Relax, but Do Not Sleep: A New Perspective on Green Wireless Networking

Chenfei Gao*, Weiyi Zhang†, Jian Tang*, Chonggang Wang‡, Shihong Zou§, and Sen Su§,
* Department of Electrical Engineering and Computer Science, Syracuse University, Syracuse, NY 13244
† AT&T Labs Research, Middletown, NJ 07748
‡ InterDigital Communications, King of Prussia, PA 19406
§ Beijing University of Posts and Telecommunication, P.R.China

***Abstract*—Saving power on base stations (BS) becomes a critical issue in wireless cellular networks. Many existing work has proposed to schedule BS into sleep to save energy. However, in reality, it is very difficult to shut down and reboot BSs frequently due to numerous technical issues and performance requirements. In this work, we propose a much more practical solution and offer a new perspective on implementing Green Wireless Networking by embracing the hot-trended small cell network idea. Instead of putting BSs into sleep, we tactically reduce the coverage (and the power usage) of each BS, and strategically place microcells (relay stations) to offload the traffic transmitted to/from BSs in order to save total power consumption. We propose approximation algorithms for various network design scenarios, with different wireless network setups and different power saving optimization objectives. Extensive numerical results are presented to confirm our theoretical analysis.**

I. Introduction

There are currently more than 4 million base stations (BSs) serving mobile users, each consuming an average of 25MWh per year. The number of BSs in developing regions are expected to almost double by 2014. Unprecedented growth in cellular industry has pushed the limits of energy consumption in wireless networks. Information and Communication Technology (ICT) already represents around 2% of total carbon emissions (of which mobile networks represent about 0.2%), and this is expected to increase every year. In addition to the environmental aspects, energy costs also represent a significant portion of network operators' overall expenditures (OPEX). The rising energy costs and carbon footprint of operating cellular networks have led to an emerging trend of addressing energy-efficiency amongst the network operators and regulatory bodies such as 3GPP and ITU [23] [24]. European Commission has recently started new projects within its seventh Framework Programme to address the energy efficiency of mobile communication systems, viz. energy Aware Radio and NeTwork TecHnologies (EARTH), Towards Real Energy-efficient Network Design (TREND), and Cognitive Radio and Cooperative strategies for Power saving in multi-standard wireless devices (C2POWER) [25], [26], [27].

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Green communications and networking, especially power efficiency on BSs and wireless infrastructure, has attracted many researchers' attentions recently. [1] and [9] are two surveys summarizing the current research works on green wireless network, especially on green cellular networks. Many BS equipment manufacturers have begun to offer a number of eco and cost friendly solutions to reduce power demands of BSs and to support off-grid BSs with renewable energy resources. Nokia Siemens Networks Flexi Multiradio Base Station, Huawei Green Base Station and Flexenclosure Esite solutions are examples of such recent efforts [28]–[30].

In current literatures, *the most straightforward way to reduce power consumption of BSs is to turn off idle BSs or put them into sleep*. [2], [3], [6], [7], [10], [11], [12], [8] are all working on shutting down some of under-utilized base stations in order to achieve the power savings via different approaches while satisfying various constraints in the network. In [2], Peng *et al.* proposed a profile-based approach to green cellular infrastructure, which leverages emporal-spatial traffic diversity and node deployment heterogeneity, and powers off under-utilized BSs based on historical data. The authors of [3] provided an algorithm that minimizes power consumption by selectively turning on or off cell towers and deciding which power to assign to the active nodes and what frequencies to use, so as to maintain full coverage and respect users' capacity demands. In [6], Elayoubi *et al.* investigated network sleep mode for reducing energy consumption of radio access networks. They proposed an offline-optimized controller that associates traffic with an activation/deactivation policy that maximizes a multiple objective function of QoS and energy consumption. In [7], the authors showed how to optimize the energy saving, first assuming that any fraction of cells can be turned off, and then accounting for the constraints resulting from the cell layout. [10] proposed a concrete methodology for saving energy, which is based on re-arranging the user-cell association so as to allow shutting down under-utilized parts of the network. [11] investigates the energy saving potential of exploiting cell size breathing by putting low loaded cells in to sleep mode. In [12], the authors developed a system selection algorithm that finds the optimal traffic allocation for the different systems that minimizes power consumption while insuring the target QoS. In [8], X. Sheng *et al.* proposed to leverage load migration and BS consolidation for green communications and considered a power-efficient network planning problem in virtualized Cognitive Radio Networks with the objective of minimizing total power consumption while meeting traffic load demand of each MVNO. Besides utilizing sleep mode to save energy, the authors in [4] studied the effect of cell sizes on the energy consumption and proposed a practical, 2-level scheme that adjusts cell sizes between two fixed values, and showed an energy saving of up to 40%. In [5], the authors first studied how to adaptively vary the processing speed based on incoming load and then proposed and analyzed a distributed algorithm, called Speed Balance, that can yield significant energy savings. However, without careful network planning, turning off BSs might lead to loss of coverage and unsatisfied traffic demands. Furthermore, in reality, it is very difficult to shut down and reboot BSs frequently due to numerous technical issues and performance guarantees. Shutting down BSs would lead to loss of coverage due to handover delays, which were not carefully considered in above works. Rebooting BSs requires air conditioners to spend extra power on heating to indoor temperature. The extra power consumption was usually ignored in most works. Hence, in practice, to find a feasible short-term solution, we need to seek other opportunities.

Small cell network has gain momentum in the past few years and become a hot trend for next generation wireless networking. The authors in [20] tackle the problem of placing the minimum number of relays to achieve bandwidth sufficiency when real-time multimedia streams need to be sent to the sink. They considered the constraints of heterogeneous link capacity and transmission range. Zhang *et al.* in [18] studied a distance-aware relay placement problem in WiMAX Mesh Networks with the goal of placing the minimum number of RSs to cover all the subscribers while satisfying subscribers' data rate request constraint. They considered a two-tiered network and proposed several efficient algorithms to solve the optimization problems on both tiers, respectively. Gao *et al.* in [19] improved the work of [18] by extending a new framework, with not only solving the same relay placement problem with taking into consideration the SINR threshold on the received signal at subscriber's side but also studying the transmission power allocation problem with the objective of minimizing sum of the transmission power of all placed RSs. Several efficient algorithms were presented to support the framework. [17] investigated a joint optimization problem on relay node placement and route assignment for two-tiered wireless networks and proposed a recursive weighted clustering binary integer programming algorithm to maximize the total number of information packets received at the BS during the network lifetime. In [21], Elgendy, O.A. *et al.* proposed an optimization framework to maximize either the total cell capacity or the total cell-edge capacity, while taking into consideration the effect of co-channel interference. In [22], the authors investigated the problem of optimal relay placement for coverage extension in relay assisted LTE-A networks. They studied both DL and UL transmission scenarios for optimal relay placement taking into account the SINR of the received signal on the evolved-NodeB (eNB)-RN and RN-User Equipment (UE) links. However, our work is different from all these previous ones. We know that more than 60% power consumption on wireless infrastructure is spent on wireless radio access network and transmission power of base stations is the major part of total power consumption on radio access network. Since transmission power is exponentially increasing with the transmission range, we consider to reduce the transmission range of macro base stations meanwhile deploying multiple micro base stations to support the coverage and users' QoS requirements, which can save power consumption on wireless access network to a great extent. Hence, our purpose of placing relays is to save power consumption in the network, Or we can say, to make BS feel relax while covering all the users each of which has a certain amount of throughputs. We are the first one to propose the new perspective of embracing hot-trended small cells on Green Wireless Networks. However, most of the studies on small cell have focused on network capacity improvement. To the best of our knowledge, nobody has considered how (or if) small cell networks can provide a more energy-efficient greener wireless network.

In this work, we propose a more practical solution and offer a new perspective on implementing Green Wireless Networks by embracing the hot-trended small cell networks. Instead of putting BSs into sleep, we tactically reduce the coverage (and the power usage) of each BS, and strategically place microcells (small cells) to offload the traffic transmitted to/from BSs in order to save total power consumption. The rest of the paper is organized as follows. Section II provides problem statements and our solutions, which is followed by extensive numerical results in Section III to confirm the performances of our proposed schemes. This paper is concluded in section IV.

II. Problem Statements

In this paper, we consider a wireless network with $N(\geq 1)$ base stations (BS) and M users. We assume that the locations of BSs and users are known. In other words, users in this work are large static wireless service subscribers, such as Wal-mart, McDonald's and gas stations, which are static but usually have large traffic demands. Since all the users in this work share similar communication characteristics and QoS, we assume that all users have the same data rate service L. Most previous works on green wireless network introduce a sleep mode for BSs. If a base station has a low traffic load or idle during a certain time period, then it could be shut down in order to save wasting power consumption on some components such as air cooling, power amplifier, digital data processing and so on. However, in reality, it is very difficult to shut down and reboot BSs frequently due to numerous technical issues and performance guarantees. In this work, we do not propose to shut down BSs, instead, we "relax" the BSs by reducing their burden of service coverage. Meanwhile, hot-trending small cells (called relay station (RS) in this work) are applied to provide enough coverage with less total network energy consumption. Before we present our problem definitions, let us first introduce the power consumption model for BSs and RSs.

A. Power Models of Base Station and Relay Station

Power consumption of a BS or RS consists of various power costs, including transceiver, power amplifier, digital signal processing, air cooling and so on. Also, it is not only relevant to the transmission power of the antennas but also the traffic loads from the users and some other factors. Many previous literatures [13]–[16] were working on it and proposing several useful ones. In our work, we select the power models in [13], [2]. The power model of BS proposed in [13] is:

$$\begin{aligned} &P_{el/macro} \\ &= n_{sector}(P_{el/rect} + F(n_{Tx}(P_{el/amp} + P_{el/trans}) + P_{el/proc}) \\ &+ P_{el/link} + P_{el/airco} \end{aligned}$$

with n_{sector} the number of sectors, F the load factor, n_{Tx} the number of transmitting antennas, and $P_{el/rect}$, $P_{el/amp}$, $P_{el/trans}$, $P_{el/proc}$, $P_{el/link}$ and $P_{el/airco}$ the power consumption (in Watt) of the rectifier, the power amplifier, the transceiver, the digital signal processing, the microwave link, and the air conditioning, respectively.

The power model of RS proposed in [13] is:

$$\begin{aligned} P_{el/micro} =& P_{el/rect} + P_{el/airco} \\ &+ F(P_{el/amp} + P_{el/trans} + P_{el/proc}) \end{aligned} \tag{2.1}$$

with F the load factor, and $P_{el/rect}$, $P_{el/airco}$, $P_{el/amp}$, $P_{el/trans}$, and $P_{el/proc}$ the power consumption of the rectifier, the air conditioning, the power amplifier, the transceiver, and the digital signal processing (in Watt), respectively.

Simply put, some energy consumption is related with the transmission (distance and traffic), some are related with the traffic, such as rectifier cost, and others are fixed cost, such as air conditioning cost. Therefore, we simplified our energy consumption model as following:

$$P_{el/macro} = (a_0 r_{bs}^2 + b_0) \times L_{bs} + c_0; \tag{2.2}$$

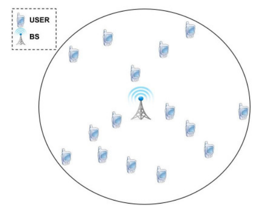
$$P_{el/micro} = (a_1 r_{rs}^2 + b_1) \times L_{rs} + c_1; \tag{2.3}$$

where a_0,a_1,b_0,b_1,c_0,c_1 are constants we can know, r_{bs} and r_{rs} are the transmit range of BS and RS, L_{bs} and L_{rs} are the traffic loads of BS and RS, respectively.

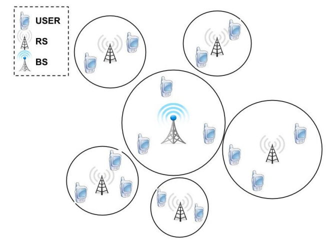
Our power models take transmit range, users' traffic loads, and some constant power costs into consideration. Thus, our models are feasible and practical ones. Furthermore, our power model of base station is consistent with that proposed in [2].

B. Green Relaxed Energy Aware Network Problem

In this section, we present our **G**reen **R**elaxed **E**nergy **A**ware **N**etwork (GREAN) problem. Our goal of our proposed scheme is to tactically reduce the coverage, and then the power consumption, of the BS. For the uncovered users, we strategically place RSs, which have much smaller energy consumption compared to BS, while keeping the total energy consumption reduced. An illustration of our strategy is shown in Fig. 1. The traditional BS-takes-all network in Fig. 1(a) will be replaced by a hybrid Macro+small cells network in Fig. 1(b). Also, in our study, an RS has a maximum transmission range d_R^{max}, but can select its own transmission power range based on coverage designs. Our goal is to minimize the total network energy by strategically placing RSs, as well as adjusting radius (and power usage) of BS and RSs.



(a) BS covers all the users



(b) Both BS and RSs cover all the users

Fig. 1: Illustration of GREAN design

Definition 1 (Green Relaxed Energy Aware Network (GREAN) problem)**.** Given a network with a BS, a set of users $V = \{v_1, v_2, ..., v_n\}$, with traffic rate L, the GREAN problem seeks a network design with K RSs such that:

1) the placement of the K RS, and the transmission power of each placed RS
2) the transmission power of BS
3) User must be covered by BS or RS
4) the total power consumption of BSs and RSs should be minimized. □

It is straightforward to see that the GREAN problem is closely related with K-*center* problem or *Dominant set* problem. Therefore, we speculate that GREAN is also *NP-hard*, and try to present approximation schemes for the problem.

C. A Special Case: GREAG Problem

In the GREAN problem, there are infinite number of locations for placing RSs. To find a final solution for GREAN, first, we try to tackle a problem with limited number of RSs locations, which is defined in following:

Definition 2 (Green Relaxed Energy Aware Grid (GREAG) problem)**.** Given a grid network with grid size d_s, a BS is in the center of the network, and a set of users $V = \{v_1, v_2, ..., v_n\}$, with traffic rate L, locate *on the grids*, shown in Fig. 2. The maximum power range of a RS is assumed to be $d_R^{max} = 2 \cdot d_s$, the GREAG problem seeks placement of K RSs and transmission power allocation strategy for RSs and BS such that:

1) *RSs can only be placed in the center of a grid*
2) the placement of K RSs, and the transmission power of each placed RS
3) the transmission power of BS
4) the total power consumption of both BSs and RSs should be minimized. □

Given the maximum coverage range of RSs, d_R^{max}, we can construct a grid network with grid size $d_s = d_R^{max}/2$, as shown in Fig. 2. By enforcing a grid network, now we have limited number of potential locations for RSs, which are center of each grid in Fig. 2.

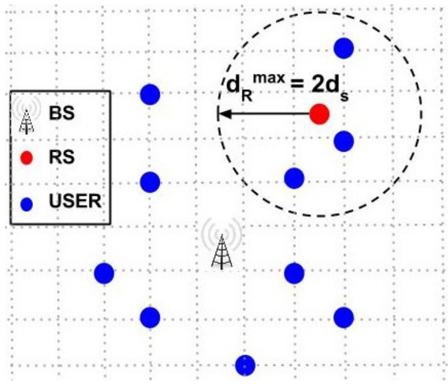


Fig. 2: An illustration for GREAG problem

For this special case, we first present and prove an approximation solution, which is listed in **Algorithm** 1.

Algorithm 1 GREAG(d_R^{max}, K)

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Let E(v_i, v_j) ≜ power consumption of RS or BS placed at v_i to cover user v_j;
V = {v_0, v_1, ..., v_n} with v_0 is BS, users = {v_0, v_1, ..., v_n};
Let s_0 = v_0, and B_0 ← {v_1, ..., v_n}, the users that covered by B_0;
for k ← 0 to K − 1 do
    h ← max{E(s_j, v_i) | v_i ∈ B_j and 0 ≤ j ≤ k};
    Let v_i be a user whose covering station s_j's energy consumption E(s_j, v_i) would be h;
    v_i needs to be covered by a new RS s_{k+1}; Move v_i to B_{k+1};
    Find the nearest candidate location (center of a grid) to v_i, and place s_{k+1} in the location;
    for each v_t ∈ (B_0 ⋃ ... ⋃ B_k) do
        let j be such that v_t ∈ B_j;
        if E(v_t, s_j) ≥ E(v_t, s_{k+1}) and dis(v_t, s_{k+1}) ≤ d_R^max then
            move v_t from B_j to B_{k+1};
        end if
    end for
end for
if B_0 is empty then
    h_0 ← min{E(B_0, v_i) | v_i ∈ B_0 ⋃ ... ⋃ B_{K+1}};
    let v_i be the user who consumes B_0 h_0 and whose energy consumption for its corresponding RS s_l is maximal;
    move v_i from B_l to B_0;
end if
Return B_0, ..., B_K;
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Theorem 1. Algorithm 1 is a $(8\mathcal{M})$-approximation for the GREAG problem. In other words, let the power consumption returned by Algorithm 1 be P, and OPT be an optimal solution for GREAG, we know $P \leq 8\mathcal{M} \cdot OPT$, where $\mathcal{M} = \max\{\frac{a_0}{a_1}, \frac{b_0}{b_1}, \frac{c_0}{c_1}\}$ from the power model in (2.2)(2.3). □

Proof: For any user i, let OPT_i denote the power consumption for a station (BS or RS) to cover user i in an optimal solution OPT, and let OBJ_i denote the power consumption for a station (BS or RS) to cover user i in our GREAG solution. For a user i in V, let d_{min} denote the distance from i to its covering RS/BS s_i. Following the energy consumption model, OBJ_i, the energy consumption for s_i to cover user i, is

$$OBJ_i \leq (a_0 d_{min}^2 + b_0)L + c_0 \quad (2.4)$$
$$\leq (a_0 (d_R^{max})^2 + b_0)L + c_0 \quad (2.5)$$
$$\leq \mathcal{M} \cdot a_1 (d_R^{max})^2 \cdot L + \mathcal{M} \cdot b_1 \cdot L + \mathcal{M} \cdot c_1 \quad (2.6)$$

Meanwhile, given the fact that users are all on the grids, and RS/BS are in centers of grids, the minimum distance between an RS/BS to a user is $\frac{\sqrt{2}}{2} d_s$, where d_s is the grid size. Therefore, we have

$$OPT_i \geq (a_1 (\frac{\sqrt{2}}{2} \cdot d_s)^2 + b_1)L + c_1 \quad (2.7)$$

According to our assumption, $d_R^{max} = 2 \cdot d_s$, we have

$$OPT_i \geq (a_1 (\frac{\sqrt{2} d_R^{max}}{4})^2 + b_1)L + c_1 \quad (2.8)$$
$$\geq (a_1 \frac{(d_R^{max})^2}{8} + \frac{b_1}{8})L + \frac{c_1}{8} \quad (2.9)$$
$$= \frac{1}{8}(a_1 (d_R^{max})^2 L + b_1 L + c_1) \quad (2.10)$$

Combining (2.6) and (2.10), we know that

$$OBJ_i \leq 8 \cdot \mathcal{M} \cdot OPT_i \quad (2.11)$$

Since $P = \sum_{i=1}^{N} OBJ_i$ and $OPT = \sum_{i=1}^{N} OPT_i$, summing all the users, we can see that

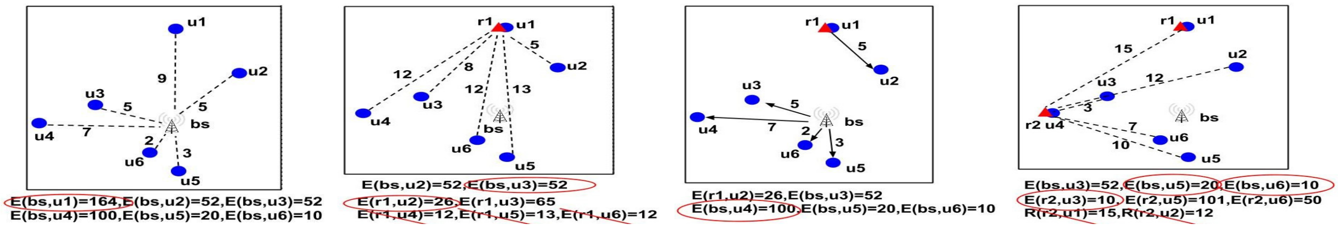
$$P \leq 8 \cdot \mathcal{M} \cdot OPT$$

■

D. Solution to GREAN problem

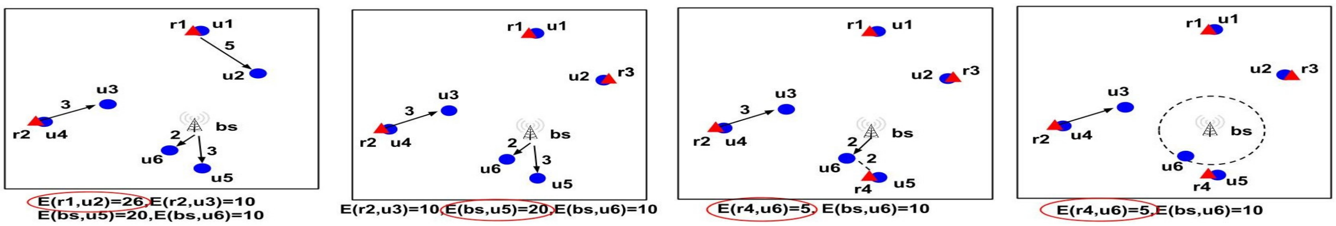
Now in this section we propose a solution to the GREAN problem, where users and BS can be at any place, and there is no constraint on the locations of RSs. Our solution is very similar to the solution to GREAG problem. But the major difference of is that we now *choose the users locations as potential RS placement locations* (shown in Line 8 of Algorithm 2).

Let us use an example in Figs. 3 and 4 to illustration how the algorithm works. There are six users, $u1 \ldots u6$ in the cell. First, we find the maximum energy for BS to cover a user, which is user u_1 with the longest distance, shown in figure 3(a). Then we place an RS, r_1, co-located with u_1. Next, we adjust users coverage comparing energy consumption for each user's from r_1 with energy from BS. Since distances between r_1 and u_4, $u5$ and $u6$ are all larger than RS's maximum transmit range d_R^{max}, they can only be covered by BS. On the other hand, energy consumption of covering u_2 from r_1, $E(r_1, u_2)$, is smaller than $E(bs, u_2)$, the energy consumption of covering u_2 by BS. Therefore, u_2 would be covered by r_1 now. Next, we keep finding the largest energy consumption for a RS/BS to cover any of its covering user. Now $E(bs, u_4)$ has the maximum energy. Then we place another RS r_2 at u_4's location, shown in Fig. 3(c). Now we have r_1 covers u_1, u_2, r_2 covers u_3, u_4 and BS covers u_5, u_6. Following same process, we place r_3 to cover u_2, r_4 to cover u_5, u_6, and leave no user to be covered by BS. In order to keep BS alive, we force BS



(a) Place $r1$ (b) Adjust $r1's$ covering set (c) Place $r2$ (d) Adjust $r2's$ covering set

Fig. 3: Illustration of GREAN (place $r1$ and $r2$)



(a) Place $r3$ (b) Adjust $r3's$ covering set (c) Place $r4$ (d) Adjust $r4's$ covering set

Fig. 4: Illustration of GREAN (place $r3$ and $r3$)

Algorithm 2 GREAN(d_R^{max}, K)

Let $E(v_i, v_j) \triangleq$ power consumption of RS or BS placed at v_i to cover user v_j;
$V = \{v_0, v_1, ..., v_n\}$ with v_0 is BS, users = $\{v_0, v_1, ..., v_n\}$;
Let $s_0 = v_0$, and $B_0 \leftarrow \{v_1, ..., v_n\}$, the users that covered by B_0;
for $k \leftarrow 0$ to $K-1$ **do**
  $h \leftarrow max\{E(s_j, v_i) \mid v_i \in B_j$ and $0 \le j \le k\}$;
  Let v_i be a user whose covering station s_j's energy consumption $E(s_j, v_i)$ would be h;
  v_i needs to be covered by a new RS s_{k+1}; Move v_i to B_{k+1};
  Place s_{k+1} **at the same location with user** v_i;
  for each $v_t \in (B_0 \bigcup ... \bigcup B_k)$ **do**
    let j be such that $v_t \in B_j$;
    if $E(v_t, s_j) \ge E(v_t, s_{k+1})$ **and** $dis(v_t, s_{k+1}) \le d_R^{max}$ **then**
      move v_t from B_j to B_{k+1};
    end if
  end for
end for
if B_0 is empty **then**
  $h_0 \leftarrow min\{E(B_0, v_i) \mid v_i \in B_0 \bigcup ... \bigcup B_{K+1}\}$;
  let v_i be the user who consumes B_0 h_0 and whose energy consumption for its corresponding RS s_l is maximal;
  move v_i from B_l to B_0;
end if
Return $B_0, ..., B_K$;

to cover one nearest user with the minimum energy. In Fig. 4(d), BS covers u_6 since $u6$ is the one nearest to BS. Final solution is shown in Fig. 5.

Theorem 2. Algorithm 2 is a $(1+\alpha)$-approximation for the GREAN problem. More specifically, if the power consumption of both BS and RSs returned by Algorithm 2 is denoted as P, we have $P \le (1+\alpha) \cdot OPT$, where $\alpha = \frac{a_1 R_{max}^2 L}{b_1 \cdot L + c_1}$ and OPT is an optimal solution for the GREAN problem. □

Proof: For any user i, we let OPT_i denote the power consumption for a station (BS or RS) to cover user i in the optimal solution, and OBJ_i denote the power consumption for a station (BS or RS) to cover user i in our GREAN solution. Since we know that $a_0 \ge a_1, b_0 \ge b_1, c_0 \ge c_1$, if user i is covered by BS in an optimal solution, we have

$$\begin{aligned} OPT_i &= (a_0 (r_{bs}^{opt})^2 + b_0) L + c_0 \\ &\ge b_0 L + c_0 \ge b_1 L + c_1 \end{aligned}$$

where r_{bs}^{opt} is the distance between BS and i in the optimal solution.

If user i is covered by a RS in optimal solution, we also have

$$\begin{aligned} OPT_i &= (a_1 (r_{rs}^{opt})^2 + b_1) L + c_1 \\ &\ge b_1 L + c_1 \end{aligned}$$

where r_{rs}^{opt} is the distance between an RS and i in the optimal solution. Thus, no matter if user i is covered by BS or RS, we have

$$OPT_i \ge b_1 L + c_1 \quad (2.12)$$

Case 1: If in our GREAN solution, user i is covered by an RS. Then we have

$$OBJ_i \le (a_1 R_{max}^2 + b_1) L + c_1$$

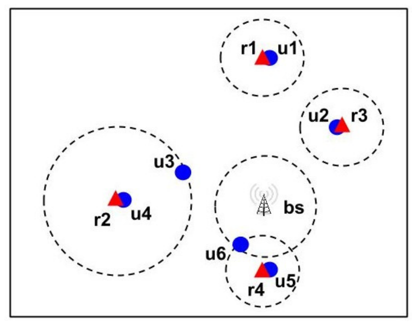


Fig. 5: Illustration of covering sets

Therefore, in this case, we have

$$\frac{OBJ_i}{OPT_i} \leq \frac{(a_1 R_{max}^2 + b_1)L + c_1}{b_1 L + c_1} = (1 + \frac{a_1 R_{max}^2 L}{b_1 \cdot L + c_1})$$

Let $\alpha = \frac{a_1 R_{max}^2 L}{b_1 \cdot L + c_1}$, we have

$$OBJ_i \leq (1+\alpha) OPT_i$$

Case 2: If in our GREAN solution, user i is covered by BS. Let d_{min} be the distance between i and its nearest RS placed in GREAN solution. Following our algorithm, the reason for a user i covered by BS is because

$$\begin{aligned} OBJ_i = (a_0 \cdot d_{BS,i}^2 + b_0)L + c_0 &\leq (a_1 d_{min}^2 + b_1)L + c_1 \\ &\leq (a_1 R_{max}^2 + b_1)L + c_1 \end{aligned}$$

Like in Case 1, $OBJ_i \leq (1+\alpha)OPT_i$ in Case 2.

Therefore, for each user i, we have $OBJ_i \leq (1+\alpha)OPT_i$. Since $P = \sum_{i=1}^{N} OBJ_i$ and $OPT = \sum_{i=1}^{N} OPT_i$, summing all the users, we can easily see

$$P \leq (1+\alpha) OPT$$

where $\alpha = \frac{a_1 R_{max}^2 L}{b_1 \cdot L + c_1}$. ■

E. Minimize the number of Relay Stations for GREAN

In previous sections, we have studied the case placing a fixed number,K, of RSs in the network. In this section, we try to see if we can use less number of RSs ($\leq K$) for better solutions.

Definition 3 (Budget Aware Power Saving (BAPS) problem)**.** Given a network with a BS, a set of users $V = \{v_1, v_2, ..., v_n\}$ with traffic rate L the BAPS problem seeks an optimal amount of relay stations R and transmission power allocation strategy for R such that:

1) the placement of $\leq K$ RSs
2) the transmission power of each placed RS
3) the transmission power of BS
4) the total power consumption of both BSs and RSs should be minimized. □

Based upon the observation that we obtain the results from GREAN problem (using a fixed K RSs), we present a solution to the BAPS problem based upon GREAN solution via a linear search on the number of RSs to place.

Algorithm 3 Budget Aware Power Saving (BAPS)(d_R^{max}, K)

```
P ← ∅;
for k ← 1 to K do
    p_k ← GREAN(d_R^max, K);
    P ← P ⋃ p_k;
end for
P_min ← the minimum value in P;
return P_min;
```

F. Multi-cell Scenarios

So far, we have studied all the problems in a single cell. But in practice, network carriers will deploy multiple macro cells in a market. The number of RS will be used for the whole market (multiple cells), instead of for each cell. Therefore, in this section, we study how to set up RSs for the multi-cell scenario.

Definition 4 (Multi-Cell Budget Aware Power Saving (MC-BAPS) problem)**.** Given B BSs in a network market, a set of users covered by these BSs, a total number of RSs (or micro cells) that can be distributed in the market (among B BSs). the MC-BAPS problem seeks:

1) the amount of RS (micro cells) to be allocated for each BS (macro cell)
2) the placement of RSs for each BS (macro cell)
3) the transmission power of each placed RS in each BS (macro cell)
4) the transmission power of each BS
5) the total power consumption of all BSs and RSs should be minimized □

In order to solve the MC-BPAS problem, one intuitive solution is to convert the multi-cell problem into the previously studied single cell problem. If the number of placed RS for each single cell is known, we can use BAPS algorithm to solve the single cell power saving problem. One major question to answer is *how to allocate RSs among multiple BSs (macro cells)?*. In other words, we need to know how many RSs (micro cells) to be used in each BS (macro cell), with the constraint that the total RSs placed cross the whole market is no more than K. We start by distributing RSs evenly among all of the B BSs. Then, we will try to check if we can achieve more savings if we move an RS from one macro cell (BS) to another. We will keep redistributing RSs among macro cells to save power until no more power can be saved.

Let us use an example in Fig. 6 to illustrate our algorithm. There are 4 cells in this market, denoted sa c_1, c_2, c_3, c_4. The maximum number of RSs K in this market is 16. Initially, we equally divide 16 RSs into each cell. So each cell has 4 RSs at the beginning. Then, for each cell we calculate the power consumption with 3 RSs, 4 RSs and 5 RSs. Next, we check if redistribution of RS numbers will provide more power savings. If C_2 reduce its RS to 3, while C_1 gets one more RS, we can see $P|_{k1=5} = 5$ and $P|_{k2=3} = 2$. Since $[P|_{k1=5} + P|_{k2=3}] = 7 > [P|_{k1=4} + P|_{k2=4}]$, no power can be saved during this RS redistribution. Thus, no RS redistribution between these two cells. However, RS redistribution between some cells do provide power savings, such as $\{3 \mid C_3 \rightarrow C_1\}$, $\{5 \mid C_3 \rightarrow C_2\}$ and $\{5 \mid C_3 \rightarrow C_4\}$. After RS redistribution, the number of RS in each cell is determined. Then, we will apply BAPS algorithm for each cell to find RS placement and power consumptions.

III. Numerical Results

In this section, numerical results are presented to show the effectiveness of our schemes, including GREAN, BAPS, MC-

Algorithm 4 MC-BAPS(d_R^{max}, K)

Initialize S_i and k_i to be empty;
for each user v_i in U **do**
  Assume user v_i access to the nearest BS bs_j: $S_j \leftarrow S_j \bigcup v_i$;
end for
Evenly distribute $\lfloor \frac{K_{budget}}{|L_{bs}|} \rfloor$ RSs into each BS;
while not DONE **do**
  $P \leftarrow \emptyset$;
  for each BS bs_i **do**
    $p_i \leftarrow \text{BAPS}(d_R^{max}, k_i)$;
    $p_i' \leftarrow \text{BAPS}(d_R^{max}, k_i + 1)$;
    $p_i'' \leftarrow \text{BAPS}(d_R^{max}, k_i - 1)$;
  end for
  for each BS bs_i **do**
    for each BS bs_j $(j \neq i)$ **do**
      if $(p_i' + p_j'') < (p_i + p_j)$ **then**
        Record energy saving $\triangle P_{ij} = [(p_i + p_j) - (p_i' + p_j'')]$ and add it into P;
      end if
    end for
  end for
  if P is empty set **then**
    DONE == 1;
  else
    pick $\triangle P = \max\{P_{ij} \forall i, j\}$;
    //Reduce 1 RS from bs_j, and shift the quota (1 more RS) to bs_i;
    $k_i \leftarrow k_i + 1$; $k_j \leftarrow k_j - 1$;
  end if
end while
for each BS bs_i **do**
  $p_i \leftarrow BAPS(d_R^{max}, k_i)$;
end for
$P_{total} \leftarrow 0$;
for each BS bs_i **do**
  $P_{total} \leftarrow P_{total} + p_i$;
end for
return P_{total};

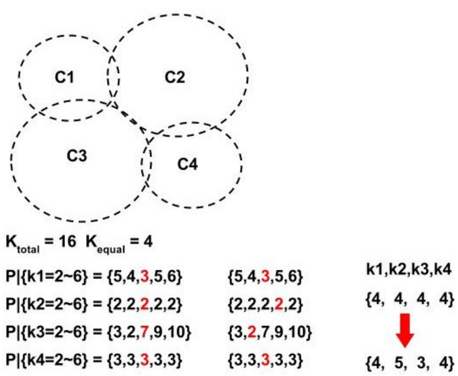


Fig. 6: Illustration of MC-BAPS

BAPS algorithms. All the simulations are run on a Intel Core i7 CPU of 2.7GHz with 8GB types of memory. All the users and BSs are uniformly distributed in a square testing field. All the figures illustrate the average of 10 test runs for various scenarios.

A. Simulation Environment Settings

In order to test the performance of GREAN and BAPS algorithms, we set a square region with size of $2km \times 2km$. The BS is placed at the centre of this region. We assume that this BS covers all the users in this region. There are $[50 - 550]$ users uniformly distributed in this two-dimensional region. Each user has a throughput of $[0.4Mbps - 1.4Mbps]$. The number of RSs K is changing from 3 to 36 for testing GREAN in this single cell. The maximum transmit range of RS is set to $300m$. In testing MC-BAPS algorithm, we set a multi-cell region with size of $3km \times 3km$. 4 BSs are uniformly distributed in this two-dimensional region. The number of users in multi-cell region is changing from 200 to 2200. The maximum number of RSs in this multi-cell region is changing from 20 to 130. We refer to [13], [14] and [2] for the parameters of our power models. We list all the parameters which are used in our power models in Table I.

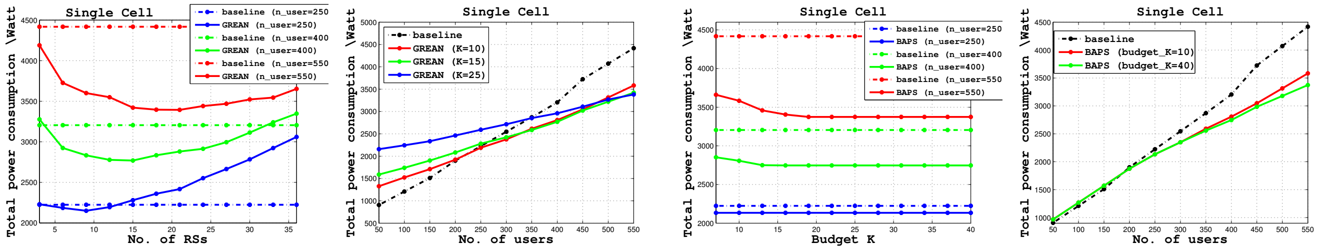
Symbols	Macrocell	Microcell
n_{sector}	3	n/a
n_{Tx}	2	n/a
$P_{el/rect}$	100 W	100 W
$P_{el/amp}^{max}$	156.3 W	16.6 W
$P_{el/trans}$	100 W	100 W
$P_{el/proc}$	100 W	100 W
$P_{el/link}$	80 W	n/a
$P_{el/airco}$	1500 W	60 W
R_{max}	1000 m	300 m
a	1.95e-6	7.7e-7
b	1.875	0.8
c	605	60

TABLE I: POWER MODEL PARAMETERS

In our work, we are targeting 4G LTE macrocell base station with 2×2 MIMO antennas in each sector. There are total three sectors in each base station. We present the evaluations of our schemes in the following sections.

B. Evaluation of GREAN algorithm

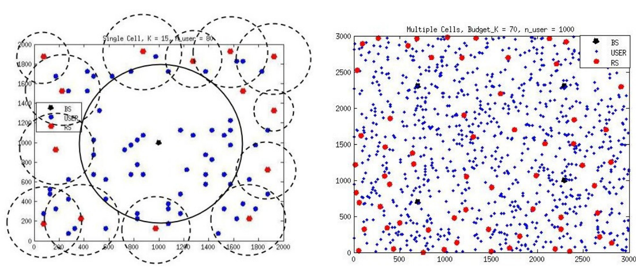
From Fig. 7(a) and 7(b), we can see that GREAN algorithm has good performance on power saving. Comparing with baseline in which no RS exists and all the users must get access to BS, GREAN can save up to 23% power consumption. More power can be saved especially when there are more users in the cell since power saving from more users can better counterbalance the static power consumption of placing K RSs. If we are given the exact number of RSs to place, network operator need to pay the static power consumption of these K RSs, air conditioning and rectifier consumption for instance. The dynamic power saving of each user can be seen as the difference between the power consumption for BS to cover this user and that for one RS to cover this user. If sum of the dynamic power saving for all the users is more than all the static power consumptions of K RSs, then we can say that total power consumption from current placements is lower than baseline. Thus, for the case of only a few users in the cell, sum of the dynamic power saving from all the users cannot counterbalance the static power consumptions of K RSs. Total power consumptions of both BS and K RSs would be larger than baseline. In other words, no power can be saved especially for the cell with few users. It can be easily seen from Fig. 7(a) and 7(b). In Fig. 7(b), we can easily find that when the number of users is less than 250, placing more



(a) Different no. of RSs (b) Different no. of users (c) Different budget K (d) Different no. of users

Fig. 7: GREAN and BAPS in different scenarios

than 10 RSs will cause over-baseline power consumptions. Our scheme does not work well in these cases. Moreover, larger K would require more users to counterbalance the static power consumptions in order to achieve power saving. It can be seen from Fig. 7(b) between blue line and red/green line. In Fig. 7(a), we can see a trend of power consumptions for a fixed number of users with increasing the number of RSs placed. More RSs being placed does not mean more power can be saved in the cell. For a fixed number of users, placing the first few RSs will easily achieve power saving since the dynamic power saving for covering all the users can easily counterbalance the static power consumption of these few RSs. With more RSs placed in this cell, the static power costs will grow linearly with the number of RSs while the dynamic power saving will grow more and more fast at the beginning and then grow slowly down. Thus we can see the trend. From this trend, we can know for a single cell with fixed number of users, there would be a maximum power saving corresponding to a certain number of RSs placed in. We illustrate the GREAN results in Fig. 8(a) with the number of RSs fixed to 15 and that of users fixed to 80. We can see the coverage circles of each station in this cell.



(a) GREAN results (b) MC-BAPS results

Fig. 8: Illustration of GREAN and MC-BAPS results

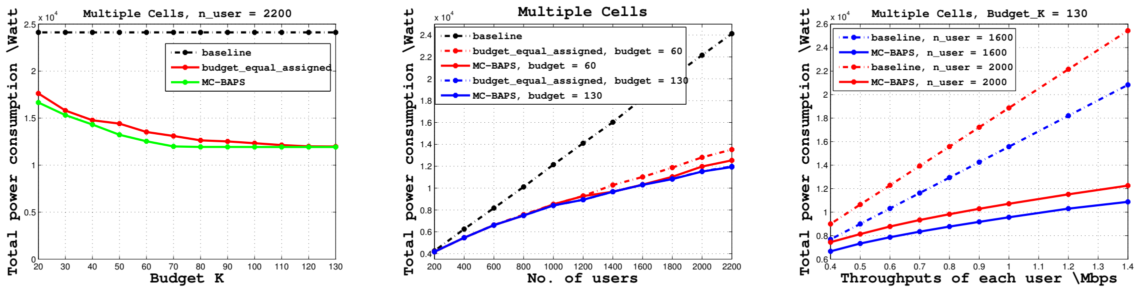
C. Evaluation of BAPS algorithm

From Fig. 7(a) we know, there would be an optimal number of RSs achieving the most power saving in a fixed user scale. Since BAPS is based on linear searching on the number of RSs and selecting the minimum power consumption as its result, it will always return the same result if the given maximum number of RSs is more than the optimal number of RSs. Hence we can see in Fig. 7(c), the solid red line is decreasing with maximum number of RSs increasing until K_{max} reaches 19. We can say, for this single cell with a user scale of 550, in order to achieve the most power saving, we need to place 19 RSs in this cell. We denote the optimal number of RSs as K_{opt}. From Fig. 7(c), we can see $K_{opt} = 19$ for a user scale of 550, $K_{opt} = 13$ for a user scale of 400, and $K_{opt} < 10$ for a small user scale of 250. From Fig. 7(d) we see, in a user scale larger than 200, we can see BAPS has good power saving comparing with baseline. The more power saving, the more users get involved in this cell.

D. Evaluation of MC-BAPS algorithm

In the multi-cell cases, we add one more baseline in which we set the maximum number of RSs in each cell is equally divided from the maximum number of RSs in this region. Comparing with this new added baseline, we can see how much our MC-BAPS algorithm outperforms the equal assignment solution. From Fig. 9(a) and 9(b), we see both MC-BAPS and equal assignment solution outperforms baseline pretty much. Furthermore, MC-BAPS outperforms equal assignment solution up to 11%. MC-BAPS saves more power comparing with equal assignment solution and baseline in a larger user scale. From Fig. 9(b) we can see, when $K_{total} = 130$, MC-BAPS and equal assignment solution has the same performance since K_{opt} for each cell is much smaller than 32 ($\lfloor \frac{130}{4} \rfloor$). Each cell achieves the same power saving with either one more RS placed in or one less RS placed in so that no K transference is needed. Without K transference, our MC-BAPS makes no improvement against equal assignment solution. They have the same results.

In Fig. 9(c), we vary the throughputs of each user from $0.4Mbps$ to $1.4Mbps$. With a larger throughput, both baseline and our scheme will have a higher power consumption since BS or RSs need to consume more power to maintain the communication link with its covering users when they have a larger traffic demand. However, our scheme can achieve a larger power saving when each user has a higher throughput, as can be easily seen in Fig. 9(c). Also, in a multi-cell region, we can find that our scheme can have more than 50% power saving in some scenarios. All the numerical results show that our schemes outperforms baseline pretty much. They can achieve a large amount of power saving, especially in a large user scale. We illustrate the MC-BAPS results in Fig. 8(b) with maximum number of RSs for this multi-cell region fixed to 70 and the number of users set to 1000. From Fig. 8(b), we can



(a) Different K_{total} (b) Different no. of users (c) Different throughputs of each user

Fig. 9: Multiple cells

see 4 BSs are located near the four corners of this region. All the red points construct a RS set which is our MC-BAPS result.

IV. Conclusion

In this work, we proposed a new perspective on Green Wireless Networking. Without turning off BSs, our proposal is to deploy small cells to offload traffic from macro cell base stations to achieve power saving. We proposed the GREAN problem to find a joint solution for RS placement and RS/BS power consumption to save total network energy. An approximation algorithm was presented for a special case problem GREAG. Then a $(1+\alpha)$-approximation algorithm was presented for the GREAN problem. This paper also studied the MC-BAPS problem for multi-cell scenarios. Extensive numerical results have been conducted to support our theoretical analysis and showed that our schemes can provide up to 52% network power consumption compared to traditional wireless macro cell networks.

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