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RESEARCH ARTICLE

Energy-Efficient Sleep Mode Schemes for Cell-Less RAN in 5G and Beyond 5G Networks

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ABSTRACT In 5G and beyond 5G networks, the new cell-less radio access network architecture is adopted to overcome the extreme network capacity challenges generated by massive wireless devices used for diverse scenarios and various applications. At the same time, the evolution of mobile communications faces the important challenge of increased network power consumption. To fulfill user demands for various user densities and meanwhile reduce the power consumption, we present a novel energy-efficiency enhancement scheme, i.e., $(3 \times E)$ to increase the transmission rate per energy unit, with stable performance within the cell-less radio access network (RAN) architecture. Our proposed $(3 \times E)$ scheme activates two-step sleep modes (i.e., certain phase and conditional phase) through the intelligent interference management for temporarily switching access points (APs) to sleep, optimizing the network energy efficiency (EE) in highly loaded scenarios, as well as in scenarios with lower load. An intelligent control over underutilized/unused APs is considered, taking their interference contribution into account as the primary main criteria in addition to load-based conditional criteria. Therefore, our proposed scheme assures a stable performance enhancement and maintains an efficient power saving when the number of UEs increases, improving existing works not addressing this performance stability in peak-traffic hours. Simulation results show that the network EE is improved up to 30% compared to the reference algorithm and up to 60% with respect to the baseline algorithm in which all APs are active all the time.

INDEX TERMS Cell-less, radio access network, sleep mode approach, energy-efficient, 5G and beyond.

I. INTRODUCTION

Escalating traffic demands for different use cases and new applications of the evolving mobile communications generation (i.e., 5G and beyond (B5G)) lead to the action requirement from the operators to expand their networks for supporting more capacity. At the same time, the increased traffic is consuming huge energy in the wireless networks, which impacts greenhouse effect significantly. Research communities from both academia and industry are now focusing on novel technologies, architecture, infrastructures, and solutions to execute the capacity expansion plan while minimizing energy consumption as possible from both access and backhaul networks [1], [2], [3].

Recently, a new radio access network (RAN) architecture known as cell-less (or cell-free)[1] [4] is approached to provide high spectral efficiency, flexible and cost-efficient deployment, ensure high quality of service and low path loss propagation conditions. In the cell-less architecture, the cell boundaries are removed from the user equipment (UE) view point. However, it is not practical to serve all UEs by the entire available transmitters due to the capacity constraint

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[1] "Cell-free" is the term which is often used when referring to the advances of the physical layer transmission techniques using massive MIMO. Here we use "cell-less" as a more general term pointing to a new architecture, independently of the type of transmission used.

of a particular transmitter. In order to have a practical and feasible architecture, new technical solutions adoptable to the architecture are needed to meet the key performance indicators (KPI)s and afford the resource consumption, including energy. At the same time, the industry players are interested in novel architectures involving green implementation and improving the network energy efficiency (EE) to reduce energy consumption. The open RAN solution has been considered as an enabler for EE in 5G Networks [5]. Therefore, it requires novel technologies being customized for an energy efficient implementation. The key contributing operators in open RAN just started to focus on energy performance parameters and solutions for candidate technologies and architectures [6]. Having the different traffic load over time based on the user condition diversity leads to huge amounts of wasted energy by keeping the access points (APs) with the same transmitting power status all the time. Considering the sleep mode technique as a recognized feature to improve EE, proper management of energy utilization in the APs will enhance the network EE. Therefore, in this paper, we propose an energy efficient sleep mode scheme for a cell-less RAN architecture in 5G and beyond 5G networks.

The organization of the paper is as follows: Section I-A discusses the related literature and research gaps whereas Section I-B summarizes the contribution. The system model of the cell-less architecture is described in Section II. In Section III the research problem is formulated mathematically and the novel energy-efficiency enhancement ($3 \times E$) scheme is proposed. Section IV evaluates the performance and analyzes the results. Finally, the conclusion is made at Section V.

A. LITERATURE REVIEW

Although the newly deployed small cells use a lower transmitting power, still the circuit power consumption is high. As a result, a significant enhancement in energy saving is feasible by switching off the low loaded APs. Cell zooming [7] is considered as one of the potential candidates of green communication deployment in order to optimize the transmitting power. Not only power, but management of the entire radio resources (considering radio units (RU)s among these resources) is an effective aspect of green communication, which will ensure the feasibility of a new solution and its interest for the operators. As the major part of the network energy consumption occurs on the base station/access point (BS/AP) sites, the joint energy saving through small cell BS/AP sleeping and interference coordination mechanisms were addressed in [8] and [9]. The authors proposed an online solution to minimize the energy consumption as a function of aggregated users' traffic with QoS boundaries for users. The two-level controllers in global and local states support the performance of the algorithm. An efficient traffic-aware user association method to switch off BSs with traffic below a predefined threshold is proposed in [10]. In this paper the traffic across the BSs is monitored continuously to detect best candidate resources to save energy. However, the effect of switching off BSs on the amount of data transmission ratio per energy unit is not considered. In [11], a grid-based traffic map BS switch off algorithm is proposed to reduce the energy consumption in dense 5G networks. There are different types of BS/AP mode selection techniques in [12], considering if they are applied in a competitive or cooperative manner. Competitive schemes would be performed at each BS/AP without considering metrics regarding others. On the other hand, cooperative schemes are applied to the network considering other BS/AP status in switching off. In [13], authors proposed a new scheme to mitigate the network interference through selecting the unnecessary femtocells to enter sleep mode and enhance network EE. This mechanism allows the UEs in any femtocell in sleep mode to reconnect to other femtocells.

In [14], the authors presented a detailed survey about energy efficient resource allocation in shared RAN. The work gave an overview with a classification of energy efficient schemes and highlighted gaps. Powering on/off RRHs according to load variation is considered among the self-optimization techniques for achieving EE. The proposal in [15] leveraged an EE sleep mode criteria in BS/AP to optimize the network energy efficiency through total power minimization using a load transfer algorithm. However, the scheme ignored the network traffic load loss caused by small cells that are unnecessarily switched off. A system throughput-based sleep mode scheme is proposed to enhance the total EE and reduce power in [16]. In [17], a power minimization technique for cell-free massive MIMO networks is proposed, which makes inefficient APs sleep during non-busy hours. Although the simulation results of this paper show that the proposed low complexity algorithm reaches near optimal performance regarding power consumption, while satisfying the minimum spectral efficiency requirements of all users, it is not addressing the transmission rate per energy unit as the parameter to be optimized, not yielding a solution of the problem being targeted here. EE optimization problems are managed through throughput optimization and energy saving models. However, energy saving will cause throughput degradation, since both parameters are highly correlated. Therefore, it is needed to focus on a joint optimization to obtain an optimum EE [18], [19]. Minimum individual EE is ignored in the so-far reviewed joint optimization literature.

In [20], the authors proposed cell-level EE enhancement, instead of network-level, through adaptive BS sleep control to maximize the minimum EE of active BSs. However, the impact on network EE and traffic losses of switching BSs off is not considered. A sleep control technique is proposed in [21] to jointly improve network EE and throughput. The proposed technique maintains the system throughput in 99% of the cases when there is no implemented sleep mode technique. However, it is not providing a stable performance against traffic fluctuations when the number of UEs is increased. This is because of not handling the interference within a dynamic load of the network. The proposed on/off switching algorithms in [22] and [23] improve the network

TABLE 1. Energy Efficient AP ON-OFF Switching Approaches in Literature.

Reference	Objective	Contribution	Limitation	UA	LD	IM	TREU Max.	EEE Stability	EE Max.
[7]	PC Min.	Centralized and distributed cell zooming AP on/off switching according to traffic load and spectral efficiency	A, B, C, D	Yes	Yes	No	No	No	No
[8]	EE Max.	Interference-based AP on/off switching to enhance capacity (and EE) in HetNets	C, D	Yes	No	Yes	No	No	Yes
[9]	PC Min.	(a) Online learning approach using AP on/off switching (b) Propose user association, power control, and interference management accordingly	A, D	Yes	Yes	Yes	No	No	No
[10] [11]	PC Min.	Traffic load-based AP on/off switching to minimize power consumption	A, C, D	Yes	Yes	No	No	No	No
[12]	PC Min.	Captures spatio-temporal fluctuation of traffic demand to jointly optimize clustering for cooperative transmission and AP on/off switch	A, C, D, E	Yes	Yes	No	No	No	No
[13]	EE Max.	Spectrum management to mitigate interference and enhance individual and network capacity and EE in addition to performing UE-BS association	C	Yes	Yes	Yes	Yes	No	Yes
[15]	PC Min.	Spectrum and load sharing for AP on/off switch	A, C, D, E	Yes	Yes	No	No	No	No
[16]	EE Max.	Throughput based AP on/off switching in HetNet	C, D	Yes	Yes	Yes	No	No	Yes
[17]	PC Min.	Utilizes optimized transmit powers to enable sleeping BSs and achieve EE load balancing in cell-free networks	A, C, F	Yes	Yes	Yes	No	No	No
[18]	PC Min. EE Max.	(a) Cooperative sleep mode for group-based sub-frame configuration per BS (b) Focused on energy saving and EE optimization simultaneously via fairness-based sub-channel allocation and power allocation	C	Yes	Yes	Yes	Yes	No	Yes
[22] [23]	EE Max.	Interference contribution rate-based AP on/off switching considering the serving signal strength measurements of UEs and load of BS	D, G	No	Yes	Yes	No	No	Yes
[26]	EE Max.	Propose goodness of-fit (GoF) AP on/off switching based on non-uniform spatial traffic density to adapt to both the number and the statistical distribution of UEs in the cell-less network	C, D, E	Yes	Yes	No	No	No	Yes
[27]	PC Min.	A sleep mode scheme is proposed in several states including transferring, ready, listening, and sleeping to decrease energy consumption in cell-less networks	A, C, D	Yes	Yes	Yes	No	No	No
Proposed ($3 \times E$) Scheme	EE Max.	(a) Interference contribution rate-based AP on/off switching according to the serving signal strength measurements of UEs and load of APs in cell-less RAN networks. (b) Through 2 steps scheme to maximize network EE and control traffic loss, EE enhancement performance is kept stable in higher user density	H	Yes	Yes	Yes	Yes	Yes	Yes

A = Not focused on EE maximization; B = Inconsistency between cells may cause uncovered area using cell zooming;
C = Stability of EE performance enhancement is not considered at higher user density; D = Not focused on increasing the amount of transmitted data per energy unit;
E = No interference management; F = More focused in non-busy hours;
G = Stability of power saving is not considered at higher user density; H = Not considering minimum power consumption as targeting EE maximization.
UA = User Association; LD = Load Management; IM = Interference Management; TREU = Transmission Rate per Energy Unit;
EEE = Energy Efficiency Enhancement; PC = Power Consumption; EE = Energy Efficiency.

EE and the total data rate, while controlling traffic losses considering the interference between BSs. However, it is required to consider the number of transmitted bits per energy unit to ensure that the EE optimization is achieved in the network irrespective of the user density. Hence, we should maximize the network EE through an efficient scheme applicable to the networks with any user density. Then, individual EE degradation because of co-channel interference increment by increasing the density of users is avoided. Otherwise, the network would not be energy efficient in highly loaded scenarios.

Moving toward 5G and beyond network enablers, considering the novel cell-free architecture, the authors of [24] proposed a power consumption model to have an improved EE by the analytical determination of pilot reuse factor, BS/AP density and number of antennas per AP for the cell-free massive MIMO network, which would improve the EE. The performance was reflecting a certain optimal point for the number of users, antennas and BS/AP density. Beyond that certain point, the EE per area would be decreased due to interference increment. In [25], the authors proposed a power allocation scheme for the cell-free massive MIMO network and by combining with the BS/AP selection algorithm in order to control the power consumption of the backhaul links, the EE of the network was improved while addressing the fact that for a particular user, only a small number of antennas are actively serving it. In [26], the authors proposed a dynamic energy-efficient sleep mode selection for the cell-less millimeter wave massive MIMO network that is adaptive to the number and statistical distribution of the user equipment's (UEs) in the network. Traffic load management within BS/AP sleep mode selection techniques are also proposed in cell-less networks [27]. The software defined network (SDN)-based network architecture [1], thanks to a centralized controller support for RAN, is a strong enabler to make the cell-less implementation practical. Table 1 shows a comparison and key differentiators of existing energy efficient sleep-mode techniques in the literature.

B. CONTRIBUTIONS

In the existing proposed solutions, the energy efficiency performance has yet been an important topic for novel architectures such as cell-less, among the enabling technologies of 5G and beyond networks. The target of this work is to design a customized energy efficient technique which can bring the cell-less network implementation practical and advantageous from the energy consumption and implementation complexity point of view for the open RAN network solutions. The so far reviewed papers are not comprehensive and not fully adapted to the cell-less architecture in which there are no cell boundaries. The UE is already distinguishing the entire radio resources as a common pool where the RAN is transparent from this perspective. Moreover, the UE does not need to do handover in a cell-less architecture and thanks to this, the cooperative association scheme could be implemented without extra signaling due to handover procedures but with higher energy efficiency performance through applying our proposed sleep mode selection scheme customized for a cell-less design. This scheme would consider the fact that the UE needs to be able to be served by any particular radio resources within the time intervals in an energy efficient continuously running converged network.

To the best of the authors' knowledge, no literature has been found investigating network EE optimization, through increasing transmission rate per energy unit, that assures the stability of the performance enhancement irrespective of the demand and density of users. With focus on these research gaps, aiming to optimize the total network EE and the minimum EE of the active RUs in addition to managing their interference contribution, an energy efficient scheme is proposed. We have considered an efficient customization through a two-step sleep mode technique, in a way that EE performance enhancement against user density fluctuation in the network will be managed. Our scheme will enhance network EE significantly and outperforms the previous works. Hence, the main advantage of our proposed ($3 \times E$) scheme is the fact that it is optimizing the minimum EE of active RUs and network EE within different user densities thanks to our applied strategy for selecting sufficient RU candidates to save energy and enhance data transmissions per energy unit. The scheme could save energy not only in the non-busy-hours, but also enhance energy efficiency in busy-hours. This contrasts with the reviewed literature, which did not maintain efficient power saving when the load increases because of the user density increment. Although it is needed to re-associate a higher number of users from highly loaded sleeping RUs in our scheme compared to the referenced techniques, the proposed criteria will manage and avoid high traffic loss and performance degradation instead. In addition to this, handover procedures are removed as a benefit of using the cell-less architecture. Our contributions can be summarized as:

- We propose an energy-efficient scheme in the cell-less architecture towards its practical deployment in 5G and beyond networks. This includes a two-step sleep mode selection (i.e., certain phase and conditional phase) with an intelligent controller that dynamically updates the user and RU association and switches the unnecessary RUs to sleep.
- Our proposed approach controls the interference at dense environments in a way that transmission is performed only if it is beneficial for the increment of the network EE. Meanwhile, the proposed ($3 \times E$) scheme employs conditional sleeping criteria with traffic load-based customization in addition to an interference consideration to assure maintaining efficient power saving for networks with various user densities. The simulation results show that the network throughput and EE are improved for the proposed scheme as compared with the conventional algorithms.

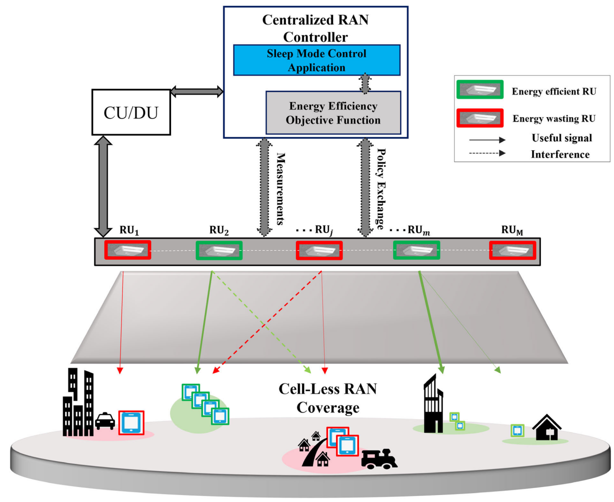

FIGURE 1. High level architectural view of a cell-less RAN.

II. SYSTEM MODEL

We assume a cell-less architecture of the RAN for a dense scenario depicted in Fig. 1 where the UEs are connecting to the entire radio resources without being limited by the cell boundaries and they experience the RAN as a common unique zone. The disaggregated RAN inspired from the open RAN architecture - having disaggregated RU, centralized unit (CU), distributed unit (DU) - is considered, where RU shows similar attributes to BS/AP. The users associated with each RU may be served randomly or by any well-established scheduling technique. The central RAN controller is supporting the coordination of RAN and the network information exchanging and storage. The UEs may be re-associated to different RUs at each transmission time interval (TTI).

In the following, let us consider a set of RUs $\mathcal{M} = \{1, \ldots, M\}$ and a set of UEs $\mathcal{K} = \{1, \ldots, K\}$, where M and K are the total number of RUs and UEs in the network accordingly. The antennas of the RUs are considered omni-directional. The set of users under a particular RU $m \in \mathcal{M}$ coverage is denoted by U_m. Channel gain between user $k \in \mathcal{K}$ and RU m is $h_{m,k}$ including pathloss and shadowing effects. P^m is the transmission power of RU m and σ^2 is the additive white Gaussian noise power at each receiver. The signal-to-interference-plus-noise ratio (SINR) for the k-th user served by RU m in the downlink (RU to UE) is denoted by $\gamma_{m,k}$. Considering μ_m as the sleep mode indicator, which is representing RU in sleep mode if $\mu_m = 1$, and in active mode if $\mu_m = 0$, the SINR in the downlink $\gamma_{m,k}$ can be written as

$$\gamma_{m,k} = \frac{(1-\mu_m)P^m \left|h_{m,k}\right|^2}{\sum_{j \neq m, j \in \mathcal{M}} (1-\mu_j)P^j \left|h_{j,k}\right|^2 + \sigma^2}. \tag{1}$$

Aggregating the throughput per resource block (RB)[2] of the set of users that are served by RU m, that is the set U_m, denoted by $R_{m,i_{\text{RB}}}$, the total throughput of the particular RU m can be obtained as [22]

$$R_m = \sum_{i \in U_m} N_i \, R_{m,i_{\text{RB}}} \tag{2}$$

where N_i is the minimum required number of RBs for a particular user.

According to the EARTH power model [28], the total consumed power P^m_{Total} is the summation of circuit power and transmit power (i.e., $P^m_{\text{Total}} = P^m_{\text{cir}} + \alpha P^m_{\text{out}}$) while the transmit power P_{out} would be limited to the maximum power at full load.

α, P_{out}, ρ_m, and N_T represent the power amplifier efficiency, transmission power, load for a particular RU m, and the total number of RBs. The transmitted power can be written as

$$P^m_{\text{out}} = \rho_m P^m_{\max} \tag{3}$$

$$\rho_m = \frac{\sum_{i \in U_m} N_i}{N_T}. \tag{4}$$

As the major source of power consumption is the circuit power of an active RU, through switching a RU to the sleep mode with zero transmission power, much lower circuit power could be consumed. The circuit power can be measured as

$$P_{\text{cir}} = (1-\mu)P^{\text{active}}_{\text{cir}} + \mu \, P^{\text{sleep}}_{\text{cir}} \tag{5}$$

while we consider $P^{\text{active}}_{\text{cir}}$ and $P^{\text{sleep}}_{\text{cir}}$ as circuit power for active and sleep RU respectively. The total network EE can be calculated as the aggregation of the RUs throughput divided by the total network power consumption, namely

$$EE_{\text{Total}} = \frac{\sum_{m \in \mathcal{M}} R_m}{\sum_{m \in \mathcal{M}} P^m_{\text{Total}}}. \tag{6}$$

[2] A resource block is the smallest unit of resources that can be allocated to a user.

III. PROBLEM FORMULATION AND PROPOSED ENERGY-EFFICIENCY ENHANCEMENT (3 x *E*) SCHEME

A. PROBLEM FORMULATION

Let $\boldsymbol{A}$, which is a matrix of size $K \times M$, represents the status of the users' connection to RUs. If $\mu_m = 0$ and the user k is connected to RU m, we have $A(k,m) = 1$, otherwise $A(k,m) = 0$. In order to find the efficient dynamic user association to the cell-less RAN and deciding to switch inefficient RUs in sleep mode that maximize the network EE, the optimization problem can be expressed as

$$\boldsymbol{A}^* = \arg\max_{\boldsymbol{A}}(EE_{\text{Total}}) \tag{7}$$

Subject to:

$$\begin{aligned}
&C1: A(k,m) \in \{0,1\}, \quad \forall k = 1,\ldots,K, \quad \forall m = 1,\ldots,M \\
&C2: \sum_{j \in \mathcal{M}} R_j \geq \ ((1-\beta) \sum_{j \in \mathcal{M}} R^{\text{baseline}}_j) \\
&C3: \sum_{k \in \mathcal{K}} A(k,m) \ \leq \ N_T, \quad \forall m = 1,\ldots,M \\
&C4: \sum_{m \in \mathcal{M}} A(k,m) \ \leq \ 1, \quad \forall k = 1,\ldots,K \\
&C5: \ R_k = N_k \, R_{m,k_{\text{RB}}} \ > \ R_{k_{\min}}, \quad \forall k = 1,\ldots,K \\
&C6: \ \min(EE_j = \frac{R_j}{P^j_{\text{Total}}}) \geq \min(EE_m), \\
&\qquad \forall j \in M^{\text{temp}}_{\text{active}}, \quad \forall m \in M_{\text{active}} \\
&C7: \ P^m_{\text{out}} \leq P^m_{\max}, \quad \forall m = 1,\ldots,M
\end{aligned}$$

The constraint C1 represents the binary value matrix $\boldsymbol{A}$. Constraint C2 is ensuring that the network throughput does not suffer a big loss (considering R^{baseline}_j as the total throughput of a particular RU j before applying our sleep mode technique on the system and β as the allowed traffic loss ratio, which is configurable based on network conditions and operator preferences). According to constraints C3 and C4, each RU can use up to a maximum number of available RBs and each UE may be served by maximum one RU, respectively. Constraint C5 ensures that the required throughput of each UE is achieved, where $R_{k_{\min}}$ denotes the minimum required throughput for user k. Constraint C6 (assuming $M^{\text{temp}}_{\text{active}}$ as the temporary RU active set where $M^{\text{temp}}_{\text{active}} = M_{\text{active}} \cup \{\text{RU}\, j\}$ to include RU j temporary) ensures that the number of transmissions per energy unit will be increased along with saving the energy consumption. Finally, the constraint C7 will keep the transmission power limited to a maximum transmission power of any particular antenna.

The aim is to enhance the EE through the choice of the active and sleep sets of RUs including UE-RU association. The optimal solution could be found through an exhaustive search, which is not time and computationally efficient. Hence, we propose a scheme which enhances the EE ending up with a near optimal solution as it is shown in the performance evaluation section. In this work, the customized

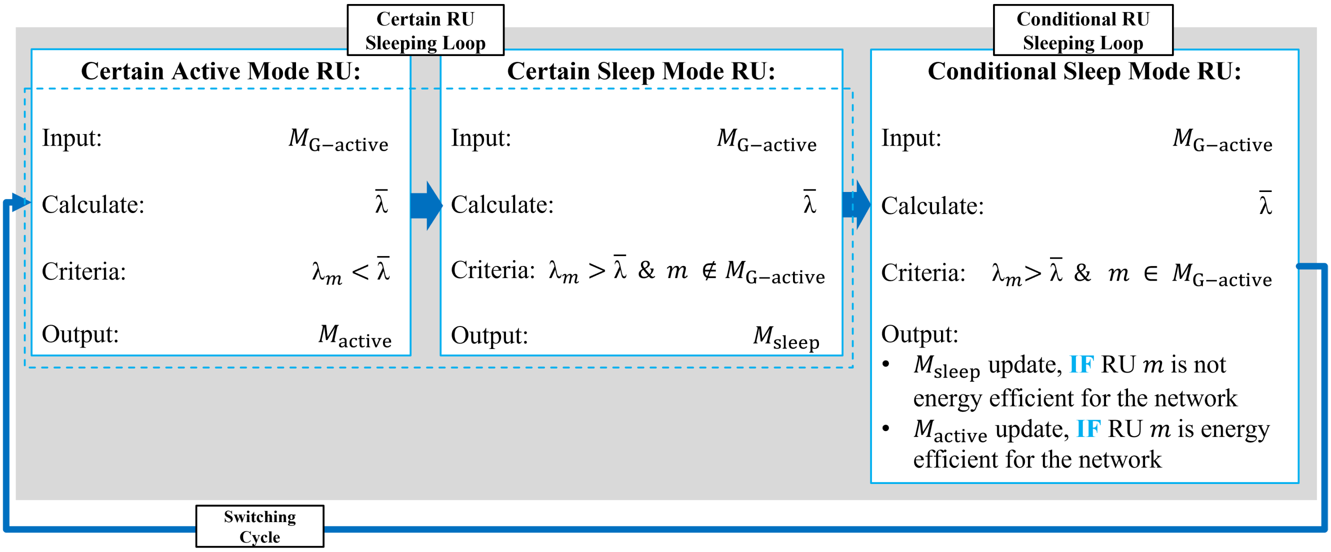

FIGURE 2. High level view of the proposed ($3 \times E$) scheme.

RU sleep mode selection solution will consider the interference that each RU is causing to the network in comparison to its provided useful signal. Therefore, the interference ratio parameter in the downlink is defined as follows, which is adapted from the interference contribution ratio (ICR) concept [22]

$$\lambda_m = \frac{\sum_{i \notin U_m} P^m \left|h_{m,i}\right|^2}{\sum_{i \in U_m} P^m \left|h_{m,i}\right|^2}. \tag{8}$$

The higher ICR a particular RU has, the lower useful signal it provides toward the network. However, the higher ICR will reflect propagating more interference to the network. Therefore, the RU will cause the entire network transmission performance to be degraded. In this case, such active RU will be considered as energy wasting and the cell-less network could gain more by saving energy consumption through making it sleep. Therefore, users' radio conditions improve thanks to interference mitigation.

B. OUR PROPOSED ($3 \times E$) SCHEME

Our proposal is an energy-efficient UE-RU association with the possibility of making inefficient RUs sleep. It contains two phases: (i) initial UE-RU association, (ii) RU sleep mode selection. As it is addressed in [23], using the RU sleep mode selection considering load, reference signal received power (RSRP)[3] of serving UEs and interference, could reduce the power consumption and enhance throughput.

1) INITIAL UE-RU ASSOCIATION

In the first step, the initial association will be executed with the link providing the highest RSRP $P_r(k, m)$ for each user k from a particular RU m in the network. In the cell-less network, this information can be obtained at the central RAN controller thanks to the information that UEs periodically feed back. The pseudo-code of user association is given in **Algorithm 1**.

Algorithm 1: The Initial UE-RU Association Phase of Sleep Mode Proposed Technique

```
Input  : A = [0]_{K×M}; 𝒦; ℳ; P_r
Output: A
for i = 1 : K do
    m* = arg max_A (P_r(i, m))
    A(i, m*) = 1
end for
return A
```

2) RU SLEEP MODE SELECTION

The sleep mode control application will execute the ($3 \times E$) scheme in a cooperative manner (i.e., considering a set of RU's conditions and constraints) thanks to the central RAN controller support.

The proposed ($3 \times E$) RU sleep mode selection scheme would dynamically update the association and sleep RUs set considering the latest network states; this result could be used within any particular scheduling time. In this work each cycle is performed under two separate loops, denoted as a certain and conditional RU sleeping loop. The high level view of the proposed ($3 \times E$) scheme is portrayed in Fig. 2.

Let us define $M_{\text{G-active}}$ as the set of RUs satisfying

$$\max(RSRP_j) > RSRP_{\text{thr}} \quad \text{or } \rho_j > \rho_{\text{th}} \tag{9}$$

[3]The RSRP is defined as "linear average over the power contributions (in Watts) of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth [29]".

where $\max(RSRP_j) = \max(P^j \left|h_{j,i}\right|^2)$, $i \in U_j$. $RSRP_{\text{thr}} = 5 \min(RSRP_j)$ and $\rho_{\text{th}} = 0.5\ N_T$ [23] represent network RSRP and load thresholds, respectively. The set $M_{\text{G-active}}$ satisfies that $\|M_{\text{G-active}}\|_0 = L$ ($\|.\|_0$ indicates the set cardinality). Given $M_{\text{G-active}}$, average ICR parameter $\overline{\lambda}$ can be obtained as

$$\overline{\lambda} = \frac{\sum_{j \in M_{\text{G-active}}} \lambda_j}{L}. \quad (10)$$

In the first stage, the certain RU sleeping loop determines the certain active mode RU and certain sleep mode RU sets, that is, the RUs that will surely be either active or put to sleep, respectively.

- **Certain Active Mode RU:** M_{active} set formed by each particular RU m satisfying

$$\lambda_m < \overline{\lambda}, \ m \in \mathcal{M}. \quad (11)$$

- **Certain Sleep Mode RU:** M_{sleep} set formed by each particular RU $m \notin M_{\text{G-active}}$ satisfying

$$\lambda_m > \overline{\lambda}. \quad (12)$$

Now, in a second stage, some RUs will be conditionally considered to be either active or asleep, as follows:

- **Conditional Sleep Mode RU:** In this loop, each particular RU $j \in M_{\text{G-active}}$, will be included in $M_{\text{active}}^{\text{temp}}$ set temporary if it satisfies that

$$\lambda_j > \overline{\lambda}. \quad (13)$$

Each RU $\in M_{\text{active}}^{\text{temp}}$ would be included in M_{active} set permanently if satisfying (14) and (15) conditions. Otherwise, it would be included in M_{sleep} set permanently.

$$\min(EE_j) > \min(EE_m), \ j \in M_{\text{active}}^{\text{temp}}, m \in M_{\text{active}}. \quad (14)$$

$$\frac{\sum_j R_j}{\sum_j P_{\text{Total}}^j} > \frac{\sum_m R_m}{\sum_m P_{\text{Total}}^m}, \ j \in M_{\text{active}}^{\text{temp}}, m \in M_{\text{active}}. \quad (15)$$

Algorithm 2 shows the details of the proposed $(3 \times E)$ RU sleep mode selection scheme. Separating the loops in order to have a conditional interference management, apart from a certain sleeping loop, would give the higher level of enhancement of network EE in the lower populated interfering scenarios. The conditional sleeping loop enhances the power saving and increases the transmission rate per energy unit, which is shown in the performance evaluation section. These efficient steps to enhance the EE (i.e., activation/deactivation process to separate loops and conditional interference management) are beyond the available reviewed works such as [22] and [23]. While satisfying constraint C2, the proposed $(3 \times E)$ RU sleep mode selection scheme is performed continuously (each iteration is denoted as switching cycle) along time in the cell-less network. This process updates the UE-RU association and the RU sets dynamically and based on the latest status of the RUs to reach a near optimal and network energy-efficient association. The entire flow diagram of the proposed algorithm is illustrated in Fig. 3.

In the proposed scheme, the maximum number of iterations required for the certain RU sleeping loop is $|\mathcal{M}|\,|\mathcal{K}|$ and the maximum number of iterations required for the conditional RU sleeping loop is $|\mathcal{M}|\,|\mathcal{K}|$. Therefore, the maximum

Algorithm 2: Proposed $(3 \times E)$ RU Sleep Mode Selection Scheme

```
Input  : A; R_{k_min}, k ∈ 𝒦; N_T; RSRP_j, ρ_j, j ∈ ℳ;
         RSRP_thr; ρ_th; M_G-active = [ ]; M_active = [ ];
         M_sleep = [ ]; β
Output: M_sleep; M_active; Updated A
1  Obtain Network baseline throughput R_Total^baseline =
   ∑_{j∈M} R_j^baseline by (2)
2  Calculate EE_Total by (6) using (2)
3  for each RU j ∈ ℳ set do
4      if RU j satisfies (9) then
5          M_G-active ← RU j
6      end if
7  end for
8  Calculate λ̄ by (10) given M_G-active
9  for each RU j ∈ ℳ set do
10     if RU j satisfies (11) then
11         M_active ← RU j
12     end if
13 end for
14 for each RU j ∉ M_G-active do
15     if RU j satisfies (12) then
16         M_sleep ← RU j
17     end if
18 end for
19 Find set of UEs not assigned to any RU j ∈ M_active as
   un-defined UE set 𝒦_UD
20 for each UE i ∈ 𝒦_UD and RU j ∈ M_active do
21     Repeat Algorithm 1
22     Update A
23 end for
24 for each RU j ∈ M_G-active do
25     if RU j satisfies (13) then
26         if RU j satisfies (14) and (15) then
27             M_active ← RU j
28         else
29             M_sleep ← RU j
30         end if
31     end if
32 end for
33 Update 𝒦_UD
34 Go to (Repeat step 19:23)
35 Calculate Network throughput R_Total = ∑_{j∈M_active} R_j
   by (2)
36 if R_Total ≥ (1- β) × R_Total^baseline then
37     Go to next switching cycle (Repeat step 2:35)
38 end if
```

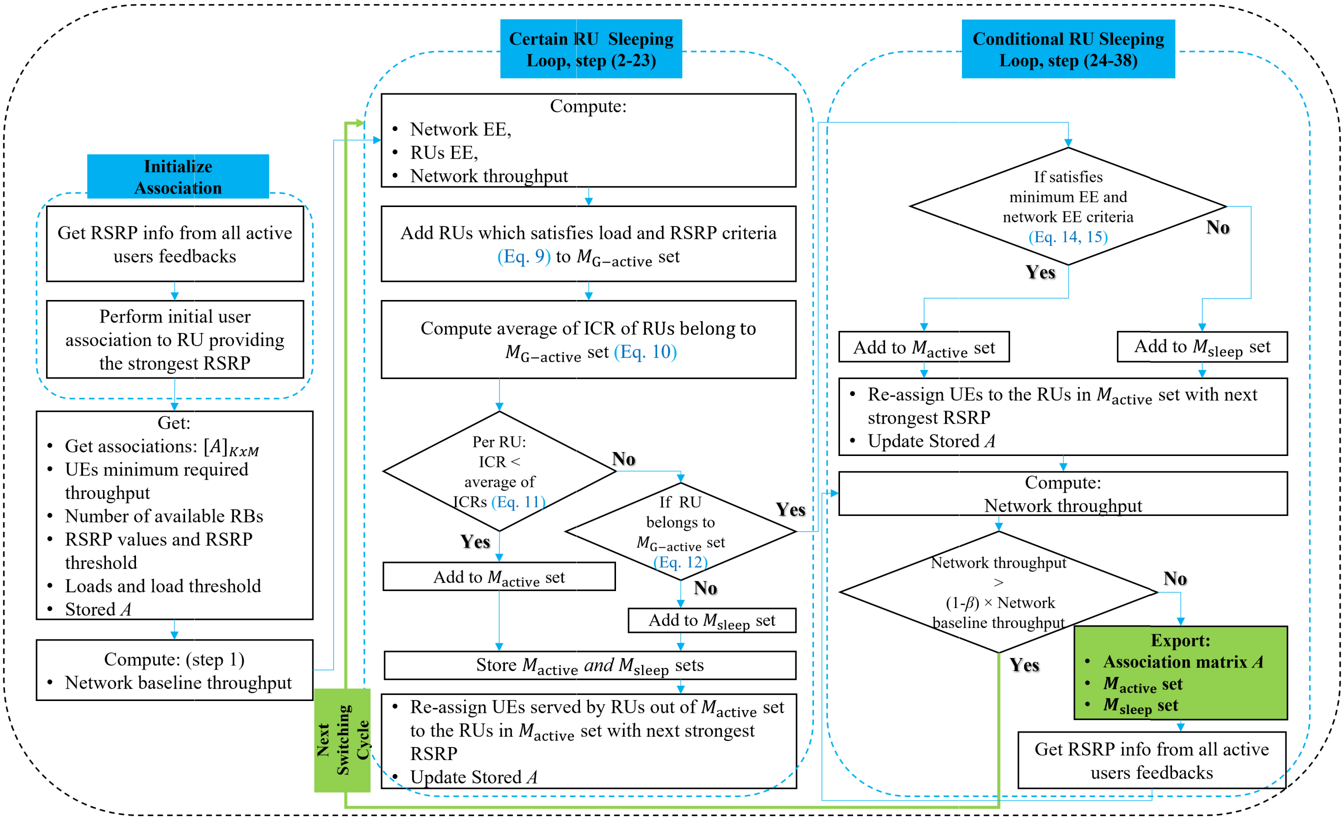

FIGURE 3. Flow diagram of the (3 × E) RU sleep mode selection scheme within cell-less RAN architecture.

number of iterations for **Algorithm 2** is $(2\,|\mathcal{M}|\,|\mathcal{K}|)$. Hence, the asymptotic complexity of our proposed algorithm is of $O(|\mathcal{M}|\,|\mathcal{K}|)$. Even though the computational complexity is not reported in [22] and [23], we found a linear complexity of the same order when implementing them.

IV. PERFORMANCE EVALUATION AND RESULT ANALYSIS

A. SIMULATION SCENARIOS AND PARAMETERS

In our simulation setup of a cell-less architecture, we assume a hexagonal network topology with 150 m inter site distance (ISD), with 20 MHz bandwidth over a carrier frequency of 4 GHz. In addition, we also consider a Voronoi RU deployment scenario for the results shown in Fig. 5, where the locations of RUs follow a Poisson point distribution with the same minimum distance of RUs as in the hexagonal topology scenario. This scenario is used for the sake of comparison, to check whether the RU distribution has an impact on the performance. All other simulation parameters remain the same for both hexagonal and Voronoi topology. RU height is 3 m and UE height is 1.5 m. The RU and UE antenna gains are assumed to be 5 dB and 0 dB respectively. The required UE throughput is considered as 1 Mbps for all users. The UEs are randomly deployed over the entire network. We consider the power consumption parameters from [28] to calculate EE. The maximum transmit power for RU m is set as 0.13 W, with setting 6.8 W and 4.3 W for the circuit power in active and sleep mode respectively. The channel model is implemented based on a simplified version from the defined model in Annex 1 in [30] mapped with the Indoor Hotspot-eMBB test environment, and the path-loss models used in simulations are from Table A1-2 in Annex 1 in [30],

$$PL_{\text{InH-Los}} = 16.9\log_{10}(d_{3D}) + 32.8 + 20\log_{10}(f_c) \quad (16)$$

$$PL_{\text{InH-NLos}} = 43.3\log_{10}(d_{3D}) + 11.5 + 20\log_{10}(f_c) \quad (17)$$

where d_{3D} is the distance between the transmitter and receiver in meters and f_c is carrier frequency in GHz. Other related configurations are aligned with the system-level simulation parameters in [30].

B. SIMULATION RESULTS AND ANALYSIS

In this section, we evaluate the following schemes and compare their performances:

- Baseline Algorithm: This performs the best cell (strongest link) UE-RU association without any sleep mode scheme.
- EE Algorithm - Reference: The sleeping scheme is based on [23].
- EE Algorithm - Non-conditional (3 × E) scheme: This sleeping scheme performs as described in III-B, while it will not check the conditions (14) and (15). The candidate RUs of the conditional loop entirely would be

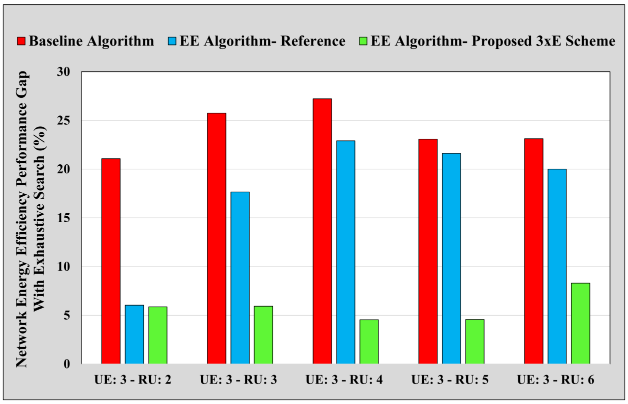

FIGURE 4. Network EE gap with respect to Exhaustive Search.

included in M_{sleep} set. The switching cycle is executed only once per TTI.

- EE Algorithm - Conditional $(3 \times E)$ scheme: This is the scheme as described in III-B with a switching cycle executed only once per TTI.
- EE Algorithm - Proposed $(3 \times E)$ scheme: This is the proposed scheme as described in III-B. The algorithm switching cycle will be continued while satisfying C2 from (7), where we have configured $\beta = 4\%$.

Figure 4 depicts the gap in the obtained network EE between the proposed $(3 \times E)$ RU sleep mode selection or the benchmark schemes and the exhaustive search algorithm. As exhaustive search is a time consuming and complex technique to achieve the optimal solution, the simulation is performed in small scale scenarios for up to 6 RUs serving 3 UEs. To have a fair comparison, C2 and C6 constraints are excluded from all the implemented schemes in this simulation.

For the very small scale scenario of 2 RUs and 3 UEs, as there is only the possibility of sleeping 1 RU, no performance difference is observed between the reference algorithm and our proposal scheme. This performance enhancement for the proposed $(3 \times E)$ RU sleep mode selection scheme is more noticeable in higher RU scale scenarios that provide more options of sleeping mode candidate RUs. Simulation results show that the proposed scheme achieves the lowest network EE performance gap with respect to exhaustive search with an average gap around 6%. The baseline algorithm without any sleep mode scheme has the highest gap and the reference algorithm is achieving lower performance than the proposed one. It is important to remark that these results correspond to simplified scenarios where the exhaustive search is feasible, while the performance of the proposed scheme improves in larger scenarios, as discussed. Then, it is foreseen that this gap would be even lower for a higher number of RUs, although it cannot be practically estimated.

The conditional RU sleeping loop benefit is illustrated in Fig. 5 with Voronoi RU deployment and Fig. 6 with hexagonal RU deployment that shows the cumulative distribution

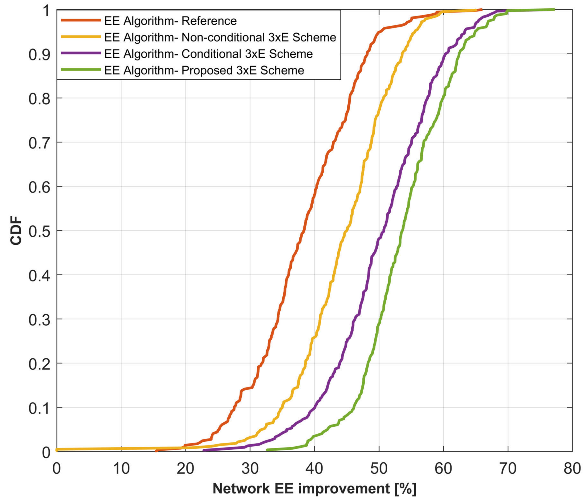

FIGURE 5. Network EE improvement over baseline with Voronoi RU deployment.

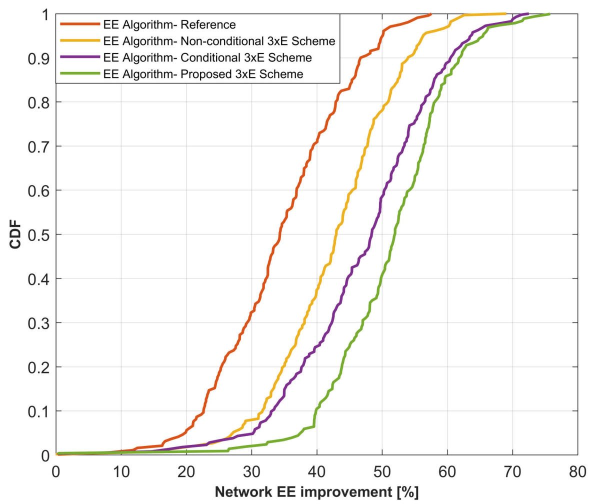

FIGURE 6. Network EE improvement over baseline with hexagonal RU deployment.

function (CDF) of network EE enhancement of different options for 150 RUs and 150 UEs. The Voronoi deployment has been implemented just to have an initial comparison with a random deployment of RUs. However, it is shown that the performance of the algorithms is similar with both deployments. Therefore, the rest of the analysis has been done for the hexagonal deployment to consider a uniform deployment within the cell-less RAN architecture, aligned with a cellular network topology. The figures (Fig. 5 and Fig. 6) show the benefit of conditional interference management in interfering scenarios with lower population of UEs. In such scenarios, low loaded RUs with high λ_m(interference contribution ratio) will be prevented from being active through a certain loop. However, highly loaded RUs with high λ_m that are not energy efficient will also be made sleep through the conditional loop. In this case, due to the lower user densification, a lower number of RUs with low load will have high λ_m in order to

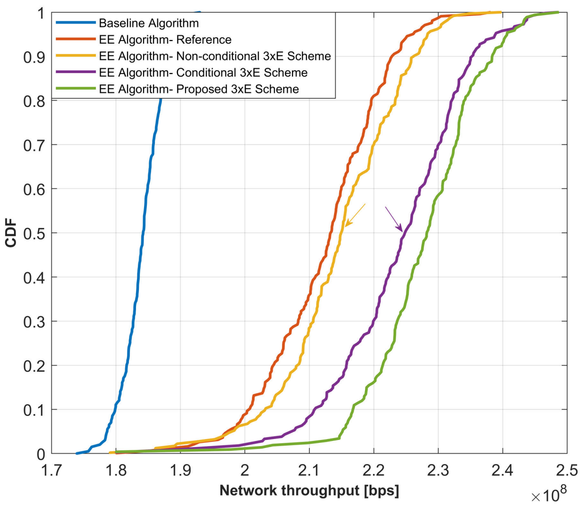

FIGURE 7. Network throughput with 150 RUs and 150 UEs.

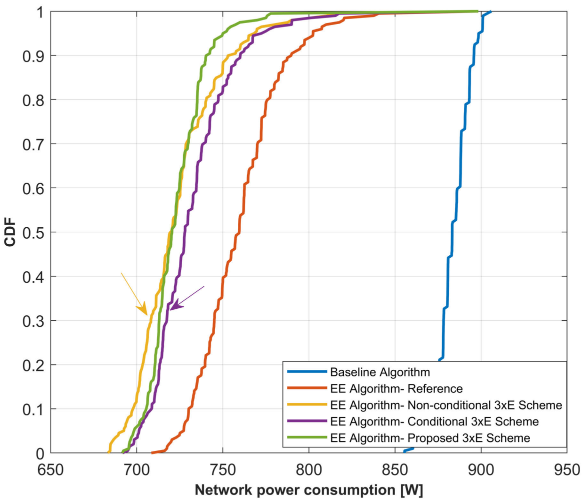

FIGURE 8. Network power consumption with 150 RUs and 150 UEs.

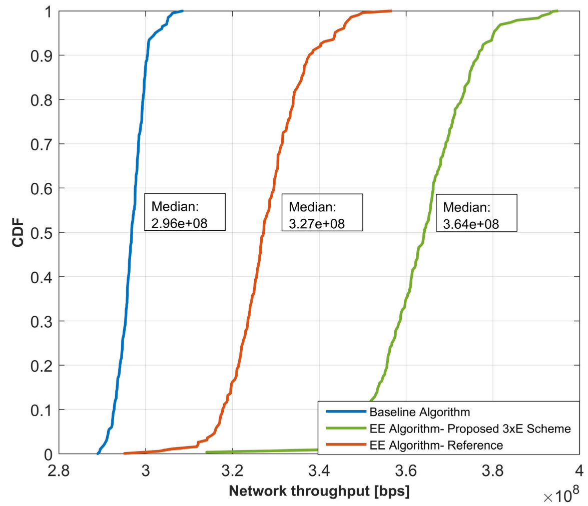

FIGURE 9. Network throughput with 150 RUs and 250 UEs.

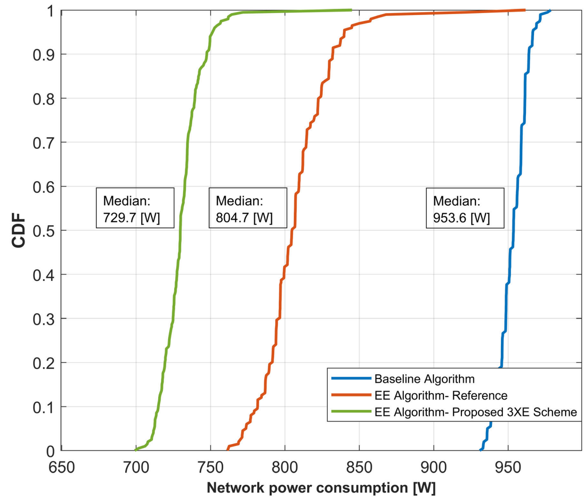

FIGURE 10. Network power consumption with 150 RUs and 250 UEs.

enter the certain loop. Therefore, the conditional loop will make the remaining higher loaded RUs sleep depending on their impact on the network and minimum individual EE performance. Fig. 7 shows that the conditional and proposed $(3 \times E)$ schemes provide a higher amount of transmitted bits and network throughput compared to the reference algorithm and the non-conditional scheme. As it is shown in Fig. 8, the non-conditional scheme has lower power consumption due to placing more RUs in sleep mode as compared to the conditional scheme. However, some of the slept RUs may have been efficient in terms of transmitted bits per energy unit. Therefore, reconsidering RUs from the $M_{\text{G-active}}$ set for sleep mode through a conditional scheme will assure an EE gain as compared to the non-conditional scheme in low loaded scenarios, as shown in Fig. 6.

The remaining simulations are performed for 150 RUs and 250 UEs to analyze more general scenarios reflecting dense networks. Fig. 9 presents the simulation results for network throughput. The proposed $(3 \times E)$ algorithm outperforms [23] and the baseline algorithm within the dense cell-less network. The interference management considerations within proposed loops and traffic loss control support the network throughput enhancement, compared with the conventional scheme. The total power consumed by all the RUs is shown in Fig. 10. Considering the applied proposed certain sleep loop to make inefficient RUs sleep, in addition to strict control over the RUs in terms of energy efficiency which do not violate all the criteria, will not let any power wasting RU stay active through the conditional loop. This is the reason why the proposed scheme shows the lowest consumed power compared with the other three algorithms. The CDF of the network EE improvement is shown in Fig. 11. It is observed that the expected performance enhancement was satisfied thanks to the network throughput improvement and saving the power consumption through certain and condition sleeping RU loops. There is an improvement over the baseline algorithm in the order of 60%, almost doubling the EE enhancement with respect to existing competing alternatives.

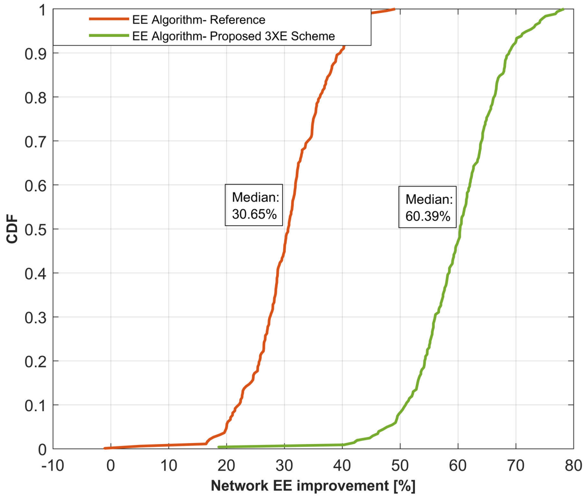

FIGURE 11. Network EE improvement over baseline with 150 RUs and 250 UEs.

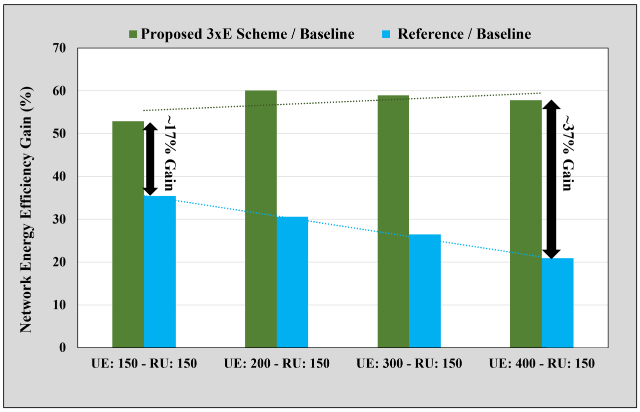

FIGURE 12. Network EE sensitivity to UE densification with 150 RUs.

To analyze the sensitivity of our proposed scheme to UE densification, we have simulated the schemes with an increased number of UEs and a fixed number of 150 RUs. The obtained network EE gain of the proposed $(3 \times E)$ RU sleep mode selection and the reference algorithm over the baseline algorithm are plotted in Fig. 12. The UE densification increment will increase the load of the RUs and reduce the interference ratio per RU. The number of RUs meeting the criterion to enter the sleep mode will be decreased due to the high load in the RUs. Hence, the energy saving will be smaller. Therefore, the reference algorithm will have a significant EE performance degradation in user-densified scenarios because of its main criteria based on the RUs load. On the other hand, having a lower interference contribution ratio will cause lower interference in the network and, therefore, higher throughput will be achieved. In high user-densification scales, our proposed scheme will gain in EE performance thanks to the certain loop criteria based on the interference contribution of low loaded RUs. This is in addition to making highly loaded and non-energy efficient RUs sleep through a conditional loop. Therefore, the proposed $(3 \times E)$ scheme

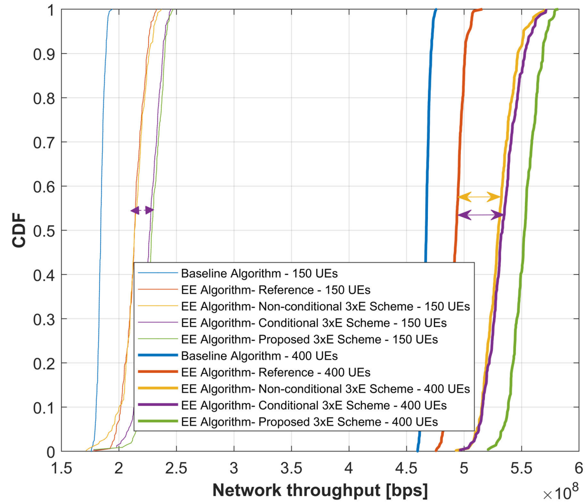

FIGURE 13. Network throughput sensitivity to UE densification with 150 RUs.

has a higher performance gain with respect to the reference algorithm, more than 35% within the more populated area. It shows that our proposed scheme manages interference in the network even in the densely populated scenarios, while the conditional sleeping RU loop will take care of the performance dependency on the densification intensity. Thus, it avoids the performance degradation in low-loaded environments. The stability of the performance of the proposed $(3 \times E)$ to the user densification as compared to the reference scheme is shown in Fig. 12.

Fig. 13 shows how the conditional loop avoids a throughput degradation in a low-load network as compared to the non-conditional $(3 \times E)$ scheme. In contrast, in a highly densified scale, such as 400 UEs in our simulation setup, the conditional loop does not add any advantage, while the performance is maintained. Thanks to these facts, the network will keep running in an energy-efficient way for different scales in a very stable manner. These attributes prove the stability of our proposed approach regarding EE.

V. CONCLUSION

In this paper, we propose an energy efficient sleep mode scheme $(3 \times E)$ that carefully selects and makes inefficient RUs sleep to enhance the EE of a cell-less RAN architecture in 5G and beyond 5G networks. The proposed scheme approaches EE optimization by increasing the transmission rate per energy unit by means of energy saving (instead of a mere power consumption minimization approach). To ensure a stable performance enhancement in networks with a higher user density, as well as in scenarios with lower density of users, the interference contribution of each RU is considered within the proposed criteria. The $(3 \times E)$ scheme manages the interference through the two-step sleeping loop in a way that not only it enhances the network EE, but it also ensures that the minimum EE of active RUs is not being degraded as an additional constraint. Considering the network EE as the main objective function, we make a conditional sleeping loop for RUs to guarantee the EE enhancement. The conditional interference mitigation in our proposal would control the lower populated networks' EE even if the distributed load within RUs is temporarily meeting the configuration thresholds. Simulation results have shown that the proposed scheme provides a significant advantage (up to 60%) over several competing alternatives not only in low-load scenarios, but also in highly-loaded ones. It is worth to note that our proposal adds a performance improvement as compared to the reference algorithms in scenarios with higher density of users. In contrast to previous works that did not address the performance stability of sleep mode schemes in peak-traffic hours, $(3 \times E)$ scheme provides a stable enhancement against various loads and interference due to the increment of the number of UEs in the network within the same topology. The current findings add substantially to our understanding of network EE regardless of user density variations and the load of 5G and beyond 5G networks. Further works will consider other KPIs (e.g., reliability and latency) for enhancing the cell-less network performance as a strong solution for the open RAN specific EE targets.

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