RNP-SA: Joint Relay Placement and Sub-Carrier Allocation in Wireless Communication Networks with Sustainable Energy

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***Abstract*—Green energy is emerging as a promising alternative energy source to power network devices in next-generation wireless networks. Different from traditional energy, green energy is replenished from nature, e.g., solar and wind, and is highly dependent on the capacities and locations of the electronic devices. As such, the fundamental design criterion in the network deployment and management is shifted from energy efficiency to energy sustainability due to the sustainable nature of green energy. In this paper, we study the network resource management issues in next-generation wireless networks with sustainable energy supply. Our objective is to deploy the minimal number of green RNs, i.e., RNs powered by green energy, and optimize resource allocation to ensure full network connectivity and users' Quality of Service (QoS) requirements can be fulfilled with the harvested energy based on the cost threshold. To this end, the RN placement and sub-carrier allocation (RNP-SA) issues are jointly formulated into a mixed integer non-linear programming problem. Two low-complexity heuristic algorithms, namely RNP-SA with top-down/bottom-up algorithms (RNP-SA-t/b), are presented to solve the non-linear programming problem in different network scenarios. Extensive simulations show that the proposed algorithms provide simple yet efficient solutions and offer important guidelines on network deployment and resource management in a green radio network with sustainable energy sources.**

***Index Terms*—Wireless communication networks, sustainable energy, relay node placement, sub-carrier allocation.**

I. Introduction

WIRELESS communication has become an indispensable part in our daily lives, which allows us to exchange information and access to ubiquitous multimedia services from anywhere at any time. The growing user demands and the expansion of wireless communications have led to a tremendous growth of energy consumption in wireless access. With the increasing concern on environmental protection and the preservation of natural resources, constructing green wireless networks has become a critical issue in the design and deployment of next-generation radio communication networks. Recent advances in green energy technology make it possible to use alternative energy sources, e.g., solar, wind, etc., to power wireless network devices, including base stations (BSs) and relay nodes (RNs), and to achieve a sustainable green radio communication network. However, unlike traditional energy sources, green energy is variable in its capacity and is highly dependent on the location and weather, which makes it a challenging task to exploit green energy sources in the deployment and management of a green network.

Energy efficiency is one of the utmost issues in wireless communications. Based on network planning and resource allocation, some works focus on minimizing energy consumption with traditional energy sources. In [1], BSs placement and optimal power allocation were investigated to minimize the energy consumption of a cellular network. In [2], the deployment of a single frequency network was proposed with energy efficiency as the objective function, i.e., low carbon emissions and exposure. With the development of environmental sound technologies, green energy has become a promising alternative energy source to power wireless communication networks. Different from conventional network, for network devices powered by green energy, the most critical issue is how to ensure energy sustainability, i.e., the charged energy can sustain the traffic demands of network users. In [3], multi-hop radio networks powered by renewable energy sources were considered. The work formulated the problem as an integrated admission control and routing framework, and then proposed routing algorithms to achieve high performance by utilizing the available energy sources. These works studied either network planning or resource allocation to improve network sustainability with green energy sources as the first step. We envision network planning and resource allocation as two tightly related issues that have mutual impact on each other to achieve long term energy sustainability. In this paper, we jointly address the network planning and resource allocation problems in a wireless network with renewable energy, taking into account the bandwidth, cost and energy sustainability constraints.

In specific, we study the relay node placement and sub-carrier allocation problem in green wireless networks, where the BSs and RNs are powered by renewable energy. A realistic two-tiered network scenario is considered, in which green BSs are *a priori* deployed and a set of candidate locations are provided to place green RNs. We aim at minimizing the number of RNs and allocating appropriate numbers of sub-

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carriers to each BS and RN, such that the network can be fully connected and the QoS requirements of users can be fulfilled by the harvested energy along with the allocated sub-carriers based on the cost threshold. The joint RN placement and sub-carrier allocation (RNP-SA) problem is formulated as a mixed-integer non-linear programming (MINLP) problem. As MINLP is NP-hard in general, we focus on designing effective heuristic algorithms and propose two low-complexity yet efficient algorithms, namely, RNP-SA with top-down/bottom-up algorithms (RNP-SA-t/b). A novel metric, referred to as Sub-carrier and Traffic over Rate (STR), is introduced, which characterizes the throughput and energy demand of each user associated with a RN or BS. Based on the STR, candidate locations are selected iteratively and then users are connected to the deployed RNs until any of the cost threshold, energy sustainability constraint or the bandwidth requirement of users cannot be satisfied. By allowing each RN to serve as many users as possible, the minimal number of RNs can be obtained to fulfill the network traffic demand.

The remainder of the paper is organized as follows. Related work is presented in Sec. II. The system model of a two-tiered wireless network with sustainable energy is described in Sec. III. Based on the system model, a joint RN placement and sub-carrier allocation problem is formulated as an MINLP problem in Sec. IV. Two heuristic algorithms are proposed in Sec. V. The performance of our algorithms is compared with that of a greedy algorithm in different network scenarios in Sec. VI, followed by conclusions in Sec. VII.

II. Related Work

Network planning and resource management with traditional energy sources have been well studied in the context of different communication networks, including cellular networks, IEEE 802.16 WiMAX, and sensor networks [1], [4], [5]. Such kind of works are typically modeled as optimization problems to maximize the network performance [6], [7] or to minimize the network deployment and/or operation cost [1], [4], [8]. Usually, network planning problem focuses on finding the optimal locations of the minimal number of nodes, i.e., BSs, RNs, and APs, under the network connectivity, throughput, and/or energy consumption constraints. According to the geographic scenarios, the placement problem can be categorized into continuous or discrete one. In the continuous problem, where no restriction is applied to the locations of the placement [9], [10], the traditional optimization algorithms, e.g., direct search and quasi-Newton methods [11] can be used to solve the optimization problem. In reality, nodes usually can only be placed at some candidate locations due to the geographical constraint. Thus, many works [1], [4], [7], [8], [12] focus on discrete problem. In [12], a relay node placement problem was investigated considering the physical constraints of sensor nodes. In [8], how to place the minimal number of APs was studied under the physical and protocol interference models; and it was found that the underlying interference models have a significant effect on the AP placement problem. In [1], the optimization of the number of base stations and their locations was investigated in order to minimize the energy consumption of a cellular network, considering a practical case of non-uniform user distributions.

On the other hand, it is recognized that efficient resource management, e.g., sub-carrier allocation, power control, scheduling, etc., [13]–[16], can significantly improve the resource utilization. In [17], a clustering algorithm and a tax-based sub-carrier allocation scheme were proposed for wireless mesh networks to achieve Pareto optimal resource allocation. Some recent works found that network planning coupled with resource allocation can further improve the network performance. In [6], AP placement and channel allocation were jointly studied to achieve the maximal network throughput and maintain good fairness in radio resource sharing among multiple wireless users. In [18], RN placement and radio resource re-use strategies were investigated for a multi-hop relay network to improve both per-user throughput and network throughput. All these works are based on conventional communication networks.

Recent advances in green energy technologies provide a feasible and sustainable solution for green-energy-powered wireless communication networks [19]. So far, there are only a few works on the network planning and resource management in wireless networks with renewable green energy, considering the sustainability performance of the network. Generally, most previous works focus on network outage mitigation and cost minimization. In [20], a statistical power saving mechanism and a control algorithm were proposed to maintain outage-free operations of the node match based on the future load conditions and solar insolation. In [21], the solar panel size of the BSs or APs were studied to mitigate the network outage by using the minimal cost of energy according to the recorded historical solar insolation traces. Some works aim at ensuring the sustainability of the network by using the minimal cost. In [22], the classic minimum AP placement problem was revisited under the energy sustainability and users' QoS constraints. In [23], a resource management scheme was proposed to distribute the traffic load across the network according to the dynamic energy charging and discharging processes in green wireless communication networks. For networks powered by green energy sources, the bandwidth and charged energy are the two main resources that should be efficiently utilized. As the charging capacity varies in different locations and devices, we need to balance the bandwidth allocation with the variable charging capacities of APs and RNs. In this paper, we jointly investigate the network placement and resource management and study the relationship between them.

III. System Model

We consider a two-tiered wireless network composed of multiple BSs, RNs, and wireless users, as shown in Fig. 1. The network architecture is motivated by the explosive growth of the network density and traffic intensity, which requires the deployment of extra RNs in the existing cellular network infrastructure to improve the network capacity and QoS provisioning capabilities. In the existing cellular network, BSs have been *a priori* installed while a given number of RNs can be deployed on a set of candidate locations. By employing solar panels or wind turbines, BSs and RNs can harvest energy from the environment while wireless users use traditional power sources, e.g., battery, to power their personal devices due to the hardware and cost constraints. As green energy sources

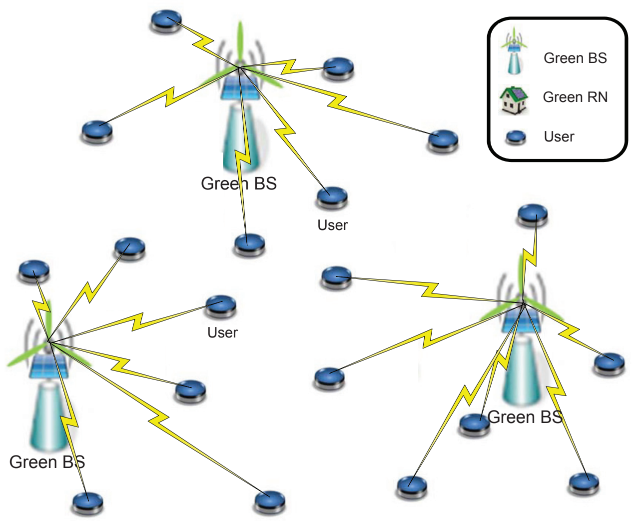


Fig. 1: Two-tiered network architecture.

are inherently variable and dependent on the locations and weather, green BSs and RNs, i.e., the BSs and RNs powered by green energy sources, distributed at different locations have various charging capabilities. Such kind of network scenario is common in real life. For example, we consider a community with several BSs powered by green energy. Each building is a user and has people work or live in it, and RNs can be installed on the roof of the buildings that are marked as candidate locations. The traffic demand of each user and solar insolation or wind speed level of BSs or candidate locations can be obtained from the historical statistics.

In the two-tiered wireless network, each RN is associated with a BS, while each user can be served by either a BS or a RN. When a user connects to a RN, the RN needs to relay the user's traffic to a BS; and the BS forwards the traffic to the user's destination cell through the wired backbone network. Therefore, a two-hop transmission is involved when a user is associated with a RN; while a direct link transmission is used when a user is connected to a BS. All nodes in the network share a set of sub-carriers, denoted as S. A sub-carrier can be re-used by users in the space domain if and only if the sub-carriers occupied by users are sufficiently far away from each other, and thus cause negligible interference to each other. As users with different traffic demands are distributed over the network, and different candidate locations provide different charging capacities, it is essential to appropriately select locations of RNs and allocate a proper set of sub-carriers to RNs based on the energy charging capacity and user demands so that the allocated bandwidth can be fully utilized by a node without energy outage.

We build a network communication graph $G(V = U \cup R \cup B; E)$ to model the network topology, where V is the total set of nodes, i.e., BSs, RNs, and users, E is the set of communication links between any two nodes, and U, R, B are the set of users, RNs, and BSs, respectively. Let D_{xy} denote the distance between a pair of nodes, x and y, and P_x^T denote the transmission power of node x. The received signal to noise ratio of link (x, y), called SNR_{xy}, is given by

$$SNR_{xy} = \frac{P_x^T \cdot D_{xy}^{-\alpha}}{N}, \tag{1}$$

where α is the path loss exponent, and N is the background noise. Let c_{xy} denote the achievable data rate of link (x, y), then we have

$$c_{xy} = |S_{xy}| W \log_2 (1 + SNR_{xy}), \tag{2}$$

where W is the sub-carrier bandwidth. S_{xy} represents the set of sub-carriers allocated to link (x, y), and $|S_{xy}|$ is the number of allocated sub-carriers. The set of sub-carriers allocated for each link can be expressed as

$$\begin{cases} S_{xy} = \begin{pmatrix} s_1 \\ s_2 \\ \vdots \\ s_m \end{pmatrix}, \forall (x, y) \in E \\ m = |S_{total}| \\ s_i \in \{0, 1\}, \end{cases} \tag{3}$$

where $s_i = 1$ represents that sub-carrier s_i is allocated to link (x, y), and $s_i = 0$ otherwise.

We allocate sub-carriers to each BS and RN so that users associated with the BS/RN can use the same set of sub-carriers to communicate with its BS/RN. x is in the interference range of y if the received signal strength of x from y, SNR_{yx}, exceeds a threshold θ, i.e.,

$$SNR_{yx} \geq \theta. \tag{4}$$

We define an interference collision set of node y, which is the set of nodes within the interference range of y, denoted by I_y. Nodes within the same interference collision set are not allowed to transmit at the same time.

IV. Problem Formulation

Our RNP-SA problem focuses on placing the minimal number of RNs into the network and allocating an appropriate number of sub-carriers to each BS/RN to provide full coverage, i.e., any user in the network is served by either a BS or a RN, and users' throughput requirements can be fulfilled by the harvested energy along with the allocated sub-carriers based on the cost threshold. Generally, RNs are required when the charging capacities of the BSs cannot sustain the traffic demands of users. By cooperating with RNs, some users can achieve a higher throughput, and reduce the energy consumption at the BSs. With more allocated sub-carriers, a higher throughput can be achieved at the cost of higher energy consumption over a wider spectrum band. Due to the limited charging capabilities of green BSs/RNs, the number of allocated sub-carriers should be jointly determined by the users' traffic demands and the charging capacities of the BSs/RNs. This is because, for a BS/RN with a low energy level, allocating a large number of sub-carriers will drain out its energy quickly and cause the green BS/RN to be temporarily out of service, which degrades the utilization efficiency of the spectrum band and is not desirable. Therefore,

TABLE I: Notation for Problem Formulation

U	Set of users
R	Set of relay nodes
B	Set of base stations
β_{xy}	Achieved flow throughput from node x to y
β'_{xy}	User's throughput requirement
$\mathcal{E}_x^-$	Consumed energy of node x during a unit time
$\mathcal{E}_x^+$	Harvested energy of node x during a unit time
e_{xy}	Connection status between node x and y

it is very important to carefully formulate a joint optimization problem to achieve satisfactory sustainability performance.

We study the RNP-SA problem for a given set of users (U), a set of existing BSs (B), the charging capacity of each BS, the expected charging capacities of RNs at various candidate locations, the throughput requirement of each user, the cost threshold and the available set of sub-carriers. We formulate RNP-SA as an MINLP problem as follows,

$$\begin{array}{lll} Minimize & |R| & \\ Subject\ to: & \sum_{x\in R\cup B} e_{ux}=1, & \forall u\in U \\ & \sum_{b\in B} e_{rb}=1, & \forall r\in R \\ & \beta_{ux}\geq \beta'_{ux}, & \forall e_{ux}=1 \\ & \mathcal{E}_x^+\geq \mathcal{E}_x^- & \forall x\in R\cup B \\ & |R|\leq |R'| & \\ & e_{xy}\in\{0,1\}, & \forall x,y\in V \end{array} \tag{5}$$

The notations are described in Table I. The first and second constraints indicate that each user should be served by one BS or RN, and each RN should be connected to one BS. The third constraint indicates that the achieved flow throughput from node x to y, β_{xy}, should be greater than user's throughput requirement, β'_{xy}. The fourth constraint ensures the energy sustainability of node x such that the harvested energy, $\mathcal{E}_x^+$, should be able to sustain user traffic demands, $\mathcal{E}_x^-$. The fifth constraint guarantees that the cost of deployed RNs should not be over the determined cost threshold. Finally, we define $e_{xy}=1$ for node x to be associated with node y, and $e_{xy}=0$ otherwise.

A. QoS and Energy Sustainability Constraints

In this subsection, we further specify the energy constraint and throughput requirement defined in (5). Denote t_{xy} as the active time of link (x,y) during a unit time. For all two-hop uplink transmissions, e.g., from users to BSs via RNs, the input traffic of RNs should be equal to its output traffic, which is given by

$$\sum_{u\in U}(e_{ur}c_{ur}t_{ur})=\sum_{b\in B}e_{rb}c_{rb}t_{rb},\forall r\in R. \tag{6}$$

Let γ_u^{up}, γ_u^{dn} be the uplink and downlink throughput of user u, respectively. To meet the uplink throughput requirements of users, we have

$$\sum_{r\in R}e_{ur}c_{ur}t_{ur}+\sum_{b\in B}e_{ub}c_{ub}t_{ub}\geq \gamma_u^{up},\forall u\in U. \tag{7}$$

The first term on the left hand side (LHS) of (7) is the achieved uplink throughput of user u if the user is connected to a RN for $e_{ur}=1$ and $e_{ub}=0$; The second term on the LHS is the achieved user throughput if the user is connected to a BS for $e_{ub}=1$ and $e_{ur}=0$.

Similarly, the input traffic of RNs should be equal to its output traffic in the downlink, and we have

$$\sum_{u\in U}(e_{ru}c_{ru}t_{ru})=\sum_{b\in B}e_{br}c_{br}t_{br},\forall r\in R. \tag{8}$$

To meet the downlink throughput requirement of users, we need to ensure

$$\sum_{r\in R}e_{ru}c_{ru}t_{ru}+\sum_{b\in B}e_{bu}c_{bu}t_{bu}\geq \gamma_u^{dn},\forall u\in U. \tag{9}$$

Suppose the average energy charging rate of node x is P_x^+. Denote P_x^R as the power consumption of user x to receive and decode the signal. In order to satisfy the energy sustainability constraint, the charged energy should be greater than the energy required for transmitting and receiving the traffic to and from other nodes,

$$P_x^+\geq P_x^T\sum_{(x,y)\in E}t_{xy}+P_x^R\sum_{(y,x)\in E}t_{yx},\forall x\in R\cup B. \tag{10}$$

Finally, to avoid harmful interference from concurrent transmissions, users in one interference collision set should transmit in different time slots. Let I_x denote the interference collision set of node x and $T_I(x)$ be the active time of the allocated sub-carriers of user x, we have

$$T_I(x)=\sum_{y\in I_x}\sum_{z\in V}(t_{yz}S_{yz}+t_{zy}S_{zy})\leq 1,\forall x\in V. \tag{11}$$

The equation indicates that the total active time of all links associated within the same interference collision set should not exceed a unit time.

V. RNP-SA Algorithms

The formulated RNP-SA problem is NP-hard, because a subproblem of RNP-SA, the RNP problem, is a well-known NP-hard problem, as proved in [24], and there is no efficient polynomial time solution to address it. In this paper, we resort to efficient heuristic algorithms for the RNP-SA problem. To this end, we first study the key parameters that affect the throughput and energy constraints. By placing a RN close to a BS, there may be little throughput gain for a user to transmit to the BS via the RN, but the energy consumption of the BS can be significantly reduced as the BS only communicates with the RN. By deploying a RN in a candidate location with high traffic load but far away from the BS, there may be little energy saving as the communication distance of BS and RN is long, but throughput requirements of users can be fulfilled as users can communicate with a close RN at a high data rate. Thus, to efficiently deploy green RNs, we need to well balance the throughput gain and energy consumption of BSs. By jointly considering the energy and bandwidth requirements, we design a novel link metric, referred to as the Sub-carrier and Traffic over Rate (STR). Based on the STR metric, we propose two low-complexity heuristic algorithms, namely, RNP-SA with top-down/bottom-up algorithms (RNP-SA-t/b).

The overview of our algorithms is introduced in subsection V-A. After that, we present the design of link metric which is used for choosing relay locations and connecting users in subsection V-B. The details of RNP-SA-t/b algorithms are described in subsection V-C and V-D. Finally, the time complexity of the proposed RNP-SA-t/b algorithms is analyzed in subsection V-E.

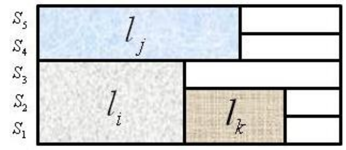
A. Algorithms overview

The objective of RNP-SA is to find the minimal number of RNs to fulfill the users' demands under the energy sustainability and cost constraints. In order to meet the throughput requirement of users, an intuitive method is to place RNs to the candidate locations with the heaviest traffic load. However, under this strategy, it is possible that some candidate locations far away from BSs are selected for RNs. In this case, the deployed RNs may not be able to efficiently relieve the energy demands at BSs, as BSs still need to communicate with faraway nodes. On the other side, to guarantee the energy sustainability of BSs, another intuitive method is to place RNs close to the BSs. Nevertheless, under this strategy, wireless users communicating with the RN may achieve similar one hop throughput as with BS, but need an extra hop transmission from RN to BS. This implies that wireless users may not be able to achieve a higher throughput by cooperating with RNs, and more RNs may be required to fulfill the traffic demands, which may lead to violation of cost threshold. Thus motivated, we design a link metric, i.e., STR, which characterizes the throughput and energy demand of each user associated with a RN or BS, and thus strikes a balance between the energy consumption and users' throughput for placing RNs in the network.

Based on the proposed metric, we then propose two heuristic algorithms to deploy the minimal number of RNs with top-down and bottom-up algorithms. In the top-down algorithm, we first place RNs in all candidate locations. All links (e.g., links between users and RNs, users and BSs, and RNs and BSs) are established in an ascending order of STR until the RNs' charging capabilities cannot sustain the users' traffic demands. We calculate the least number of sub-carriers required for meeting users' throughput demands and allocate them to users. We then delete RNs one by one based on the STR of links until any of cost, energy or throughput constraints can not be guaranteed. In the bottom-up algorithm, we first connect each user to the closest BS and calculate the least number of required sub-carriers. We check whether the current placement is a feasible solution or not, i.e., all of the cost, energy and QoS constraints can be satisfied. If not feasible, we place one more RN on a candidate location and add users to the RN according to their STR values until constraints can not be held.

B. Sub-carrier and Traffic over Rate

To solve the RNP-SA problem, the foremost issue is to decide where to place the RNs and how to establish connections between users and RNs or BSs. Since our objective focuses on minimizing the number of RNs, we let each RN partake in serving as many users as possible to relief the BSs' burden of energy and traffic demands. Since decoupling the energy and QoS constraints may not lead to an effective solution, we propose a metric that jointly considers energy consumption



(a) Top-down sub-carrier allocation

(b) Bottom-up sub-carrier allocation

Fig. 2: Top-down and bottom-up sub-carrier allocation.

and user's throughput requirement. Let γ_u be the summation of γ_u^{up} and γ_u^{dn}. The definition of our metric is given as follows:

Definition Sub-carrier and Traffic over Rate of link (u, x) or (r, b):

$$\begin{cases} STR_{ux} = \frac{|S_{ux}|\gamma_u}{c_{ux}}, \forall u \in U, x \in B \cup R \\ STR_{rb} = \frac{|S_{rb}|\sum_{u\in\{u|(u,r)\in E\}}\gamma_u}{c_{rb}}, \forall r \in R, b \in B. \end{cases} \tag{12}$$

Combining (12) with (2), we can derive STR metric as

$$\begin{cases} STR_{ux} = \frac{\gamma_u}{W\log_2(1+SNR_{ux})}, \forall u \in U, x \in B \cup R \\ STR_{rb} = \frac{\sum_{u\in\{u|(u,r)\in E\}}\gamma_u}{W\log_2(1+SNR_{rb})}, \forall r \in R, b \in B. \end{cases} \tag{13}$$

STR is the quotient of users' throughput requirements and achievable throughput of the link with a single subcarrier, which represents the minimal required active time for data transmission. A link with a smaller STR implies that this link consumes less energy and/or achieves a higher rate compared with other links using the same number of sub-carriers.

C. RNP-SA with top-down algorithm

The notations used in both algorithms are tabulated in Table II, and the detail of our RNP-SA-t algorithm is shown in Algorithm 1. Initially, RNs are deployed on each candidate location. We first connect each user to a RN or BS with the minimum STR, and then connect each RN to the BS with the minimum STR. Given that the total active time of all connected links, which are in the same interference collision set, should be smaller than a unit time, we calculate the least number of required sub-carriers. Then, we allocate the least used available sub-carriers to each link. An example of top-down sub-carrier allocation is shown in Fig. 2(a). Suppose that the total number of sub-carriers is 5, while the least number of required sub-carriers of link l_i, link l_j and link l_k are 2, 3 and 2, respectively. Based on the sub-carrier allocation sequence l_i, l_j and l_k, the least used sub-carriers are allocated first, as shown in Fig. 2(a). After that, we check the cost, energy and QoS constraints for each node. If the energy and/or QoS constraints can not be satisfied and the cost constraint is violated, the algorithm will return no feasible solution. If all constraints, i.e., cost, energy and QoS constraints are satisfied, we then calculate the STR of each RN, and delete a RN with the least contribution of total STR, which is defined as the difference of total STR with or without the RN. In other cases, the algorithm will stop and return the current number RNs. After deleting the RN, we connect its users to other RN or BS with the minimum STR and calculate the total number of STR of all associated links. The difference of total STR with or without the RN refers to the RN's contribution. Thus, we delete the RN with the least contribution of total STR as this node makes the least contribution in the network. The RNs are repeatedly deleted until any of cost, energy or QoS constraint is violated. In case deleting $n+1$-th RN will violate the constraints, the algorithm returns a placement of n RNs in the last round.

Algorithm 1 RNP-SA-t:RNP-SA with top-down algorithm

```
Place RNs on all candidate locations;
while R ≠ ∅ do
  Connect (u, r, b)/(u, b) with min(STR_urb, STR_ub),
  ∀u ∈ U, r ∈ R, b ∈ B;
  if P_r^+ < P_r^- ∨ P_b^+ < P_b^- then
    Connect u to the closest r or b with enough energy;
  end if
  Calculate the least required |S_x|, ∀x ∈ V;
  Top-down sub-carrier allocation;
  if |R| = |R'| ∧ energy and/or QoS constraints can not
  be kept then
    Return no feasible solution;
  end if
  if Cost, energy and QoS constraints can be kept then
    Save the current topology;
    for all r ∈ R do
      U* ← {u : (u, r) ∈ E}
      STR_1 ← Σ_{(u,r,b)∈E} STR_urb;
      Delete r and disconnect its links;
      for all u ∈ U* do
        Add (u, r, b)/(u, b) with min (STR_urb, STR_ub);
        STR_2 ← STR_2 + min (STR_urb, STR_ub);
      end for
      STR* ← STR_2 − STR_1;
      Load the topology;
    end for
    Delete r with min (STR*)
  else
    Return relay node number of last loop;
  end if
end while
Return 0;
```

D. RNP-SA with bottom-up algorithm

We design the RNP-SA-b algorithm to further reduce the time complexity compared with RNP-SA-t. The detail of our RNP-SA-b algorithm is shown in Algorithm 2. In the bottom-up algorithm, we first generate a graph by connecting each user to the closest BS. Similar with the RNP-SA-t algorithm, we calculate the least number of required sub-carriers under the cost, energy and throughput constraints. Then, we assign unused sub-carriers to each link by bottom-up sub-carrier allocation without time domain multiplexing. Thus, bottom-up sub-carrier allocation can achieve a lower time complexity compared with the top-down sub-carrier allocation at the cost of reduced spectrum utilization. An example of the bottom-up sub-carrier allocation is shown in Fig. 2(b). Link l_k cannot be scheduled for transmission as there is no available sub-carriers at this time. After allocating sub-carriers, we check whether the current placement is feasible or not, under the cost, energy sustainability and throughput constraints. If the cost constraint is violated, we stop the program and return the number of RNs; If the energy constraint is violated, we need to place one more RN in the network on the location closest to the BS; If the throughput constraint is violated, one more RN should be placed on the location with the heaviest traffic demand. Then, we sort users by STR of user-relay links in an ascending order. The user-relay-BS link is established only when the cost constraint is not violated, while the placement of the RN can help to reduce the energy consumption of BSs and the throughput constraint of users can also be satisfied. If the energy and/or QoS constraints can not be kept and the cost constraint is violated, the algorithm will return no feasible solution.

TABLE II: Notation for the RNP-SA-t/b algorithms

γ_u	$\gamma_u^{up} + \gamma_u^{dn}$
(u, r, b)	(u, r) and (r, b)
STR_{urb}	$STR_{ur} + STR_{rb}$
S	The set of total sub-carriers
L	The set of candidate locations
γ_r^{up}	Uplink relay traffic of RN r
γ_r^{dn}	Downlink relay traffic of RN r
b_x	The BS that x is connected including the case that x is b_x for $x \in B$.
γ_z^I	Summation of users' traffic demand within z's interference range, $z \in L$

E. Time complexity analysis of the RNP-SA-t/b algorithms

In this subsection, we analyze the worst case time complexity of the proposed RNP-SA-t/b algorithms, i.e., the cost threshold is always large enough to get a feasible deployment. Assume that the number of BSs in a two-tired wireless network is much smaller than that of RNs and their candidate locations. The time complexity of RNP-SA-t/b is analyzed as follows.

Lemma 1: The time complexity of RNP-SA-t algorithm is $O(|S||L|(|U| + |L|)^2 + |U||L|^3)$.

Proof. For each round, the time complexity of generating a new topology is $O(|U||L|)+O(|L||B|)$. As the number of BSs is much smaller than that of RNs and their candidate locations, $O(|U||L|) + O(|L||B|)$ is the same as $O(|U||L|)$. For each node the sub-carrier allocation and checking feasibility are conducted at the same time, which needs the time complexity of $O(|S|(|U| + |L|))$. There are total $O(|U| + |L|)$ nodes to be checked, thus the time for algorithm to do sub-carrier allocation and checking feasibility is $O(|S|(|U| + |L|)^2)$. For checking the energy constraint of each BS, it needs $O(|B|(|U| + |L|))$. The step of removing an RN needs $O(|U||L|^2)$, which consists of investigating all candidate locations and its attached users, $O(|U||L|)$, and rearranging them

Algorithm 2 RNP-SA-b:RNP-SA with bottom-up algorithm

```
Connect each user to the closest BS;
Calculate the least required |S_x|, ∀x ∈ V;
Bottom-up sub-carrier allocation;
if Cost, energy and QoS constraints can be kept then
  Return 0;
else
  while P_x^+ < P_x^- ∨ Σ_{(x,y)∈E} |S_xy| > |S| do
    if Cost constraint can not be kept then
      Return the number of placed RNs;
    else
      b* ← b_x
      if P_{b*}^+ < P_{b*}^- then
        r ← z with min(D_{b*z}), ∀z ∈ L ∧ SNR_{b*z} ≤ β;
      else
        r ← z with max(γ_z^I), ∀z ∈ L ∧ SNR_{b*z} ≤ β;
      end if
      U* ← sort users by STR_ur in increasing order;
      for all u ∈ U* do
        Replace (u, b) by connecting (u, r, b);
        if P_r^+ < P_r^- ∨ P_{b*}^- is increased then
          Replace (u, r, b) by connecting (u, b);
        end if
      end for
      Calculate the least required |S_x|, ∀x ∈ V;
      Bottom-up sub-carrier allocation;
      if |R| = |R'| ∧ energy and/or QoS constraints can not be kept then
        Return no feasible solution;
      end if
      if Cost, energy and QoS constraints can be kept then
        Return the number of placed RNs;
      end if
    end if
  end while
end if
```

$O(|L|)$. Since all the steps are sequential and there are at most $|L|$ rounds, the total complexity of RNP-SA-t algorithm is

$$
\begin{aligned}
&O(|L|)[O(|U||L|) + O(|S|(|U| + |L|)^2)+\\
&O(|B|(|U| + |L|)) + O(|U||L|^2)]\\
&= O(|S||L|(|U| + |L|)^2 + |U||L|^3).
\end{aligned}
$$

□

Lemma 2: The time complexity of RNP-SA-b algorithm is $O(|B||L|^2 + |L||U| \log |U| + |B||U||L|)$.

Proof. For each round, the time complexity is $O(|B||L|)$ to determine which candidate location to place new added RN. Then, it takes $O(|U| \log |U|)$ to sort users in increasing order of STR_{ur}. Adding users to the newly added RN needs $O(|U|)$, and allocating the sub-carriers for those newly connected links requires $O(|U|)$. Finally, the time complexity of checking the constraints for each BS needs $O(|B|(|U|+|L|))$. Since all the steps are sequential and there are at most $|L|$ rounds, the total complexity of RNP-SA-b algorithm is

$$
\begin{aligned}
&O(|L|)[O(|B||L|) + O(|U| \log |U|)+\\
&O(|U|) + O(|U|) + O(|B|(|U| + |L|))]\\
&= O(|B||L|^2 + |L||U| \log |U| + |B||U||L|).
\end{aligned}
$$

□

Therefore, RNP-SA-b algorithm has a lower time complexity than RNP-SA-t algorithm.

VI. Simulation Results

In this section, we compare the performance of the proposed RNP-SA-t/b algorithms to a traffic load oriented greedy algorithm with and without cost threshold. We first evaluate the minimal number of relay nodes that are required to fulfill the network requirement. Furthermore, when a cost threshold is set to limit the maximal number of relay node, we analyze the average network lifetime, which is defined as the time duration from the beginning until one of the network nodes, either a BS or RN, drains out its energy and becomes out of service. The performance is evaluated under various network settings, e.g., diverse energy charging capabilities of candidate RNs at various locations, different traffic demands of each user, variable transmission powers, and different numbers of users or BSs.

A. Simulation configurations

We set up a two-tiered wireless network with 4 BSs, 150 wireless users, 50 candidate locations of RNs within a $200m \times 200m$ region, if not specified otherwise. BSs are evenly distributed, while candidate locations and users are randomly distributed in the region. All nodes use the same transmission power, $P^T = 0.5$ W, and the receiving power, $P^R = 0.05$ W, to communicate with each other. Different BSs and RNs distributed on different candidate locations have various charging capabilities, and the energy charging rates of BSs and RNs are uniformly distributed over $[0.2, 0.4]$ W and $[0.05, 0.1]$ W, respectively. The total number of sub-carriers in the network is 50, where the bandwidth of each sub-carrier is 2 MHz. The path loss exponent is 2, the background noise $N = 10^{-4}$ W, and the interference signal threshold is 1. Different users have different throughput requirements, which is randomly distributed over $[25, 55]$ Kbps, and the downlink traffic demand is 9 times of that in the uplink. We repeat each simulation experiment 1000 times with different random seeds and compute the average values for performance evaluation. The simulator is developed using Java and Matlab. The parameters used in the simulation are tabulated in Table III.

B. Traffic load oriented greedy algorithm

We compare the performance of the proposed algorithms with a traffic load oriented greedy algorithm as a benchmark. For the greedy algorithm, we first connect each user to the closest BS. After that, the minimal number of required sub-carriers under the energy and throughput constraints is allocated to each user, which is similar to that in RNP-SA-b algorithm. With the greedy algorithm, a RN is always placed

TABLE III: Table of Parameters

region size	$200m \times 200m$
number of BSs	4
number of users	150
number of candidate locations	50
number of sub-carriers	50
maximal network lifetime	200 time slots
transmission power	$0.5W$
receiving power	$0.05W$
charging capability of BSs	$[0.2, 0.4]W$
charging capability of RNs	$[0.05, 0.1]W$
bandwidth of single sub-carrier	$2MHz$
pass loss exponent	2
background noise	$10^{-4}W$
interference signal threshold	1
data-rate demand of users	$[25, 55]Kbps$
$\gamma_u^{dn}/\gamma_u^{up}, \forall u \in U$	9

on the candidate location with the heaviest traffic load, i.e., the sum of the traffic loads within the interference range of the RN candidate location is higher than that of any other locations. The closest users to the RN are then connected to the deployed RNs iteratively, given that the placement of the RN can help reduce the energy consumption of the BS, while the deployment cost, energy, and QoS constraints of RNs can be fulfilled. Details of traffic load oriented greedy algorithm are shown in Algorithm 3.

Algorithm 3 Traffic load oriented greedy algorithm

Connect each user to the closest BS;
Calculate the least required $|S_x|, \forall x \in V$;
Bottom-up sub-carrier allocation;
while Cost, energy and QoS constraints cannot be kept **do**
  $r \leftarrow z$ with $\max(\gamma_z^I), \forall z \in L$;
  $b^* \leftarrow b$ with $\min(D_{rb}), \forall b \in B$;
  Connect (r, b^*);
  $U^* \leftarrow$ sort users by $D_{ur}, \forall u \in U$;
  for all $u \in U^*$ **do**
    Replace (u, b^*) by connecting (u, r, b^*);
    if $P_r^+ < P_r^- \vee P_{b^*}^-$ is increased **then**
      Replace (u, r, b) by connecting (u, b);
    end if
  end for
  Calculate the least required $|S_x|, \forall x \in V$;
  Bottom-up sub-carrier allocation;
end while
return the number of placed RNs;

Assuming that the cost threshold is large enough and the number of BSs is much smaller than the number of RNs or candidate locations, the worst case time complexity of the traffic load oriented greedy algorithm can be calculated as follows.

Lemma 3: The worst case time complexity of the traffic oriented greedy algorithm is $O(|L|^2(|L| + |U|))$.

Proof. For each round, it takes $O(|L|(|L| + |U|))$ time to find out the candidate location with heaviest traffic load. The time complexity of sorting users is $O(|U| \log |U|)$, and connecting users to newly added RN needs $O(|U|)$. Then, allocating the sub-carriers for those newly connected links requires $O(|U|)$. Finally, it needs $O(|B|(|U| + |L|))$ to check the energy constraints for all the BSs. Since all these steps are sequential and there are at most $|L|$ rounds, the total complexity of the traffic oriented greedy algorithm is

$$\begin{aligned} &O(|L|)[O(|L|(|L| + |U|)) + O(|U| \log |U|) + \\ &O(U) + O(U) + O(|B|(|U| + |L|))] \\ &= O(|L|^2(|L| + |U|)). \end{aligned}$$

□

Therefore, the traffic load oriented greedy algorithm has the same worst case time complexity as RNP-SA-b algorithm.

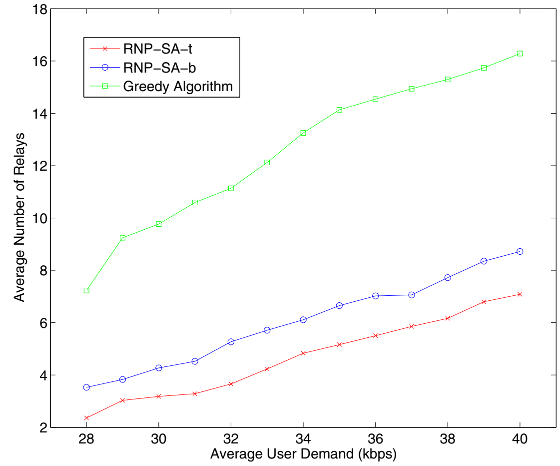


Fig. 3: Relay number of various user demand without cost threshold.

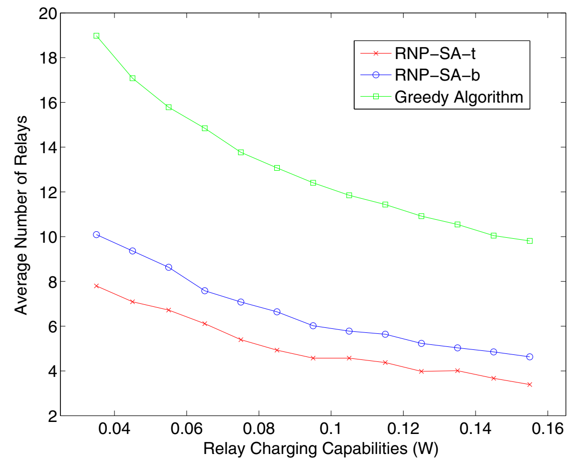


Fig. 4: Relay number of various charging capability without cost threshold.

C. Performance evaluation

We first evaluate the minimal number of required RNs with different algorithms. The number of RNs required to fulfill throughput demands of users is plotted in Fig. 3. It can be seen that more RNs are required when the traffic demands of users increase. The greedy algorithm is designed to help relieve the traffic burden of the BSs, without considering the energy consumption; while our algorithms jointly consider the

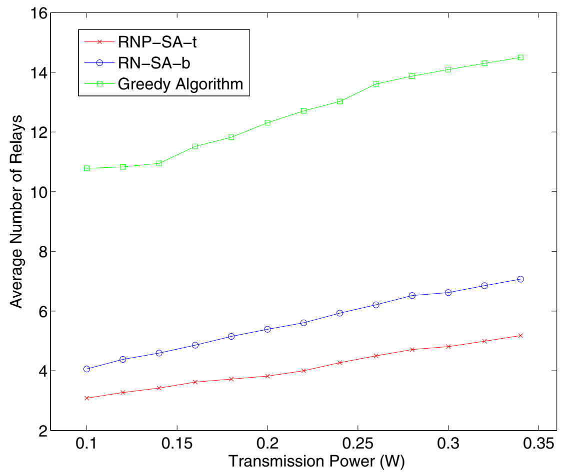


Fig. 5: Relay number of various transmission power without cost threshold.

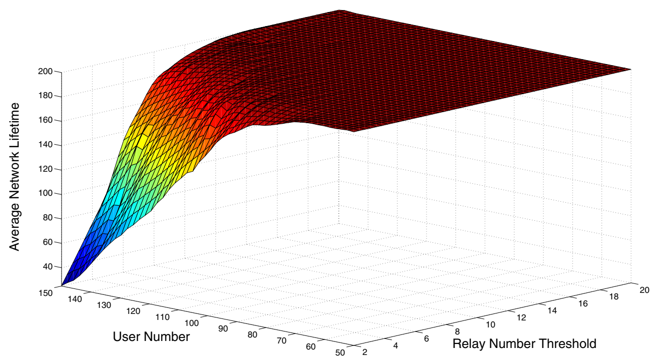


Fig. 6: Network lifetime of RNP-SA-t algorithm with various cost threshold and user number.

impact of energy sustainability and users' traffic demands, and thus achieve better performance. The impacts of variable energy charging capabilities of RNs are illustrated in Fig. 4. It is shown that the number of required RNs decreases with the increasing charging capabilitiy of RNs. A high capacity RN can serve more users, and thus a smaller number of RNs are required to serve a given number of users. The impacts of transmission power are shown in Fig. 5. Generally, when BSs use a higher transmission power to serve users, more energy is consumed at BSs and thus more RNs are required to help release the burden of BSs. In all cases, our proposed algorithms outperform greedy algorithm significantly. We also observe that the RNP-SA-t algorithm achieves better performance than the RNP-SA-b algorithm at the cost of a higher time complexity. This is because RNP-SA-t uses the top-down algorithm to iteratively remove RNs based on the network topology information, including all of the relay candidate locations; while the RNP-SA-b algorithm only uses the current topology, thus achieves a slightly lower performance than the RNP-SA-t algorithm with the reduced time complexity.

Then, we evaluate the network lifetime performance of different algorithms under a certain cost threshold. The network

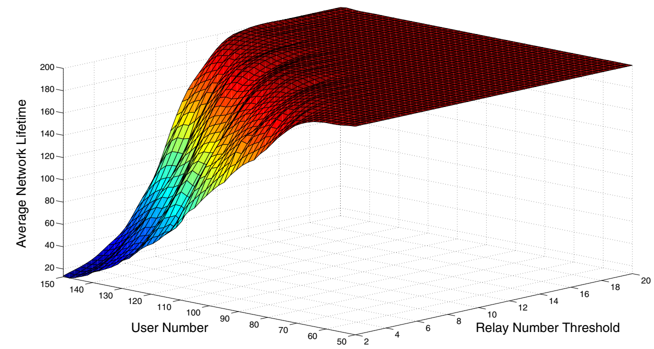


Fig. 7: Network lifetime of RNP-SA-b algorithm with various cost threshold and user number.

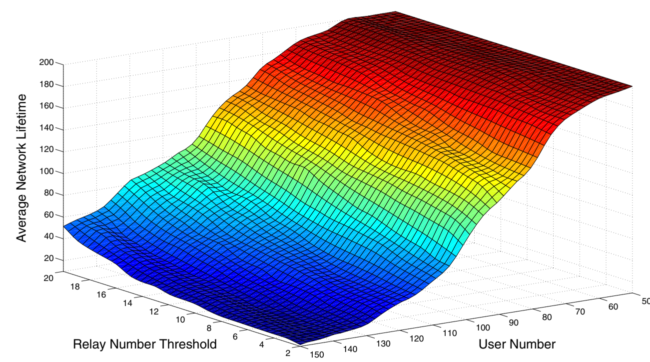


Fig. 8: Network lifetime of greedy algorithm with various cost threshold and user number.

lifetimes of RNP-SA-t, RNP-SA-b, and greedy algorithms under various cost thresholds and the number of users are shown in Fig. 6, Fig. 7, and Fig. 8, respectively. A longer network lifetime is achieved with a higher cost threshold or a smaller number of users for all algorithms. A higher cost threshold allows more RNs to be deployed and more RNs can help balance the energy consumption and traffic demands of BSs, which improve the energy sustainability of the network. Similarly, a smaller number of users implies a lower demand for energy and bandwidth, and thus a longer network lifetime can be achieved. However, as greedy algorithm only considers the throughput constraint but ignores the energy constraint, it cannot ensure high network sustainability performance. It is shown in Fig. 8 that the network life time increases slightly with the cost threshold. Our proposed algorithm jointly considers the energy and throughput constraints by employing STR metric for RN deployment. It can be seen that the increase rate of network life time of RNP-SA-t/s is much higher than that of the greedy algorithm as shown in Fig. 6 and Fig. 7.

We further study the impacts of the number of BSs on the network lifetime in Fig. 9. The cost threshold is set to allow the deployment of up to 5 RNs. The network lifetime improves significantly with the increasing number of BSs, as shown in Fig. 9. Similarly, our proposed RNP-SA-t/b algorithms significantly outperform the greedy algorithm. This is because

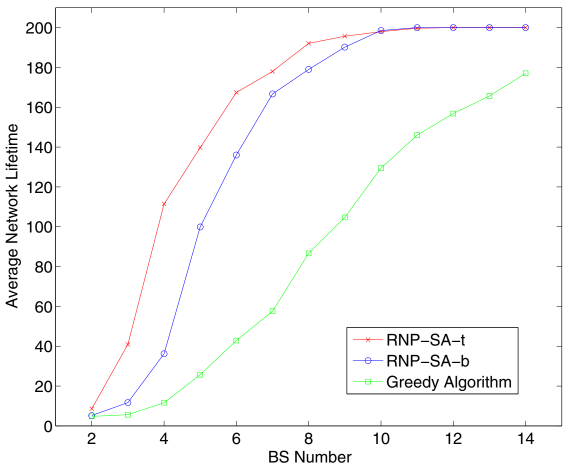


Fig. 9: Network lifetime of various number of BSs.

greedy algorithm always chooses a candidate location with the heaviest traffic load to deploy RNs. This strategy is not energy-efficient especially when the heaviest load area is far away from the BSs.

In summary, our proposed algorithms significantly outperform the traffic oriented greedy algorithm because both the energy sustainability and users' traffic demands are considered. The RNP-SA-t algorithm performs slightly better than RNP-SA-b at the cost of higher time complexity for building and maintaining the overall network topology.

VII. Conclusions

In this paper, we have studied the joint problem of RN placement and sub-carrier allocation in a two-tiered wireless communication network with renewable energy sources. We have formulated RNP-SA as a MINLP problem and proposed two low-complexity algorithms to find the minimal number of RNs to fulfill the users' QoS demands under the cost and energy sustainability constraint. It is shown that our proposed algorithms significantly outperform a greedy algorithm by jointly considering the traffic and energy constraints. In our future work, we will consider dynamic energy charging process in the RNP-SA problem.

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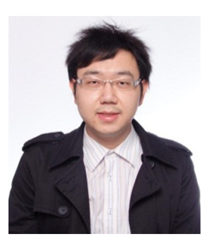

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