAN Energy Model

Parameter	Value
Simulation Duration	24 hours
Time Resolution	15 minutes
Number of Base Stations	10
Static Power per BS	150 W
Maximum Dynamic Power per BS	600 W
Sleep-State Power per BS	50 W
Auxiliary Power per Active BS	50 W
Network Bandwidth	100 MHz
Total Available PRBs	273
Maximum Users per Cell	100
Maximum Network Users	1,000
Maximum Network Capacity	20 Gbps

Table 1 presents the simulation parameters used to develop the proposed 5G RAN energy consumption model. The simulation considers a 24-hour operating period with a 15-minute time resolution and 10 base stations. Each base station is characterized by static power of 150 W, maximum dynamic power of 600 W, sleep-state power of 50 W, and auxiliary power of 50 W. The network operates over a 100 MHz bandwidth with 273 available PRBs and supports a maximum of 100 users per cell. These parameters establish the basic network configuration for evaluating the relationship between traffic demand and energy consumption.

Table 2. Dynamic Traffic Profile

Time Period	Traffic Condition	Traffic Load Used in Model	Network Condition
00:00–06:00	Low traffic	0.15–0.20	Very low demand
06:00–10:00	Morning increase	0.30–0.40	Increasing demand
10:00–17:00	Daytime	0.55–0.65	High demand
17:00–22:00	Evening peak	0.80–0.90	Peak demand
22:00–00:00	Night	0.25–0.30	Reduced demand

Table 2 describes the dynamic traffic profile used throughout the 24-hour simulation. The traffic load is divided into five periods representing realistic variations in network demand. Very low traffic occurs between 00:00 and 06:00, followed by increasing demand during the morning period. Daytime traffic increases further, while the highest traffic occurs between 17:00 and 22:00. Traffic subsequently decreases during the night. This dynamic traffic pattern provides the basis for evaluating how changes in network demand influence user density, PRB utilization, base-station activity, and overall power consumption.

Table 3. Base-Station Operating States

BS State	Traffic Load	Operating Mode	Active BSs
State 0	< 0.20	Sleep	3
State 1	0.20–0.45	Low Load	6
State 2	0.45–0.75	Medium Load	8
State 3	≥ 0.75	High Load	10

Table 3 presents the four base-station operating states used in the proposed model. When traffic is below 20%, the network enters the sleep state and only three of the ten base stations remain active. For traffic between 20% and 45%, six base stations operate under the low-load state. Eight base stations are activated for medium traffic between 45% and 75%, while all ten base stations are activated when traffic exceeds 75%. This state-based mechanism enables the network to dynamically match the number of active base stations with the instantaneous traffic requirement.

Table 4. User Density Model

Traffic Condition	Approx. Users/Network	Users/BS	User Density
Low	150–200	15–20	Low
Morning	300–400	30–40	Moderate
Daytime	550–650	55–65	High
Evening peak	800–900	80–90	Very High
Night	250–300	25–30	Moderate–Low

Table 4 represents the user-density model corresponding to different traffic conditions. During low-traffic periods, approximately 150–200 users are active across the network, whereas morning traffic produces approximately 300–400 users. During daytime operation, the number of users increases to approximately 550–650, reaching approximately 800–900 users during the evening peak. The corresponding users per base station also increase with traffic demand. This demonstrates how user density is incorporated into the proposed energy model as an important factor affecting network resource requirements.

Table 5. PRB Utilization and Radio Resource Allocation

Traffic Condition	User Density	PRB Utilization	PRBs Used	Resource Condition
Low	Low	Low	Low	Under-utilized
Morning	Moderate	Moderate	Moderate	Increasing
Daytime	High	High	High	Highly utilized
Evening peak	Very high	Very high	Very high	Peak utilization
Night	Moderate–Low	Low–Moderate	Low–Moderate	Reduced utilization

Table 5 presents the relationship between traffic conditions, user density, and PRB utilization. Low traffic and low user density result in relatively low utilization of the available 273 PRBs. As the number of users and traffic demand increase, PRB utilization also increases. The highest resource utilization occurs during the evening peak period when user density and traffic demand are highest. Since PRB utilization directly influences the dynamic component of base-station power, this relationship provides an important link between radio-resource demand and energy consumption.

Table 6. Relationship Between Traffic, Users and PRB Utilization

Variable	Model Relationship	Effect on Energy
Traffic Load	Directly affects PRB utilization	Increases power
User Density	Determines network demand	Increases power
PRB Utilization	Depends on traffic and users	Increases dynamic power
Active BSs	Determined by traffic state	Increases total power
Throughput	Proportional to traffic	Increases network activity

Table 6 summarizes the relationship among the major variables considered in the proposed model. Traffic load affects PRB utilization, while user density represents the number of users generating network demand. Increased PRB utilization results in higher dynamic power consumption, and increased traffic can cause additional base stations to become active. At the same time, throughput increases with traffic load. Therefore, the proposed model establishes an integrated relationship between traffic load, user density, PRB utilization, base-station activity, throughput, and energy consumption.

Table 7. Dynamic Power Consumption Model

Operating State	Active BSs	Power Characteristics	Overall Power
Sleep	3	Sleep power + auxiliary	Minimum
Low Load	6	Static + traffic-dependent dynamic + auxiliary	Low–Moderate
Medium Load	8	Static + traffic-dependent dynamic + auxiliary	High
High Load	10	Static + traffic-dependent dynamic + auxiliary	Maximum

Table 7 describes the dynamic power-consumption behavior of the base stations. During the sleep state, only three base stations operate at their low sleep-state power, resulting in minimum network consumption. Under low-load conditions, six base stations are active, while eight are activated during medium-load conditions. During high-load conditions, all ten base stations operate and their power consumption becomes dependent on

PRB utilization. Consequently, the model avoids maintaining all base stations at high power during periods when network demand is low.

Table 8. Overall Energy Consumption Results

Performance Metric	Obtained Value
Number of Base Stations	10
Simulation Duration	24 h
Total Energy Consumption	64.84 kWh
Average Power Consumption	2,701.60 W
Maximum Power Consumption	5,846.19 W
Minimum Power Consumption	300.00 W
Total Data Transmitted	828,051.50 Gbit
Energy Efficiency	3,547,502.97 bit/J
Energy Consumption per Bit	2.8189×10^{-7} J/bit

Table 8 presents the main quantitative results obtained from the MATLAB simulation. The proposed 10-base-station network consumes 64.84 kWh over 24 hours, with an average power consumption of 2,701.60 W. The maximum and minimum power consumption are 5,846.19 W and 300 W, respectively. The network transmits approximately 828,051.50 Gbit of data during the simulation period. The calculated energy efficiency is 3,547,502.97 bit/J, while the energy consumption per transmitted bit is 2.8189×10^{-7} J/bit. These results demonstrate that the power consumption varies substantially according to network operating conditions.

Table 9. Traffic and Power Relationship

Traffic Level	BS Activity	Power Behavior
Low traffic	3 active BSs	Minimum power consumption
Moderate traffic	6 active BSs	Power increases
High traffic	8 active BSs	High power consumption
Peak traffic	10 active BSs	Maximum power consumption

Table 9 explains the relationship between traffic load and total RAN power consumption. Under low traffic conditions, only three base stations are active, producing the minimum power consumption. As traffic increases to moderate and high levels, additional base stations are activated, resulting in progressively higher power consumption. During the peak traffic period, all ten base stations become active and the network reaches its highest power level. Therefore, the simulation confirms that traffic demand is an important factor governing the energy consumption of the RAN.

Table 10. User Density and Power Relationship

User Density	Network Users	BS Activity	Power Trend
Low	~150–200	3 BSs	Low
Moderate	~300–400	6 BSs	Moderate
High	~550–650	8 BSs	High
Very High	~800–900	10 BSs	Maximum

Table 10 presents the relationship between user density and power consumption. When approximately 150–200 users are present, only a small number of base stations are required. As the user population increases to approximately 300–400 and then 550–650 users, more base stations are activated to accommodate the increased demand. At the highest user density of approximately 800–900 users, all ten base stations are activated. This indicates that increasing user density contributes to higher network activity and consequently increases RAN energy consumption.

Table 11. PRB Utilization and Power Relationship

PRB Utilization	Network Condition	BS Activity	Power Trend
Low	Low traffic	3	Low
Moderate	Increasing traffic	6	Moderate
High	Daytime traffic	8	High
Very High	Evening peak	10	Maximum

Table 11 demonstrates the relationship between PRB utilization and power consumption. Low PRB utilization corresponds to low traffic and a small number of active base stations. As radio-resource utilization increases, the dynamic component of base-station power also increases. Under peak traffic, PRB utilization reaches its highest level and all base stations operate at high activity. Thus, PRB utilization acts as an important intermediate parameter connecting traffic demand and base-station power consumption.

Table 12. Conventional vs Dynamic BS Operation

Parameter	Conventional Operation	Proposed Dynamic Operation
BS Operation	All 10 BSs active	3–10 BSs dynamically active
Daily Energy	≈91.72 kWh	64.84 kWh
Energy Saving	—	29.28%
BS Sleep Capability	No	Yes
Traffic Awareness	No	Yes
Dynamic Resource Utilization	Limited	Yes

Table 12 compares conventional continuous base-station operation with the proposed dynamic BS operation. In the conventional approach, all ten base stations remain active irrespective of traffic demand, whereas the proposed approach dynamically activates between three and ten base stations according to network conditions. The estimated reference energy consumption is approximately 91.72 kWh/day, compared with 64.84 kWh/day for the proposed dynamic operation. This difference demonstrates the benefit of adapting base-station activity to changing traffic conditions.

Table 13. Energy-Saving Performance

Metric	Value
Reference Energy Consumption	≈91.72 kWh/day
Proposed Energy Consumption	64.84 kWh/day
Energy Reduction	≈26.88 kWh/day
Energy Saving Percentage	29.28%
Active BS Reduction	Up to 70% during low traffic
Energy Management Approach	Dynamic BS activation/deactivation

Table 13 quantifies the energy-saving capability of the proposed approach. The reference network requires approximately 91.72 kWh/day, whereas the proposed dynamic operation requires 64.84 kWh/day. Therefore, the proposed method reduces energy consumption by approximately 26.88 kWh/day, corresponding to an energy saving of 29.28%. During low-traffic periods, up to 70% of the base stations can be deactivated while maintaining at least three active base stations for network operation. This result is one of the key findings of the proposed energy model.

Table 14. Data Throughput Performance

Parameter	Value
Maximum Network Capacity	20 Gbps
Traffic-Dependent Throughput	(20\times Traffic) Gbps
Total Data Transmitted	828,051.50 Gbit
Average Data Rate	≈9.59 Gbps
Throughput Model	Traffic-dependent

Table 14 presents the throughput characteristics of the simulated network. The maximum assumed network capacity is 20 Gbps, while the instantaneous throughput is determined according to the normalized traffic level. Consequently, low traffic produces lower throughput and peak traffic produces the highest throughput. Over the 24-hour simulation, the model estimates a total data transmission of **828,051.50 Gbit**, demonstrating that the energy model considers not only power consumption but also the amount of data delivered by the network.

Table 15. Energy Efficiency Performance

Metric	Result
Total Data Transmitted	828,051.50 Gbit
Total Energy	64.84 kWh
Total Energy	233,424 kJ
Energy Efficiency	3,547,502.97 bit/J
Energy per Bit	2.8189×10^{-7} J/bit
Energy Saving	29.28%

Table 15 evaluates the energy-efficiency performance of the proposed RAN model. The network transmits 828,051.50 Gbit while consuming 64.84 kWh, corresponding to 233,424 kJ of energy. Based on these values, the calculated energy efficiency is 3,547,502.97 bit/J, while the energy required to transmit one bit is 2.8189×10^{-7} J/bit. These metrics provide a direct measure of how efficiently the RAN converts electrical energy into useful data transmission.

Table 16. Summary of Major Findings

Research Variable	Main Finding
Traffic Load	Strong driver of RAN power consumption
User Density	Higher user density increases network resource requirements
PRB Utilization	Higher utilization increases dynamic BS power
BS Activity	Dynamic activation adapts power to network demand
Low-Traffic Operation	3 BSs remain active to maintain network availability
Peak-Traffic Operation	All 10 BSs become active
Total Daily Energy	64.84 kWh
Maximum Power	5,846.19 W
Minimum Power	300 W
Energy Efficiency	3,547,502.97 bit/J
Energy Saving	29.28%

Table 16 summarizes the major findings of the proposed model. The results demonstrate that traffic load, user density, PRB utilization, and base-station activity are closely associated with RAN energy consumption. Low traffic permits the network to operate with only three active base stations and significantly lower power consumption, whereas peak traffic requires all ten base stations. Overall, the model achieves 64.84 kWh/day of energy consumption and a 29.28% energy saving compared with continuous base-station operation. These findings support the effectiveness of a dynamic, traffic-aware base-station energy management strategy for 5G RANs and provide a foundation for extending the model toward 5G-Advanced and beyond-5G networks.

IV. RESULTS

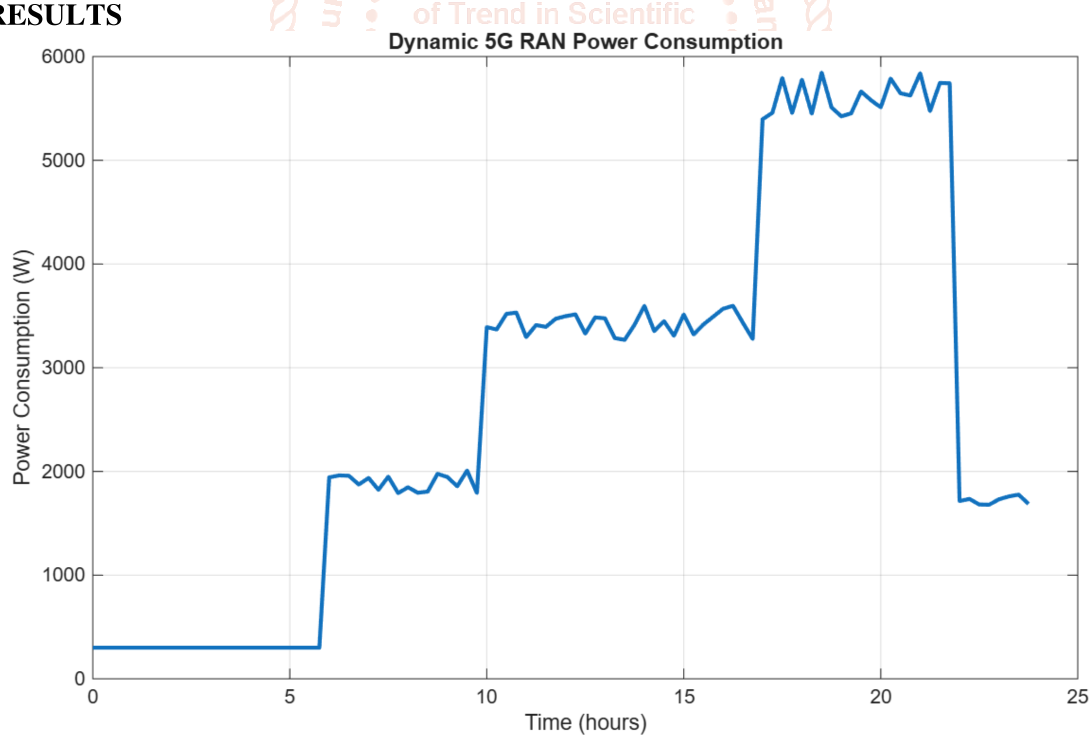

Fig. 2. Dynamic 5G RAN Power Consumption

Figure 2 illustrates the variation in 5G RAN power consumption over a 24-hour period under dynamic traffic conditions. Power remains low at approximately 300 W during the initial low-traffic period. As traffic increases, power rises to around 1,800–2,000 W, followed by a medium-load level of approximately 3,300–3,600 W. During the evening peak, power reaches nearly 5,800 W, corresponding to high network demand and increased base-station activation. After the peak period, power decreases to approximately 1,700 W as traffic reduces. This pattern demonstrates the strong relationship between traffic demand and dynamic RAN power consumption.

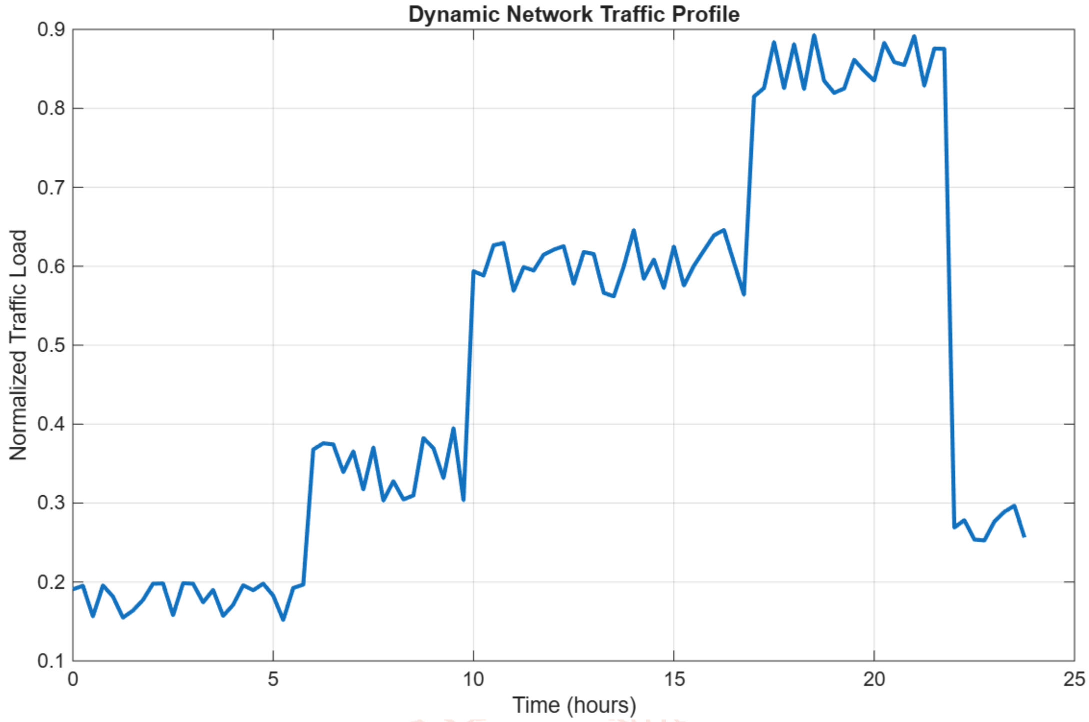

Fig. 3. Dynamic Network Traffic Profile

Figure 3 presents the normalized 24-hour traffic profile used in the proposed 5G RAN energy model. The traffic remains relatively low during the night and early morning, with a normalized load of approximately 0.15–0.20. From around 6 to 10 hours, the traffic increases to approximately 0.30–0.40, representing moderate network demand. Between 10 and 17 hours, the load remains around 0.55–0.65. The highest traffic occurs between approximately 17 and 22 hours, reaching nearly 0.90, indicating the evening peak period. After 22 hours, traffic decreases sharply to approximately 0.25–0.30. This dynamic profile drives BS activation and power consumption.

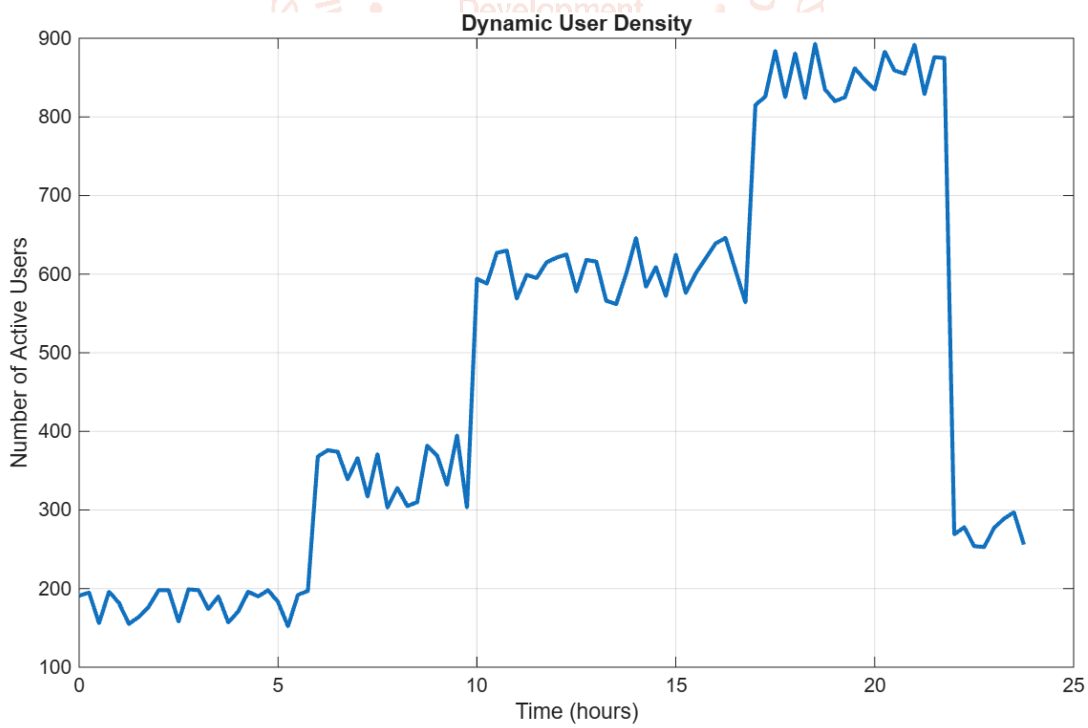

Fig. 4. Dynamic User Density

Figure 4 shows the variation in the number of active users across the 24-hour simulation period. During the early hours, user density remains low at approximately 150–200 users, indicating limited network demand. From around 6 to 10 hours, the number of active users increases to approximately 300–390 users. Between 10 and 17 hours, user density rises further and fluctuates around 560–650 users. The highest user density occurs during the evening peak, from approximately 17 to 22 hours, reaching nearly 900 users. After 22 hours, the number of active users decreases sharply to approximately 250–300 users. This trend closely follows the dynamic traffic profile and influences BS activation and energy consumption.

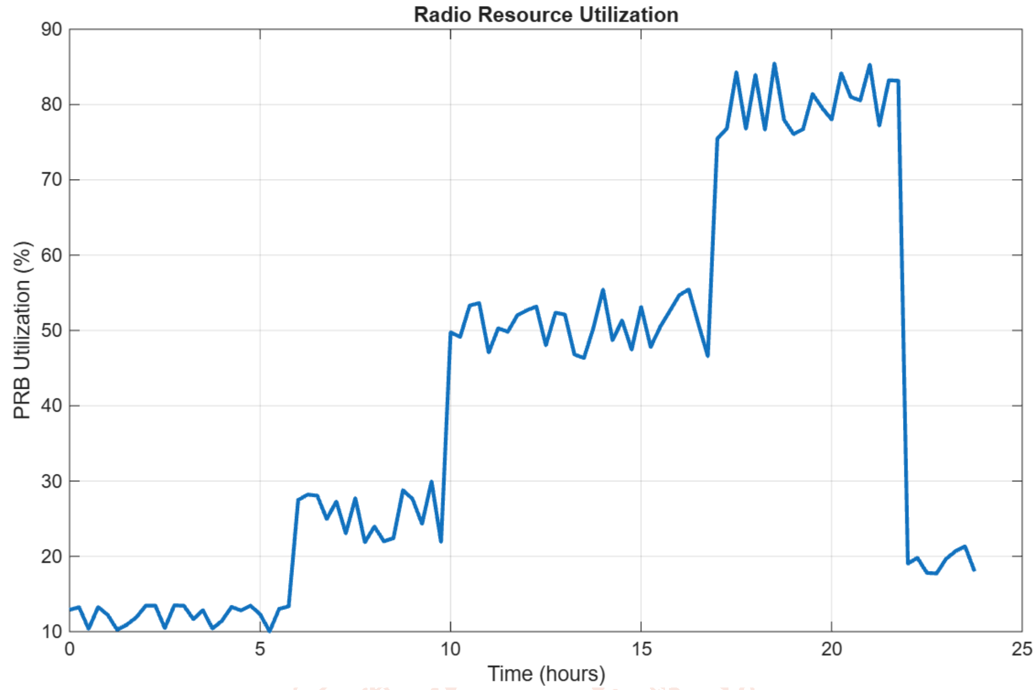

Fig. 5. Radio Resource Utilization

Figure 5 illustrates the variation in Physical Resource Block (PRB) utilization over the 24-hour simulation period. During the early low-traffic hours, PRB utilization remains low at approximately 10–14%, indicating limited resource demand. From around 6 to 10 hours, utilization increases to approximately 22–29%. Between 10 and 17 hours, PRB utilization fluctuates around 47–55%, corresponding to moderate network activity. During the evening peak period, approximately 17–22 hours, utilization increases significantly and reaches nearly 85%. After 22 hours, utilization drops sharply to approximately 18–21% as network demand decreases. The results demonstrate that PRB utilization closely follows traffic and user-density variations.

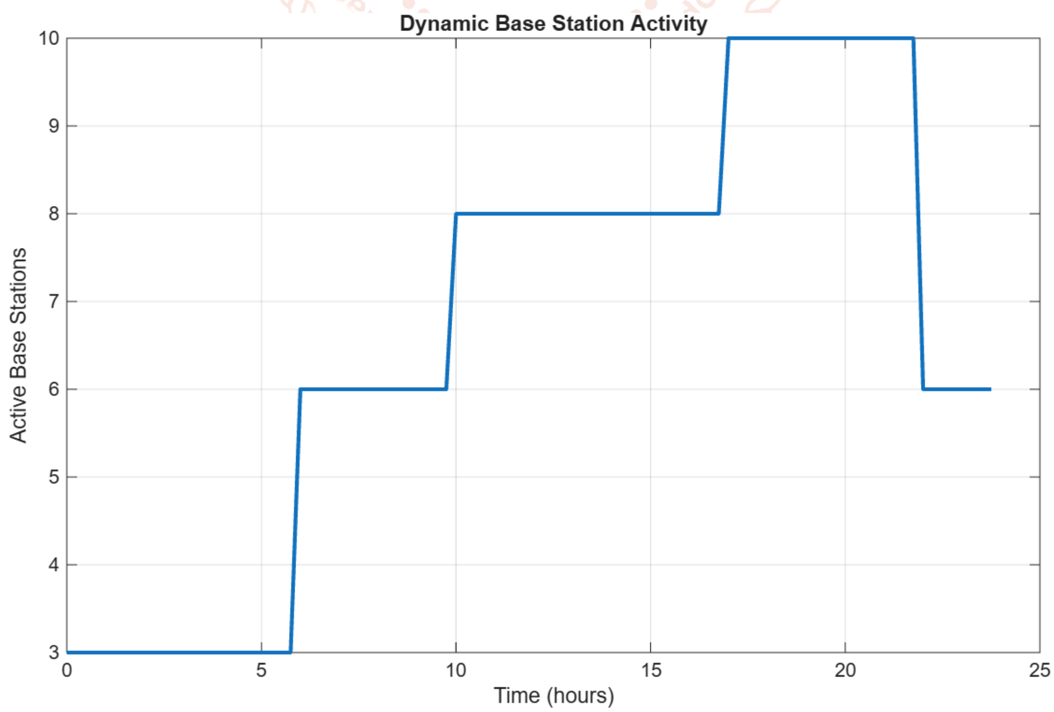

Fig. 6. Dynamic Base-Station Activity

Figure 6 shows the dynamic variation in the number of active base stations (BSs) during the 24-hour simulation. During the low-traffic period from 0 to approximately 6 hours, only 3 BSs remain active. As traffic demand increases, the number of active BSs rises to 6 BSs between approximately 6 and 10 hours. From 10 to 17 hours, 8 BSs are active to support the increased network demand. During the evening peak period, approximately 17–22 hours, all 10 BSs are activated. After 22 hours, the activity decreases to 6 BSs as traffic demand falls. This adaptive BS operation reduces unnecessary energy consumption during low-traffic periods while maintaining sufficient network capacity during peak demand.

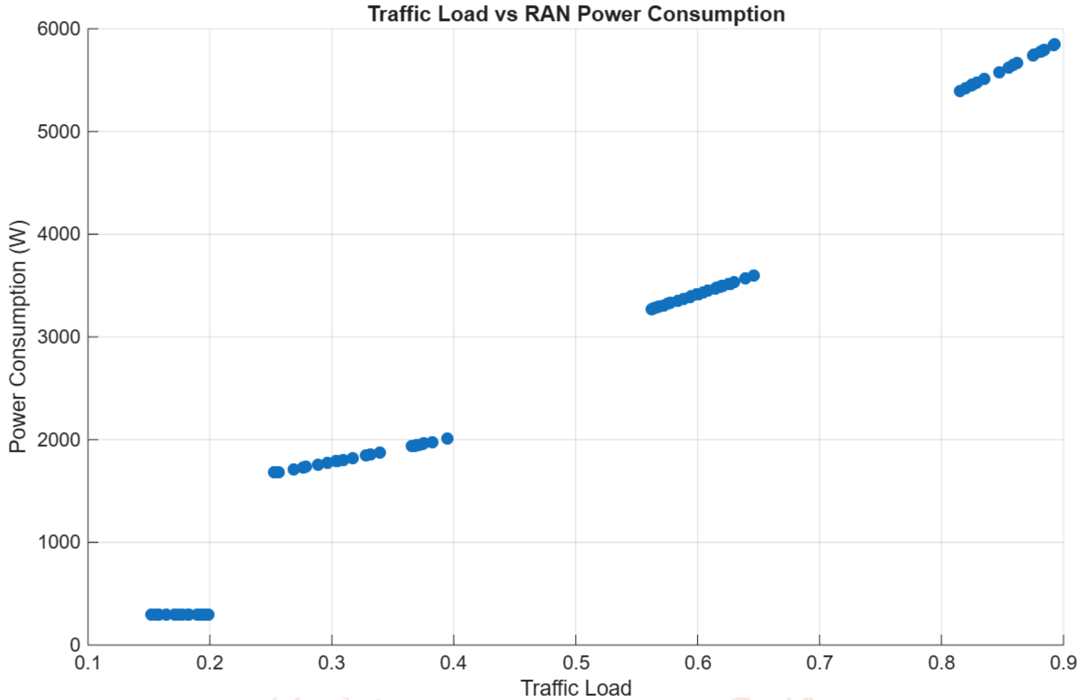

Fig. 7. Traffic Load versus RAN Power Consumption

Figure 7 illustrates the relationship between traffic load and RAN power consumption. The results show a clear positive relationship, where increasing traffic demand leads to higher power consumption. At low traffic loads of approximately 0.15–0.20, power consumption remains around 300 W. As the traffic load increases to approximately 0.25–0.40, power rises to about 1,700–2,000 W. For medium traffic loads of approximately 0.55–0.65, power consumption reaches 3,300–3,600 W. At high traffic loads of approximately 0.80–0.90, power increases to nearly 5,800 W. This confirms that traffic demand directly influences BS activation and dynamic RAN energy consumption.

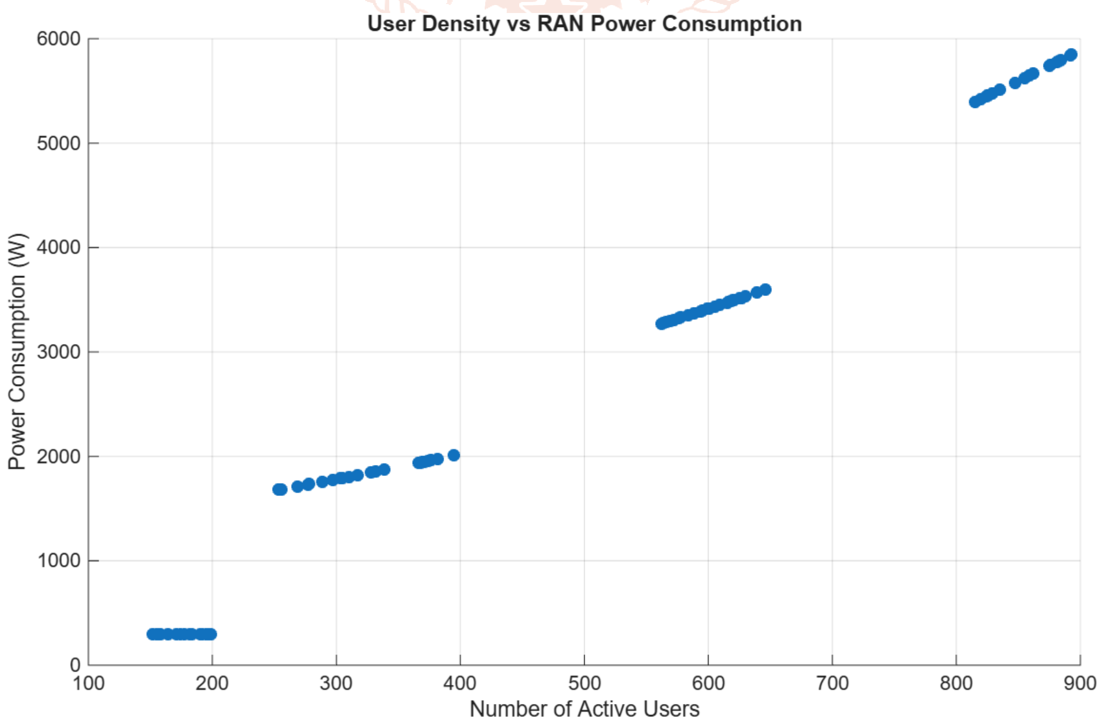

Fig. 8. User Density versus RAN Power Consumption

Figure 8 presents the relationship between active user density and RAN power consumption. The results show a clear increasing trend, indicating that higher numbers of active users require greater network resources and consequently higher power consumption. At approximately 150–200 users, the RAN consumes around 300 W. As user density increases to 250–400 users, power consumption rises to approximately 1,700–2,000 W. For 550–650 users, power consumption increases to about 3,300–3,600 W. At the highest user density of approximately 800–900 users, power reaches nearly 5,800 W. This demonstrates that increasing user density strongly influences BS activation and overall RAN energy consumption.

V. CONCLUSION

This study presented a comprehensive traffic- and user-density-aware energy consumption model for 5G and beyond Radio Access Networks (RANs) under dynamic traffic conditions. The proposed MATLAB-based framework establishes an integrated relationship between traffic load, active-user density, PRB utilization, base-station activity, power consumption, throughput, and energy efficiency. The 24-hour simulation demonstrates that network power consumption increases with traffic demand and user density, while dynamic base-station activation enables unnecessary BSs to operate in low-power or sleep conditions during periods of low demand. The simulation results show that the proposed dynamic operation consumes 64.84 kWh/day, compared with approximately 91.72 kWh/day for continuous operation of all base stations. This corresponds to an energy reduction of approximately 26.88 kWh/day and 29.28% energy saving. The network also achieves an energy efficiency of 3,547,502.97 bit/J, with an energy consumption of 2.8189×10^{-7} J/bit.

REFERENCES

[1] L. M. P. Larsen, H. L. Christiansen, S. Ruepp, and M. S. Berger, "Toward Greener 5G and Beyond Radio Access Networks—A Survey," *IEEE Open Journal of the Communications Society*, vol. 4, pp. 768–797, 2023, doi:10.1109/OJCOMS.2023.3257889

[2] L. Kundu, X. Lin, and R. Gadiyar, "Toward Energy Efficient RAN: From Industry Standards to Trending Practice," *IEEE Wireless Communications*, vol. 32, no. 1, pp. 36–43, 2025, doi:10.1109/MWC.010.2400061.

[3] N. Piovesan, D. López-Pérez, A. De Domenico, X. Geng, H. Bao, and M. Debbah, "Machine Learning and Analytical Power Consumption Models for 5G Base Stations," *IEEE Communications Magazine*, vol. 60, no. 10, pp. 56–62, 2022, doi:10.1109/MCOM.001.2200023.

[4] N. Piovesan, D. López-Pérez, A. De Domenico, X. Geng, and H. Bao, "Power Consumption Modeling of 5G Multi-Carrier Base Stations: A Machine Learning Approach," in *Proc. IEEE Int. Conf. Communications (ICC)*, 2023, doi:10.1109/ICC45041.2023.10278569.

[5] "Toward Green 6G RAN: A Survey of Energy-Efficient Mechanisms and 3GPP Standardization Efforts," *ICT Express*, 2026.

[6] L. M. P. Larsen, H. L. Christiansen, S. Ruepp, and M. S. Berger, "Toward Greener 5G and Beyond Radio Access Networks—A Survey," *IEEE Open Journal of the Communications Society*, vol. 4, pp. 768–797, 2023, doi:10.1109/OJCOMS.2023.3257889.

[7] N. Piovesan, D. López-Pérez, A. De Domenico, X. Geng, H. Bao, and M. Debbah, "Machine Learning and Analytical Power Consumption Models for 5G Base Stations," *IEEE Communications Magazine*, 2022.

[8] N. Piovesan, D. López-Pérez, A. De Domenico, X. Geng, and H. Bao, "Power Consumption Modeling of 5G Multi-Carrier Base Stations: A Machine Learning Approach," 2022.

[9] T. Chen, Y. Wang, H. Chen, Z. Zhao, X. Li, N. Piovesan, G. Zhu, and Q. Shi, "Modelling the 5G Energy Consumption using Real-world Data: Energy Fingerprint is All You Need," 2024.

[10] L. Kundu, X. Lin, and R. Gadiyar, "Toward Energy Efficient RAN: From Industry Standards to Trending Practice," *IEEE Wireless Communications*, vol. 32, no. 1, pp. 36–43, 2025.

[11] "Toward Energy Efficiency in Radio Access Networks for 5G and Beyond: A Review of the State of the Art, Comparison of Power Consumption for Popular Open 5G RANs, and Techno-Economic Cost Impact," *IEEE Access*, vol. 13, pp. 187799–187842, 2025.

[12] A. L. de Araujo, L. Deneire, G. Urvoy-Keller, and A. L. F. de Almeida, "Charting 5G Energy Efficiency: Flexible Energy Modeling for Sustainable Networks," 2025.