Greening Wireless Relay Networks: An SNR-Aware Approach

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Abstract—With the exploding popularity of wireless communication, the radio spectrum has become a scarce commodity. To further improve the network capacity, various solutions have been proposed to increase spectrum efficiency and network throughput. Small cell network is one of these new trends for next generation mobile network design. One model is using relay stations (RS) as small cell providers to achieve extended coverage, lower cost, and higher network capacity. Considering multiple related physical constraints such as channel capacity, signal to noise ratio (*SNR*) requirement of subscribers, relay power and network topology, this paper studies a joint signal-aware RS placement and power allocation problem with multiple base stations in wireless relay networks. We presented approximation schemes which first find a minimum number of RS, using maximum transmission power, to cover all the subscribers meeting each *SNR* requirement, and then ensure communications between any subscriber to a base station by adjusting the transmission power of each RS. Numerical results are presented to confirm the theoretical analysis of our schemes, and to show strong performances of our solutions.

Index Terms—Wireless relay network, relay station placement, two tiered network, power allocation, hitting set, approximation algorithm, minimum spanning tree

1 Introduction

With the exponential growth in mobile data traffic, how to better utilize the spectrum and improve network throughput has been an important issue in telecommunication. Many are using WiFi data offloading as a more efficient use of radio spectrum. Others are looking into how to improve network capacity by better reusing spectrums. Small cell network is one of many new trends for next generation wireless networks since many mobile network operators see small cells as vital to managing spectrum more efficiently. Ideally, small cell network scheme can help network carriers to achieve extended coverage and higher network capacity. One of the feasible small cell network designs is using relay stations (RS) to offload traffic that directly transmitted to/from macro cells.

Relay station placement has been an active research topic in wireless networks, especially in wireless sensor networks. By using RSs, one could deploy a network at a lower cost than using only (more expensive) BSs to provide wide coverage while delivering a required level of service to users [9], [12], [13], [16]. In [14], Lin and Xue proved the single-tiered placement problem with $R = r$ and $K = 1$ is NP-hard, where R, r and K denote the transmission range of relay nodes, the transmission range of sensor nodes, the connectivity requirement respectively. A 5-approximation algorithm was presented to solve the problem. The authors also designed a *steinerization* scheme which had been used by many later works. Beside minimizing the number of placed RSs, extensive research has been done on placement with physical constraints, such as energy consumption and network lifetime. Hou et al. studied the energy provisioning problem for a two-tiered wireless sensor network [10]. Besides provisioning additional energy on the existing nodes, they considered deploying relay nodes (RNs) into the network to mitigate network geometric deficiency and prolong network lifetime. In [17], Hassanein et al. proposed three random relay deployment strategies for connectivity-oriented, lifetime-oriented and hybrid deployment. In [15], Pan et al. studied base station (BS) placement to maximize network lifetime. Recently, a new dual-relay coverage architecture was proposed for 802.16j mobile multi-hop relay-based (MMR) networks [12], [13], where each subscriber station (SS) was covered by two RSs. [12] assumed that only one RS was placed in each cell. ILP formulation was applied to find an optimal placement of RS which could maximize the cell capacity in terms of user traffic rates. In [13], assuming a uniform distribution on user traffic demand, the authors studied how to determine the RSs' locations from a set of predefined candidate positions. Quality of service provisioning in telecommunications networks has been shown to be important to study in practice [5]. Considering channel quality, the authors of [18] studied multiple hop relay problem with consideration of channel capacity. Two tiers model was mentioned as well, but it addressed the relay placement problem on condition that all relay nodes

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forwarded traffic in their maximum transmission power. In addition, an efficient MUST algorithm was proposed to address the connectivity problem on upper tier. However, MUST worked under the physical constraint of only one base station in the field. Gao et al. [7] improved the research of [18] by taking *SNR* constraint into consideration and allowing multiple BSs in the field. Similar scenarios of two-tier network were studied. It proposed several efficient algorithms to solve not only the minimum RS placement problem but also the minimum power allocation problem.

In this paper, we extended the research of [7] by considering different *SNR* thresholds to users. Each user has its own *SNR* threshold value based on its data rate request. Generally, users have higher *SNR* thresholds when higher data rate are requested. However, the *SNR* threshold considered in [7] was a constant in a range of $[-25, -10\,dB]$ for all users. This universal setting of *SNR* threshold is not practical enough since user requests are normally heterogeneous. To the best of our knowledge, this paper is the first one to study low-cost multi-hop relay problem considering channel capacity, subscriber's *SNR* requirement, power consumption of relay nodes and multiple base stations in wireless multi-hop networks.

The rest of the paper is organized as follows. Concept definitions and problem statement are presented in Sections 2 and 3, which are followed by Sections 4, 5 and 6, which present *Linear Programming with Quadratic Constraints* (LPQC) based solutions and approximation algorithms. In Section 7, we use extensive numerical results to show the good performances of our proposed schemes. This paper is concluded in Section 8.

2 Network Model

In our model, a wireless multi-hop network consists of *subscriber stations*, *base stations*, and *relay stations*. In reality, several types of SS exist, including static SS, adhoc SS and compound SS. In recent study, [2] has demonstrated that traffic from mobile access is less than 20 percent, while majority of wireless traffic is actually coming from infotainment (such as video streaming, online gaming), which would not be used by mobile users regularly. It is also shown that most mobile users usually only check emails and browse web, which only contributes a small proportion of total traffic. In [1], it shows that web browsing accounts for 10 percent and less than 10 percent in 2013 and 2019, respectively. Given this character of wireless traffic, in this work, we assume that SSs are *static users* such as Wal-mart, McDonald's, and gas stations, which are static but have large traffic demands. Each SS represents the aggregated traffic coming from these service locations.

Similarly, all the RSs, with the function of relaying traffic coming from BS, other RSs, or SS, are assumed to be fixed as well in this paper. Our network model divides the network into two tiers, *lower tier* and *upper tier*. In the lower tier, *coverage RSs* are placed in order to *cover* all the SSs while *meeting SS's performance requirements* such as channel capacity, *SNR* threshold. Communications in the lower tier are mainly between SSs and coverage RSs, which are denoted as "*access links*". In the upper tier, *connectivity RSs* are to be placed in order to *connect coverage RSs to BSs, using possible multiple-hop relay model*. The communication links in the upper tier are denoted as "*relay links*" in this paper. The scenario described above is illustrated in Fig. 1.

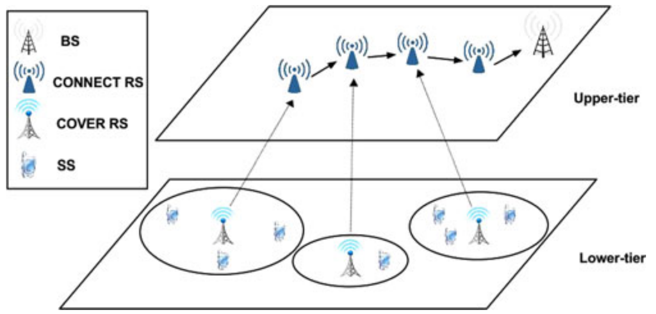


Fig. 1. Scenario illustration.

2.1 *SNR*-Aware Green Relay Allocation

Each SS needs to be covered by an RS or BS for traffic transmission. Different from most previous work, we take channel capacity and *SNR threshold* into consideration in this work. The *access links* between an SS and its coverage RS should provide enough channel capacity to satisfy the SS's data rate request. In addition, for each SS being able to correctly decode signals, *its received signal to noise ratio (SNR) is another parameter that should be considered*. Typical 802.16 adaptive modulation and coding parameters are used to estimate the throughput achievable as a function of *SNR*. The relationship among adaptive modulation, minimum *SNR* and user throughput is listed in Table 1. From Table 1 we can see, each user needs to satisfy a minimum *SNR* threshold if its throughput reaches in the range $[10, 45\,Mb/s]$. For instance, if an user has $25Mb/s$ throughput, then its received *SNR* needs to be at least $14.5\,dB$ so that it can correctly decode the signals. Hence, there are different *SNR* threshold values for the users with various data rate requests.

Definition 1 (Feasible coverage). *Let s_i be a fixed SS with known location, and b_i be its data rate request (in terms of* bps*). An RS r_m is said to provide* a feasible coverage *for s_i if the channel capacity of the link (in terms of* bps*) between s_i and r_m is sufficient for the data rate request of s_i;* ***and****, the* SNR *received at s_i is above the* SNR *threshold.*

Definition 2 (SNR for subscribers). *Let s_i be an SS,* $\mathrm{R} = \{r_1, r_2, \ldots, r_n\}$ *be the RS set and* $\mathrm{P} = \{p_1, p_2, \ldots, p_n\}$ *be the set of received power by s_i from each RS. If SS s_i receives signal from RS r_j, the* SNR *at s_i is defined as* $\frac{p_j}{\sum_{i=1}^{n} p_i - p_j}$.

To simplify the study, we transform the *capacity* and *SNR* requirements into *distance* requirements since the capacity of a wireless link is highly related to the distance between transmitters and receivers [6]. In this paper, we choose two-ray ground path loss model for modeling the long distance LOS channel with large scale signal strength. The received power P_r is given as

$$P_r = P_t G_t G_r h_t^2 h_r^2 d^{-\alpha}, \tag{2.1}$$

where P_t is the transmission power, and G_t,G_r and h_t,h_r are the gains and heights of transmitter tower and receiver tower, respectively. d is the euclidean distance between the

TABLE 1
Minimum *SNRs* with Various Throughput

Modulation	Minimum SNR, dB	User throughput, Mb/s
QPSK 1/2	10	10
16QAM 1/2	14.5	20
16QAM 3/4	17.25	30
64QAM 2/3	21.75	40
64QAM 3/4	23	45

two end nodes, α is the attenuation factor, which usually varies in a range of $2-4$. According to Shannon's theorem, wireless link capacity is given by $C = B\log(1+SNR_r)$, where B is the channel bandwidth. Thus, if noise N_0 is a constant, the channel capacity (in terms of bps) is only related to the received signal power P_r and moreover only related to the distance between two end nodes assuming transmission power P_t of RS is constant. Therefore, the capacity requests of SS are equivalent to distance requests between SS and its corresponding RS.

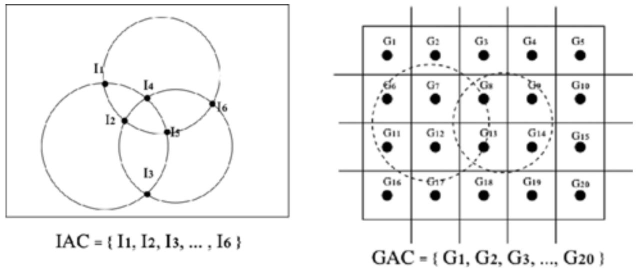
3 Problem Statements

Definition 3 (SNR Aware Green (SAG Relay problem)). *Given a wireless relay network with multiple BSs and a set of SSs $S = \{s_1, s_2, \ldots, s_n\}$, let $SNR = \{\beta_1, \beta_2, \ldots, \beta_n\}$ be the feasible* SNR *thresholds for SSs, The SAG problem seeks a minimum number of RSs R and transmission power allocation strategy for R such that:*

1) *Providing feasible coverage for each $s_i \in S$. Specifically, each SS $s_i \in S$ has enough* SNR *and an access link with enough capacity to an RS or BS;*
2) *Each placed RS must provide enough capacity on relay links to transit traffic to a BS;*
3) *Sum of transmission powers of the placed RSs should be minimized.*

Unlike previous coverage problems, which assume that RSs always transmit in maximum power, we allow to adjust power consumption of RSs as long as the adjustment does not change the coverage topology. A similar problem, DARP, has been studied in [18] without considering power minimization. Since DARP is estimated to be *NP*-hard [18], we expected SAG to be *NP*-hard as well. To solve SAG, our solution consists of two aspects, *coverage with minimum number of RSs*, and *minimizing transmission power of the placed RSs*. First, we assume that all the RSs are operating with maximum transmission power. With this assumption, we aim to find *a minimum number* of RSs to provide *feasible coverage* for all the SSs. In the second step, power optimization scheme will be applied to reduce the power consumptions. Naturally, we divide the original problem into two subproblems, *Lower-tier Coverage Relay Allocation* (LCRA) problem and *Upper-tier Connectivity Relay Allocation* (UCRA) problem, which are defined in following, and try to tackle them one by one.

Definition 4 (Lower-tier Coverage Relay Allocation problem). *Given a wireless relay network with a set of subscriber station $S = \{s_1, s_2, \ldots, s_n\}$, and the* SNR *threshold set for SSs $SNR = \{\beta_1, \beta_2, \ldots, \beta_n\}$. The LCRA problem seeks* K, minimum number *of relay stations to provide* feasible coverage *for $s_i \in S$, and* the total transmission power by deploying K RSs is minimized.



(a) IAC construction (b) GAC construction

Fig. 2. Illustration of IAC and GAC.

On the upper tier, we need to consider how to transmit all the traffic from *coverage* RSs to BSs. We name the RSs placed on the upper tier *connectivity RSs* since the function of RSs in UCRA is to relay the communications between coverage RSs and BS. Similar to LCRA problem, we first assume that RSs relay with *maximum power* so that we can determine the minimum number of RS locations.

Definition 5 (Upper-tier Connectivity Relay Allocation problem). *Given a wireless relay network with a set of coverage RSs $R_c = \{r_1, r_2, \ldots, r_n\}$, distance requirements $D_r = \{d_r^1, d_r^2, \ldots, d_r^n\}$ for R_c, set of base stations $B = \{bs_1, bs_2, \ldots, bs_m\}$, UCRA seeks a* minimum number of connectivity RSs *operating with minimum power that ensures the communications between* coverage RSs *and BSs.*

In next sections, we will first tackle LCRA and UCRA problems separately, and then provide a solution to SAG by using a combination of the solutions to LCRA and UCRA.

4 Approximation Solutions for LCRA

Unlike the *pure* coverage problems, LCRA problem needs to take SS's *SNR* requests into consideration, which makes the LCRA problem more complicated. For example, to solve pure coverage problems in [18], we could allocate circles' intersection points as candidate positions for coverage RSs, which are finite, to find best solutions. However, circles' intersection points might not guarantee feasible solutions for LCRA due to the *SNR* requirements. Though placing multiple RSs to cover multiple SSs can satisfy the distance requirements of SSs, it is likely that these RSs could interfere with each other, and result in unbearable *SNR* at some SSs.

To find a more appropriate solution for feasible coverage, we propose to use *small scale of grids spreading around entire field* as candidate RS locations. The benefit of using grids is that most of the field can be considered if we adjust the grid size small enough. However, smaller grid size will generate more candidate positions. Hence, the running time could be non-linearly increasing with smaller grid size. Therefore, *how to pick a right grid size to achieve the best tradeoff between solution quality and running time* is a critical issue. We propose two schemes to find best candidate positions:

1) *Intersections As Candidates* (IAC): *including all the intersection points between any two SS's feasible circles*, which is illustrated in Fig. 2a.

2) *Grids As Candidates* (GAC): *including all the center points of grids which divide the entire field*, which is shown in Fig. 2b.

It is easy to see that the number of candidate positions in GAC is highly related to the grid size. The smaller the grid size, the more accurate results we can obtain. Thus, we set the grid size as small as possible as long as optimizer software (e.g. Gurobi 5.0) can find results.

To solve LCRA, we first aim to find a minimum number of RS to cover SSs assuming RSs are using maximum transmission power (details in Section 4.1). Next step, in Section 4.2, we try to adjust transmission powers of RSs to further reduce the total power consumption without losing coverage. We outline the framework of our solution in the following. Details of each step are given in Section 4.1.

Algorithm 1. Framework of LCRA Solution

STEP_1: Algorithm 2 - *Cover all the users by minimum number of RSs, assume each RS using its maximum power*
  STEP_1.1: Algorithm 3 - *Split users into multiple zones, and then cover them zone by zone*
  STEP_1.2: Algorithm 4 - *Try to identify users that are covered by only one RS*
  STEP_1.4: Algorithm 5 - *Tweak RS positions to make them become feasible*
    STEP_1.5: Algorithm 6 - *update coverage map once an RS's position is modified*
STEP_2: Algorithm 7 - *Adjusting the power of each placed RS to further reduce energy consumption*

4.1 Coverage under *SNR* Constraint

Given a relay network with a set of SS $S = \{s_1, s_2, s_3, \ldots, s_n\}$, corresponding feasible distance $D = \{d_1, d_2, d_3, \ldots, d_n\}$ and *SNR* threshold $\beta = \{\beta_1, \beta_2, \beta_3, \ldots, \beta_n\}$. We first formulate an Integer Programming with quadratic constraints ILPQC to obtain optimal solutions. Let T_i and T_{ij} be the indicator variables in our ILPQC , where T_i indicates if candidate position i is chosen to place RS, and T_{ij} denotes if SS s_j has a feasible access link with RS at position i. The ILPQC is listed as below:

Objective

$$min \sum_{alli} T_i \tag{4.1}$$

Subject to :

$$T_i \leq \sum_{allj} T_{ij} \leq nT_i \qquad \forall i \tag{4.2}$$

$$\sum_{alli} T_{ij} = 1 \qquad \forall j \tag{4.3}$$

$$d_{ij}T_{ij} \leq d_j \qquad \forall i \forall j \tag{4.4}$$

$$\frac{d_{ij}^{-\alpha}}{\sum_{alli} d_{ij}^{-\alpha}T_i - d_{ij}^{-\alpha}T_i} \geq \beta_j T_{ij} \quad \forall j, \tag{4.5}$$

where (4.1) is the objective to find the minimum number of RS positions. Linear constraint (4.2) states that each placed RS covers at least one SS. Linear constraint (4.3) states that each SS can access to only one RS. Linear constraint (4.4) states feasible distance requirement for each SS. Quadratic constraint (4.5) states that each SS should satisfy its *SNR* constraint. Both IAC and GAC are used to generate the set of candidate positions.

The formulation will provide the minimum number of RSs that can provide feasible coverage, and is used as the benchmark for performance evaluation in later sections. However, with the number of SSs increasing, the running time of the formulation with quadratic constraints increases exponentially. Therefore we propose a polynomial-time solution as a practical solution for large networks, which is listed in Algorithm 2.

Algorithm 2. *SNR* Aware Minimum Coverage (SAMC) (S,D,β)

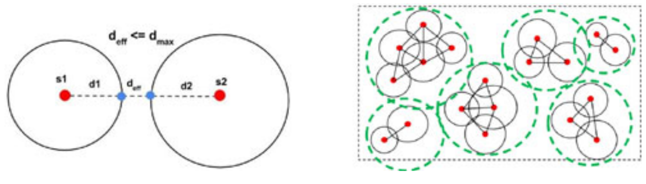
```
Initialize set L_ss = {L_ss^1, L_ss^2, ..., L_ss^m} which denotes SS
    groups to be returned from Zone Partition;
L_ss <- Zone Partition (S,D);
Initialize sets L_RS = {L_RS^1, L_RS^2, ..., L_RS^m} which denotes
    each coverage RS group placed for each SS group;
for each SS group L_ss^i do
    K_mhs^i = Minimum Hitting Set (L_ss^i, D_i);
    G_i = Coverage Link Escape(L_ss^i, D_i, K_mhs^i);
    L_RS^i = Sliding Movement(G_i, L_ss^i, D_i, beta);
end for
for any L_RS^i in L_RS do
    if there exists a L_RS^i = ∅ then
        return infeasible;
    else
        L_RS = L_RS^1 ∪ L_RS^2 ∪ ... ∪ L_RS^m;
        return L_RS;
    end if
end for
```

The first step, Algorithm Zone partition, is to partition the field into several zones such that SSs and RSs in one zone will be distant from the stations in other zones. Thus, the interferences between *inter-zone* RS/SS pairs are small enough to be ignored. Details of Zone partition are presented in Algorithm 3.

Algorithm 3. Zone Partition(S,D,N_{max})

```
calculate d_max according to N_max, where P_max G d_max^(-alpha) = N_max,
    G = G_t G_r h_t^2 h_r^2, N_max is the maximum noise which can be
    ignored;
create a new graph G involving all SSs in;
for any two SSs s_i, s_j in G do
    d_eff <- min{dist(s_i, s_j)-d_i, dist(s_i, s_j)-d_j};
    if d_eff <= d_max then
        add edge e(s_i, s_j) to G;
    end if
end for
find the connected components of G;
return SS groups of each connected component;
```

Figs. 3a and 3b illustrate how the entire field can be divided into several independent zones. In Fig. 3a, the effective distance d_{eff} between s1 and s2 is calculated as $d_{eff} = dis(s1, s2) - d1 - d2$. If d_{eff} is less than or equal to d_{max}, which



(a) Effective distance (b) Independent zones

Fig. 3. Illustration of Zone partition.

is the maximum distance between two SSs to ensure that one RS covering one SS may generate interferences to the other SS, we can add an edge from s1 to s2, which means that any RS placed to cover s1 may generate interferences to s2 (or vice versa). On the other hand, if d_{eff} is larger than d_{max}, s1 and s2 can be assigned to different independent zones. Any RS placed to cover s1 (or s2) will not interfere s2 (or s1). Using this scheme, we test each pair of SSs, and generate several independent zones as shown in Fig. 3b.

In *Line 5* of Algorithm 2, for SSs in each zone, we first find a set of RSs to cover all the SSs satisfying distance requirements by solving a *hitting set* problem. Mustafa and Ray [11] propose a $(1+\epsilon)$ approximation algorithm to solve minimum hitting set problem in geometry. Next, we aim to to satisfy the *SNR* requirements by adjusting RS positions. We notice that if one SS is covered by only one RS, named *one-on-one coverage*, then this RS could be moved closer to the covered SS (and hence further from other SSs). In this way, we can save power for the SS and RS over access links, and reduce the possibility of interfering other SSs. *Naturally, the more one-on-one coverage, the higher probability of satisfyingSNRrequirements for SSs*. To seek more one-on-one coverage, Coverage Link Escape (Algorithm 4) is used in *Line 6* of Algorithm 2.

Algorithm 4. Coverage Link Escape(S,D,K_{mhs})

construct a bipartite graph G between side A with all SSs, and side B including all the points in K_{mhs}, where K_{mhs} is the RS set returned by minimum hitting set algorithm;
for every SS s_i in side A **do**
  for every point p_i in K_{mhs} **do**
    if p_i is in or on c_i **then**
      add edge $e(s_i, p_i)$ to G;
    end if
  end for
end for
calculate $n_{max} \leftarrow$ the maximum number of edges including the same point in side B;
assume that all the edges in G and all the points in side B are not marked initially;
for n from n_{max} to 1 **do**
  for every unmarked point p in side B **do**
    if there are n edges containing p **then**
      mark these n edges;
      mark point p;
      for each recent marked edge $e(p, q)$ **do**
        delete all the unmarked edges containing point q;
      end for
    end if
  end for
end for
return bipartite graph G;

After Coverage Link Escape, it is still possible that some RSs can only provide feasible distance coverage but not *SNR* for SSs. We call these place RS "*infeasible* RSs". To reduce *infeasible* RSs and improve the performance, in *Line 7* of Algorithm 2, we propose the Sliding Movement scheme, whose details are in Algorithm 5. For each infeasible RS location, which is on each covered SS's feasible circle, we try to "*slide*" the RS along the corresponding SS's feasible circle to try to find a feasible RS location. The question is *how to slide the infeasible candidates along SS's feasible circles*. The impact of sliding is complicated because it will not only *affect the signal power received by its covering SSs* but also *the noise received by other SSs*. One SS may receive higher *SNR* at the cost of other SSs suffering lower *SNR* as the result of a sliding operation. One method is to find infeasible coverage RSs which cannot satisfy *SNR* constraints. Then, based on the coverage topology, we try to slide the infeasible RSs along its covering feasible circles in order to clear *SNR* violations. If some *SNR* violation could not be cleared, we mark its covering RS as *un-slidable*. After sliding all infeasible RSs, we get a set of *slidable* RSs and their updated locations. Since updating slidable RSs can change the coverage topology, every SS' *SNR* constraint needs to be rechecked. To avoid of exponentially large number of updating of slidable RSs, we sort slideable RSs using the following criteria: $\frac{SNR\ gain\ for\ covered\ SS's\ after\ sliding}{geneated\ noise\ to\ other\ SSs\ after\ sliding}$, and slide all the violated RSs one by one in polynomial time. The details are in Algorithm 6. If all the SSs meet their *SNR* requests, we found a feasible solution for the SAMC problem. Otherwise, SAMC will return infeasible.

Algorithm 5. RS Sliding Movement(G, S, D, β)

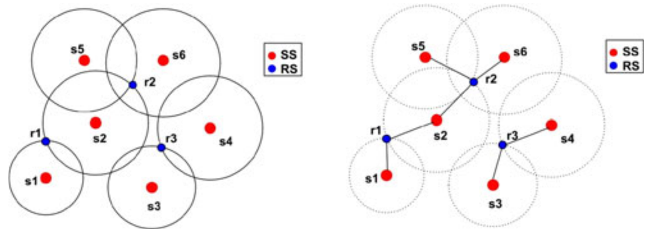
$H \leftarrow \emptyset, B \leftarrow \emptyset$;
for every point p in side B of G **do**
  if there is only one edge $e(p, q)$ containing p **then**
    if p and q are not at the same location **then**
      move p to the same location as q;
    end if
    $H \leftarrow H \bigcup \{p\}$;
    delete point p and corresponding SS in G;
  end if
end for
for every SS s_i in side A **do**
  check if *SNR* constraint β of s_i can be satisfied
  if not, mark s_i;
end for
$B = B \bigcup \{\text{all marked } s_i\}$;
if B is empty **then**
  $H = H \bigcup \{\text{all RSs in side B}\}$;
  return H;
else
  $R_u^s \leftarrow$ all the RSs in side B covering the SSs in B;
  $R_r^s \leftarrow$ all the rest RSs in side B;
  $H' \leftarrow$ update RS topology $(R_u^s, R_r^s, G, S, D, H, B)$;
  if $H == H'$ **then**
    $H' \leftarrow \emptyset$;
  end if
  return H'
end if

Algorithm 6. Update RS Topology $(R_u^s, R_r^s, G, S, D, H, B)$

for each RS r_i in R_u^s **do**
  $W \leftarrow \emptyset$;
  let s_k and s_j denote SSs whose SNR can and cannot be met under coverage of r_i, respectively;
  construct a virtual circle c_j' for each s_j to ensure that s_j's SNR can be met only if r_i moves into c_j';
  W=$W \bigcup$ {all virtual circles c_j'} $\bigcup$ {all feasible circles c_k of s_k};
  if all the circles in W have common area **then**
    mark r_i as slidable to r_i' in R_u^s, where r_i' is the centre of the common area;
  else
    mark r_i as un-slidable in R_u^s;
  end if
end for
for each slidable r_i in R_u^s **do**
  let s_j be such that s_j's SNR cannot be satisfied under the coverage of r_i;
  $\triangle_{snr}^i \leftarrow SNR_{r_i'}^{s_j} - SNR_{r_i}^{s_j}$;
  $S_i \leftarrow S/s_j$; $I_i \leftarrow 0$;
  for each SS s_k in S_i **do**
    $I_i^k \leftarrow I_{r_i'}^{s_k} - I_{r_i}^{s_k}$;
    $I_i \leftarrow I_i + I_i^k$;
  end for
  $\triangle_i \leftarrow \frac{\triangle_{snr}^i}{I_i}$;
end for
construct the pairs $(\triangle_i, r_i, r_i')$;
$i_{max} \leftarrow argmax_{i \in |R_u^s|} \triangle_i$;
update $r_{i_{max}}$ to $r_{i_{max}}'$ and obtain an updated R_u^s;
if all SNRs satisfied **then**
  $H \leftarrow H \bigcup R_r^s \bigcup R_{u'}^s$;
else
  record the unsatisfied SSs into a new set B';
  if size(B') < size(B) **then**
    $R_u^{s'} \leftarrow$
    all the RSs in side B covering the SSs in B';
    $R_r^{s'} \leftarrow$ all the rest RSs in side B;
    $H \leftarrow$
    Update RS Topology ($R_u^{s'}, R_r^{s'}, G, S, D, H, B'$);
  end if
end if
return H;

Let us use an example to illustrate how SAMC works. Because we divide the entire field into several independent zones, and all the operations in each independent zone are the same, we use one independent zone for our demonstration.

Fig. 4a shows the results from minimum hitting set algorithm. There are six SSs in this independent zone. The best solution is placing 3 RSs to cover s1 to s6. In Fig. 4a, r1 covers s1 and s2, r2 covers s2, s5, s6, and r3 covers s3 and s4. Coverage links are established in Fig. 4b.

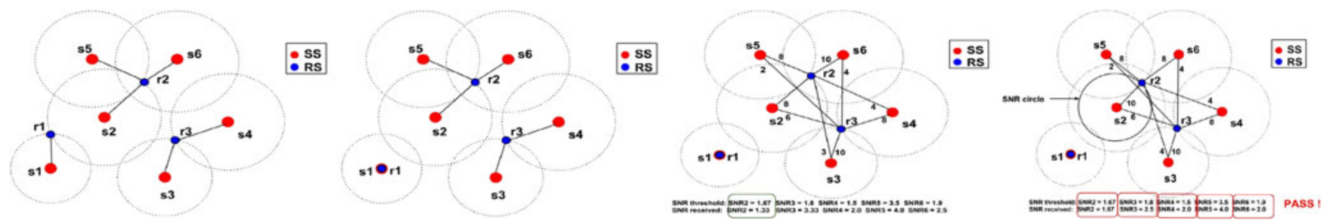


(a) Minimum hitting set (b) Coverage link establishment

Fig. 4. Minimum Hitting Set and Coverage Topology.

Figs. 5a, 5b, 5c, and 5d show how Coverage Link Escape and RS Sliding Movement work, which are the core of SAMC. In Fig. 5a, as we know, one SS can only get access to one RS. In Fig. 4b we see, s2 gets access to both r1 and r2. According to Coverage Link Escape scheme, the access link between s2 and r1 is a redundant link and it can be deleted since the degree of r1 is less than that of r2 ($2 < 3$). Now since r1 covers only one SS s1 after removing link (*s2, r1*), it can be moved to be co-located with s1 in order to avoid interfering with other SSs as Fig. 5b shows. Since r1 co-locates with s1, it only needs a very low transmission power to maintain the coverage, and generate no interference to other SSs. Then we check each SS's *SNR* requirement in Fig. 5c, and find that s2's *SNR* requirement cannot be satisfied. In terms of RS Sliding Movement, r2 needs to be slided along s5's feasible circle in order to find a feasible location which is in the common area among s2's *SNR* circle, s5's feasible circle and s6's feasible circle. s2's *SNR* circle is shown in Fig. 5d. In Fig. 5d, after massaging r2's location, we recheck each user's *SNR* requirement. Eventually, SAMC finishes when all *SNR* requirements are satisfied.

In the beginning of SAMC algorithm, we invoke *minimum hitting set* algorithm to get the coverage RSs without considering *SNR* constraints. Then we are checking if each SS's *SNR* could be met using coverage RSs topology. If there exist some SSs whose *SNR* constraints are not satisfied, we need to slide coverage RS's point along its covering SSs' feasible circles in order to find a feasible solution. During the process of SAMC, *no coverage RSs are deleted or added in order to meet SSs' SNRconstraints*. Consequently, *the result of SAMC has the same number of coverage RSs as the number returned from the minimum hitting set solution*. Therefore, SAMC's performance is highly related to minimum hitting set algorithm, following the same scheme used in [18]. Mustafa and Ray [11] gives an $(1+\epsilon)$-approximation PTAS for the minimum hitting set problem. We adopt the PTAS, and claim



(a) delete redundant access link (b) move RS co-locatedly with SS (c) test *SNR* requirements (d) slide violated RS

Fig. 5. Illustration of Coverage Link Escape and RS Sliding Movement.

that if SAMC returns a feasible solution, it is also an $(1+\epsilon)$-approximation solution. In other words, if SAMC returns a feasible solution K, the number of RS provided by K will be no more than $(1+\epsilon) * |OPT_C|$, where OPT_C is an optimal solution with the minimum number of RSs that can provide feasible coverage.

4.2 Power Reduction Optimization

In the previous section, we find feasible coverage RSs assuming that RSs are transmitting at their *maximum* powers in SAMC. In this section, we aim to *adjust transmission powers* of the placed RSs so that we can *further reduce the energy consumption while maintain coverage and SNR constraints*.

Given a fixed network topology consisting of SSs and *coverage* RSs found by SAMC, we first present another linear programming with quadratic constraints to get an optimal RS transmission power allocation so that the total transmission power is minimized. Let P_i denote the transmission power of ith RS in coverage RSs, which is in the range of $[0, P_{max}]$, and T_{ij} be the indicator of whether SS s_j communicates with RS_i. The goal is to $min \sum P_i$

Objective :

$$min \sum_{alli} P_i \tag{4.6}$$

Subject to :

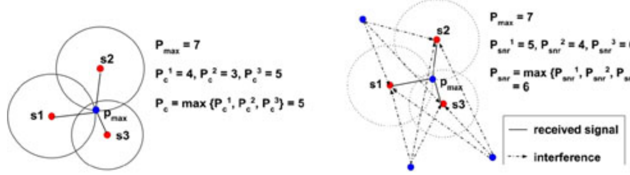
$$\sum_{alli} T_{ij} = 1 \qquad \forall j \tag{4.7}$$

$$P_i G d_{ij}^{-\alpha} \geq P_{ss}^j T_{ij} \qquad \forall j \tag{4.8}$$

$$\frac{P_i G d_{ij}^{-\alpha}}{\sum_{alli} P_i G d_{ij}^{-\alpha} - P_i G d_{ij}^{-\alpha}} \geq \beta_j T_{ij} \quad \forall j. \tag{4.9}$$

According to the two-ray model, $P_r = P_t G_t G_r h_t^2 h_r^2 d^{-\alpha}$, and $G = G_t G_r h_t^2 h_r^2$ are all constants. Constraint (4.7) means that any SS must communicate with one and only one RS. Constraint (4.8) indicates that coverage RS r_i must provide enough transmission power to ensure the data rate request from its covering SS s_j, where P_{ss}^j denotes minimum received power requested by SS s_j. Quadratic constraint (4.9) represents the *SNR* constraint for every SS. In numerical results, we will use the LPQC as the optimal solution for power cost reduction and the benchmark for performance comparison. Similarly, LPQC takes exponentially increased running time as the number of RSs or SSs increasing, it is not efficient or practically usable for large networks. Therefore, we present another efficient heuristic based on the following observation.

We observe that the reduction of transmission power of an RS will reduce the noise to SSs covered by other RSs so that these SSs could have higher probability to fulfil their *SNR* constraints. We call *the minimum transmission power of an RS under its coverage constraints* P_c. Besides coverage constraints, RSs need to meet each SS's *SNR* constraint. Similarly, we call *the minimum transmission power of RS under itsSNRconstraints* P_{snr}. *As long as the transmission power of one RS is no less than* P_c *and* P_{snr} *for its covered SSs, its transmission power can be reduced*. Let L_{low} be the coverage RS set as a result of SAMC, β be the *SNR* threshold, P_{max} be the maximum transmission power of RS, and P_{ss} be the set of minimum received power each SS needs to ensure its data rate. Moreover, let P_{min}^i denote the coverage power P_c for RS r_i and P_{SNR}^i denote the *SNR* power P_{snr} for RS r_i, respectively. It is straightforward to calculate coverage power P_c and *SNR* power P_{snr} for each RS r_i. If all the RSs can reduce power to their own coverage power P_c while meeting *SNR* constraints, the power saving approach is optimal.



(a) Coverage power (b) *SNR* power

Fig. 6. Coverage Power and *SNR* power calculation.

The details of the power saving algorithms are listed in Algorithm 7. And let us use an example to illustrate how to calculate the coverage power P_c and the *SNR* power P_{snr} for each RS.

Algorithm 7. *Power Reduction Optimization (PRO)* ($L_{low}, S, P_{ss}, \beta, P_{max}$)

$K \leftarrow \emptyset; P_1 \leftarrow \emptyset; P_2 \leftarrow \emptyset; P_3 \leftarrow \emptyset; P_{tmp} \leftarrow \emptyset$;
Initialize P_1, P_2, P_3, P_{tmp}
for each item i in L_{low} **do**
  $P_1^i = P_{max}$; $P_3^i = P_{max}$; compute P_{min}^i;
  $P_2^i = P_{min}^i$; $P_{tmp}^i = P_{max}$;
end for
put each RS point of L_{low} into K;
while K is not empty **do**
  for each item i in P_1 **do**
    if $P_1^i == P_3^i$ **then**
      $P_1^i = P_2^i$;
      check if P_1^i can meet *SNR* constraints for SS covered by RS_i;
      if yes **then**
        remove RS point i from K; $P_{tmp}^i = P_1^i$;
      end if
      $P_1^i = P_{max}$;
    end if
  end for
  clear P_1; $P_1 \leftarrow P_{tmp}$;
  if length of K is not changed **then**
    for each item i in P_1 **do**
      if $P_1^i == P_3^i$ **then**
        compute P_{SNR}^i;
      end if
    end for
    Find index i for minimum $\Delta P_i = P_{SNR}^i - P_{min}^i$;
    $P_1^i = P_{SNR}^i$; $P_{tmp}^i = P_{SNR}^i$;
    remove RS point i from K;
  end if
end while
return $\sum_{alli} P_1^i$;

In Fig. 6a, one RS covers s1, s2 and s3. Without taking *SNR* into consideration, we can figure out the minimum power to cover s1, s2 and s3, respectively. This example shows the maximum transmission power of RS is 7, the minimum power to cover s1, s2 and s3 are $4, 3, 5$, respectively. Then the coverage power p_c for this RS is the maximum value among p_c^1, p_c^2 and p_c^3, which is 5. In order to calculate *SNR* power for one RS, we need to take received interference to each SS under the coverage of the RS into consideration. In Fig. 6b, the received interference by s1, s2 and s3 can be easily determined since we assume that three surrounding RSs contributing to interference on s1, s2, s3 are transmitting in their maximum transmission power. Then we can reduce the transmission power of center RS from its maximum value to satisfy s1's, s2's and s3's *SNR* requirements, respectively. We obtain $p_{snr}^1 = 3$, $p_{snr}^2 = 2$ and $p_{snr}^3 = 6$. The *SNR* power for center RS can be easily calculated by taking the maximum value among $p_{snr}^1, p_{snr}^2, p_{snr}^3$ since all three SSs under coverage must satisfy their *SNR* requirements simultaneously.

Theorem 1. *Algorithm 7 is a $(1+\phi)$-approximation for the Power Reduction Optimization (PRO) problem. More specifically, if the power cost of all the RSs returned by Algorithm 7 is denoted by $|P|$, we have $|P| \leq (1+\phi) \cdot |OPT_P|$, where $|OPT_P|$ is an optimal solution for PRO, and $\phi = \frac{\sum_{i\in C}(P_{snr}^i - P_c^i)}{OPT_P}$.*

Proof. If all $P_{snr} \leq P_c$, then $|P| = |OPT_P|$. Otherwise, let P_c^i denote the coverage power for RS r_i, and P_{snr}^i denote the *SNR* power for RS r_i. Thus in whatever OPT_P or P, it is composed of P_c^i or P_{snr}^i for each RS r_i. For instance,

$$P = \{P_c^1, P_{snr}^2, P_{snr}^3, P_{snr}^4, P_c^5\}$$

$$OPT_P = \{P_c^1, P_c^2, P_{snr}^3, P_{snr}^4, P_c^5\}.$$

Also, we let $I = \max_i\{\text{all } P_{snr}^i \text{ occur in } OPT_P\}$ and C be the set of r_i for all $i \in [1, I]$ in OPT_P which does not operate in P_{snr}^i.

Therefore, the worse case for P is,

$$P = OPT_P + \sum_{i\in C}(P_{snr}^i - P_c^i).$$

The approximation ratio in worse case is

$$\frac{P}{OPT_P} = \frac{OPT_P + \sum_{i\in C}(P_{snr}^i - P_c^i)}{OPT_P} = 1 + \frac{\sum_{i\in C}(P_{snr}^i - P_c^i)}{OPT_P}.$$

Since $\phi = \frac{\sum_{i\in C}(P_{snr}^i - P_c^i)}{OPT_P}$, we have $|P| \leq (1+\phi)\cdot|OPT_P|$. □

5 Approximation Solutions for UCRA

After covering all the SSs with sufficient SNR, we need to relay the traffic from the covering RSs to the BSs. In [18], the authors studied a similar MUST problem, which is estimated to be *NP*-hard. MUST assumes only one BS and RSs always operate with maximum power. Therefore, MUST can be regarded as a special case of UCRA. To solve UCRA, the first challenge is how to decide the feasible distance of each RS, which is affected by the SSs or RSs being covered.

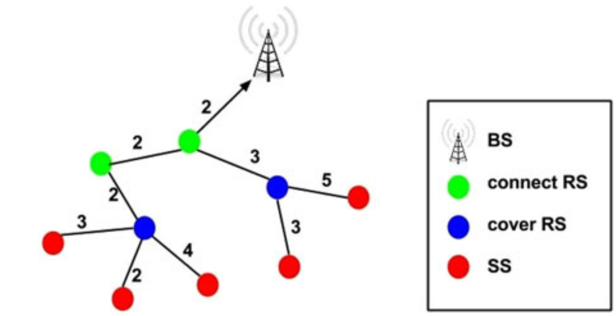


Fig. 7. Feasible distances of connectivity RSs.

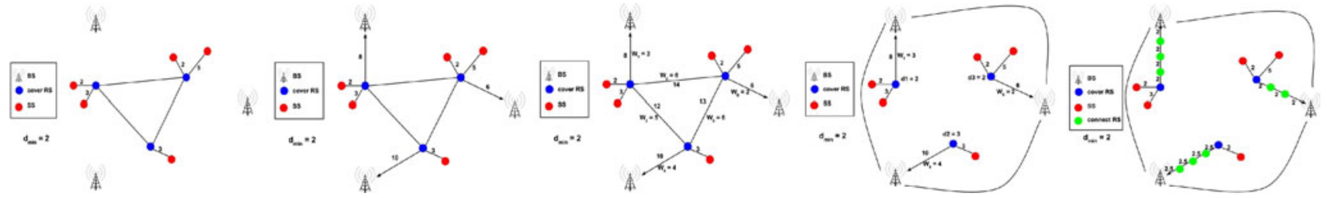
In order to guarantee the data rate of each SS, for each RS r_i, the link capacity between r_i and its parent node cannot be lower than the one between r_i and its any child. Therefore, we define *feasible distance of an connectivity RS r_i, connecting r_i and its parent station (an RS or a BS), should equals to the minimum feasible distance of all its children*, which is shown in Fig. 7.

With the assumption of connectivity RSs operating with P_{max}, we propose our solution in Algorithm 8.

Algorithm 8. Multiple Base Station Minimum Connectivity (MBMC)(R_c, S, D, B)

construct a complete graph $G = (R_c, E)$, where R_c denotes coverage RS set;
$d_{min} = \min_{i\in S} d_i$;
for each node r_i in G **do**
  create a new set K_i;
  for each BS b_j in B **do**
    calculate distance (r_i, b_j) and store it into K_i;
  end for
  find $\min K_i$ and add the corresponding BS node b into G;
  add edge $e(r_i, b)$ into G;
end for
for each edge $e(x_i, x_j)$ in G **do**
  assign weight $w_1(x_i, x_j) = \lceil\frac{\|e(x_i,x_j)\|}{d_{min}}\rceil - 1$ on the edge;
end for
Find a minimum spanning tree $\tau_m st$ of G with BS as the root;
for each RS r_i **do**
  Calculate its feasible distance d_r^i;
end for
for each RS r_i and its parent r_i^p on $\tau_m st$ **do**
  $w_2(r_i^p, r_i) = \lceil\frac{\|e(r_i^p,r_i)\|}{d_r^i}\rceil - 1$;
  Place $w_2(r_i^p, r_i)$ RSs on $e(r_i^p, r_i)$ separating the edge into $\lceil\frac{\|e(r_i^p,r_i)\|}{d_r^i}\rceil$ sections with each one with feasible distance;
end for

Let us use an example to demonstrate Algorithm MBMC, which is shown in Figs. 8a, 8b, 8c, 8d, and 8e. In this example, there are three BSs, five SSs and three coverage RSs deployed in this field. First, we calculate the overall minimum feasible distance, which is 2 in Fig. 8a. In Fig. 8b, each coverage RS builds an edge to its nearest BS. The numbers on the edges are the distances between coverage RSs to their nearest BS. Then we add additional edges to build a complete graph among all the coverage RSs. The weights on all the edges are calculated according to the scheme



(a) calculate overall d_{min} (b) select nearest BS (c) calculate link weights (d) minimum spanning tree (e) deploy connectivity RSs

Fig. 8. Illustration of MBMC.

presented in MBMC. All the edge weights are shown in Fig. 8c. Since all the BSs are backhauled to a central location, we assume that there is an edge with weight of 0 between any two BSs. Then we find the minimum spanning tree of this graph and obtain the results shown in Fig. 8d. Finally, connectivity RSs are placed on each edge between coverage RS and its connecting BS by equally separating the edge. Fig. 8e shows the results of MBMC.

Since both MBMC and MUST proposed in [18] are minimum spanning tree based algorithms, MBMC has the same $\frac{8d_{max}}{d_{min}}$-approximation ratio as MUST proved, where d_{min} and d_{max} denote the minimum and maximum feasible distances of SSs, respectively. Having locations of connectivity RSs returned by MBMC, we then try to optimize power cost of each RS. Our solution is listed in Algorithm 9. Let L_{low} denote the set of *coverage* RSs, L_{high} denote the set of *connectivity* RSs, P^i_{ss} denote the set of received power requirements of SSs covered by RS r_i, P^i_{rs} denote received power requirement of RS r_i, N_i denote the number of RSs placed on the path from RS r_i to its parent, p_{ij} denote the transmission power of jth RS on the path from RS r_i to its parent, and $G = G_t G_r h_t^2 h_r^2$.

Algorithm 9. Upper-Tier Connectivity Power Optimization (UCPO)$(L_{low}, L_{high}, P_{ss})$

```
for each RS r_i in L_low do
    put each P^i_ss into new set K_i;
    P^i_rs = max(K_i);
    D_i = distance(i,parent(i)) / N_i;
    P_i = P^i_rs / (G D_i^{-α});
    for each RS r_j on path (i, parent(i)) do
        p_ij = P_i;
    end for
end for
return Σ_{alli} Σ_{allj} p_ij;
```

6 Approximation Algorithm for SAG Problem

With the approximation solutions (in terms of number of RSs placed) for both lower tier and upper tier, we present an approximation algorithm for the SAG problem in Algorithm 10.

7 Numerical Results

In this section, numerical results are presented to show the effectiveness of our schemes, including SAMC, PRO, MBMC, UCPO and SAG algorithms. All the simulations are run on a Intel Core(TM) i5 CPU of 2.7 GHz with 8 GB memory. All the SSs and BSs are uniformly distributed in a square testing field. All the figures illustrate the average of 10 test runs for various scenarios.

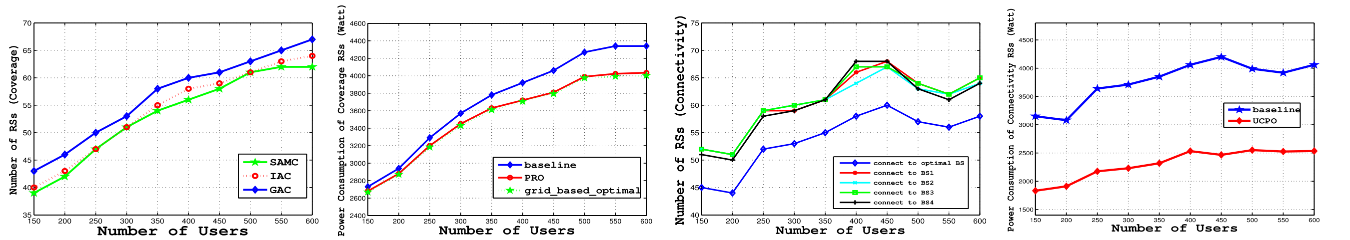
Algorithm 10. SNR -Aware Green Relay$(S, D, B, \beta, P_{ss}, P_{max})$

```
L_low ← ∅; L_high ← ∅;
L_low ← SAMC(S, D, β);
P_L ← PRO(L_low, S, P_ss, β, P_max);
L_high ← MBMC(L_low, S, D, B);
P_H ← UCPO(L_low, L_high, P_ss);
P_total = P_L + P_H;
return P_total;
```

7.1 Simulation Environment Settings

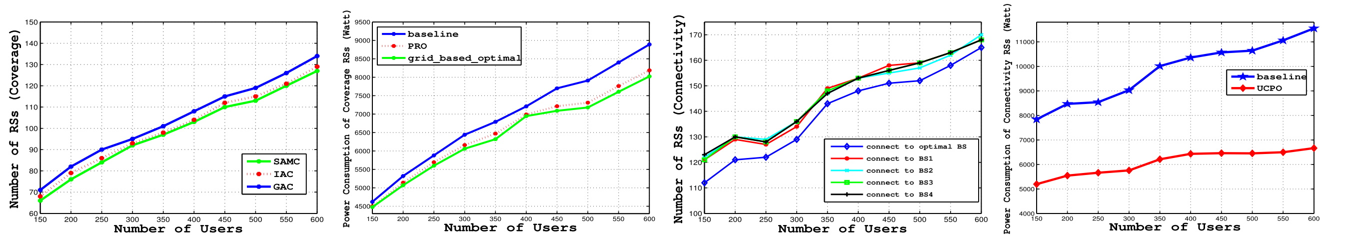
Since solving the ILP with quadratic constraints in Gurobi 5.0 [4] takes exponentially increasing running time and memory as growing the number of SSs or lessening the grid size, very large scale of testing field and huge amount of SSs are not considered in our simulations. We consider the large scale of playing field is composed of a couple of small fields and the operations in each sub-field are independent to others. More specially, the entire testing field can be divided into several sub-zones depending on the distributions of SSs in Zone Partition Algorithm. We select two scales of testing field for our numerical evaluations: $3km \times 3km$ field and $5km \times 5km$ field. And we set the grid size as small as possible as long as we can avoid out-of-memory issue from solving our ILPs. Signal-to-noise ratio threshold for each SS is set according to typical 802.16 standard document. In 802.16 standard, each user with a certain data rate request needs to satisfy a minimum (*SNR*) threshold requirement. Data rate request for each user is randomly distributed between 10 and 45 Mb/s. The number of SSs in playing fields varies from 150 to 600, which are uniformly distributed as well. We place at most 4 BSs in the testing field in order to show the performance of MBMC comparing to MUST in previous literature. Now, we have five metrics to be compared among various scenarios such as *the number of coverage RSs, power consumption of coverage RSs, the number of connectivity RSs, power consumption of connectivity RSs* and *the entire power consumption of all relay nodes*. First, we present the numerical results on both lower tier and upper tier, separately. Then we show the performance of our SAG scheme comparing with some other existing schemes. The results collected from lower tier and upper tier are shown in 7.2 and 7.3, respectively.

Table 2 lists all the parameters used in the simulation.



(a) Coverage RSs for SAMC (b) Power cost for PRO (c) Connectivity RSs for MBMC (d) Power cost for UCPO

Fig. 9. $3\ \mathrm{km} \times 3\ \mathrm{km}$ playing field.



(a) Coverage RSs for SAMC (b) Power cost for PRO (c) Connectivity RSs for MBMC (d) Power cost for UCPO

Fig. 10. $5\ \mathrm{km} \times 5\ \mathrm{km}$ playing field.

7.2 Evaluation of Heuristics on Lower Tier

On the lower tier, we test the performance of IAC, GAC and SAMC on two playing fields of $3\,\mathrm{km} \times 3\,\mathrm{km}$ and $5\ \mathrm{km} \times 5\ \mathrm{km}$, respectively. The results are shown in Figs. 9a and 10a. We can easily see that the number of coverage RSs coming from SAMC is lower than both GAC and IAC in whichever scenario. GAC has the most number of coverage RSs, which is caused by the selected size of candidate grid. The less size of candidate grid, the more accurate the results it would provide. Due to limited amount of memory in our simulation computer, we are not able to set small enough grid size in order to get the near-optimal solution so that the results from GAC are not as good as the results from IAC. Our proposed SAMC is starting from the results of minimum hitting set based on IAC. If the selected locations of coverage RSs from minimum hitting set can not satisfy all SSs' SNR threshold requirements, SAMC tries to slide violated RS location along the feasible circle of SS in order to find a location that can satisfy previous violated SNR threshold requirement. But IAC based ILPQC will not perform these following improvements. IAC based ILPQC just drops this RS location and then searches one or more RSs to replace the RS. Since the algorithm we select for solving minimum hitting set problem is a near-optimal solution, it is probable that IAC based ILPQC would find more than one RSs to replace one violated RS while ensuring the SSs under the coverage of the violated RS can still be covered. If there are many violated RSs which are selected from minimum hitting set, it is likely that IAC based ILPQC would return more number of coverage RSs than SAMC returns. Such possibility is verified by our results in Fig. 9a and Fig. 10a. When all the users' SNR requirements are satisfied based on the results from minimum hitting set, IAC based ILPQC will probably return the same amount of coverage RSs as SAMC does, which can also be seen in both Figs. 9a and 10a. From above observations, we can see that SAMC outperforms both IAC and GAC in terms of not only the number of coverage RSs but also the running times.

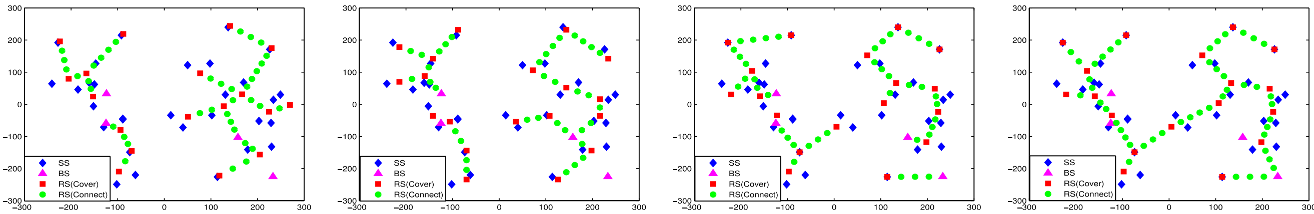
Figs. 9b and 10b show that PRO performs near to optimal and does save much power from the *baseline* model, in which all the RSs operate in *maximum power* when more users are involved. Moreover, PRO can save more power comparing with the baseline especially in larger scale of testing field with same set of users uniformly distributed. Therefore, this result confirms our theoretical analysis of PRO performance.

TABLE 2
Constant Parameters

Parameters	Values
Max. Transmit Power of RS	70 Watt (48.45 dBm)
Channel Bandwidth	10 MHz
Height of User Client	1.5 m
Height of RS	10 m
Transmitter Antenna Gain	2 dBi
Receiver Antenna Gain	2 dBi
Attenuation Factor	2
Thermal Noise	-85 dBm
Grid Size	100 m× 100 m

7.3 Evaluation of Heuristics on Upper Tier

On the upper tier, we are concentrating on showing how MBMC works and why it outperforms MUST proposed in [18]. As we discussed in previous section, MUST can only be applied to *one base station scenario* but MBMC extents MUST scheme and works well in *multiple base stations* environment, which is the more practical deployment. Thus we claim that MBMC is more practical than MUST. Assume that four base stations are deployed in the testing field. We run MUST for four times, for each of which we let MUST connect to one of the four base stations, respectively. Fig. 11d illustrates the case in which all SSs only connect to the corner BS (MUST algorithm) and Fig. 11c illustrates the case in which all SSs connect to their nearest BS (MBMC algorithm). We can compare the data collected in Figs. 9c and 10c between MBMC and MUST. Apparently, MBMC outperforms MUST from each of the scenarios adapting



(a) IAC+MBMC (b) GAC+MBMC (c) SAMC+MBMC (d) SAMC+MUST

Fig. 11. Illustration of tree topologies for various schemes.

MUST. Also, we test the scenarios of various number of BSs from 1 to 4 on both $3\,km \times 3\,km$ and $5\,km \times 5\,km$ playing fields with the number of users set to 300. From Figs. 12 and 13, we can easily find that the number of connectivity RSs from MBMC is less than or equal to that from MUST in all testing scenarios. If there is only one BS deployed in the field, MBMC and MUST return the same result. However, when the number of BSs is increasing from 2 to 4, we can see from both Figs. 12 and 13 that the number of connectivity RSs returned from MBMC is decreasing because there are more BSs to connect to and each coverage RS will choose its nearest BS to connect to according to MBMC, which leads to less number of connectivity RSs to place. From the above observation, we can say that MBMC outperforms MUST in more practical environment. Based on the connectivity topology returned by MBMC, it is probably not necessary for each connectivity RS to transmit in its maximum transmission power to maintain the connection. We reduce the transmission power of each connectivity RS according to UCPO scheme and then find that large amount of power consumption can be saved comparing with the baseline in which all connectivity RSs are transmitting in maximum power. The performance of optimal UCPO can be confirmed in Figs. 9d and 10d.

7.4 Evaluation of Heuristics for SAG

Our SAG scheme combines the solutions for both lower tier and upper tier. Figs. 11a, 11b and 11c illustrate the tree topologies coming from IAC plus MBMC, GAC plus MBMC and SAMC plus MBMC, respectively. At last, we compare the performance among SAG, SAMC+DARP, IAC+DARP and GAC+DARP, where DARP represents the deployment approaches proposed in [18] excluding their lower tier coverage approaches (since [18] does not take users' SNR

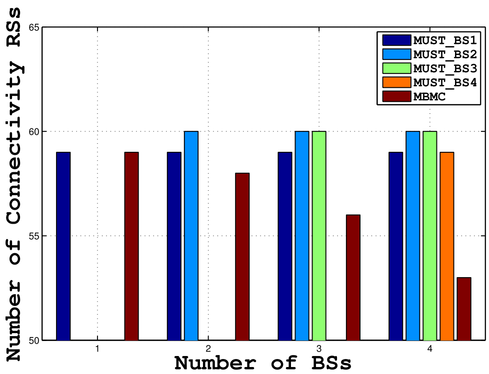


Fig. 12. Compare the performance between MBMC and MUST with various number of BSs in $3\,km \times 3\,km$ field ($N_{SS} = 300$).

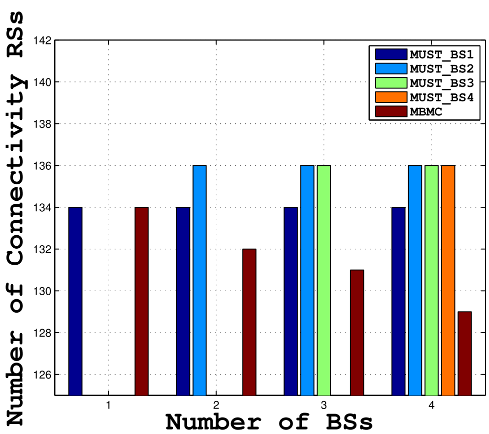


Fig. 13. Compare the performance between MBMC and MUST with various number of BSs in $5\,km \times 5\,km$ field ($N_{SS} = 300$).

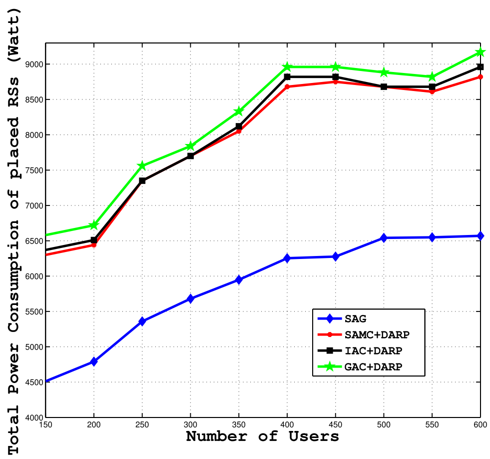


Fig. 14. SAG performance in $3\,km \times 3\,km$ field.

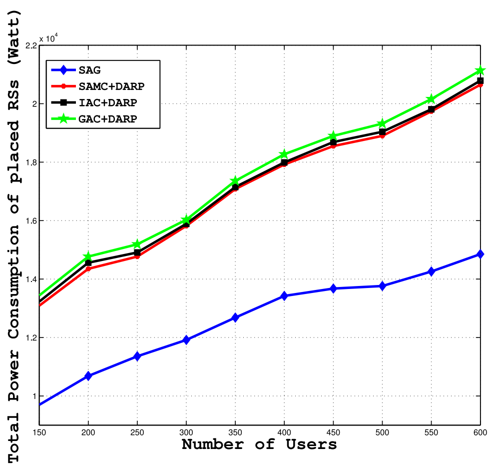
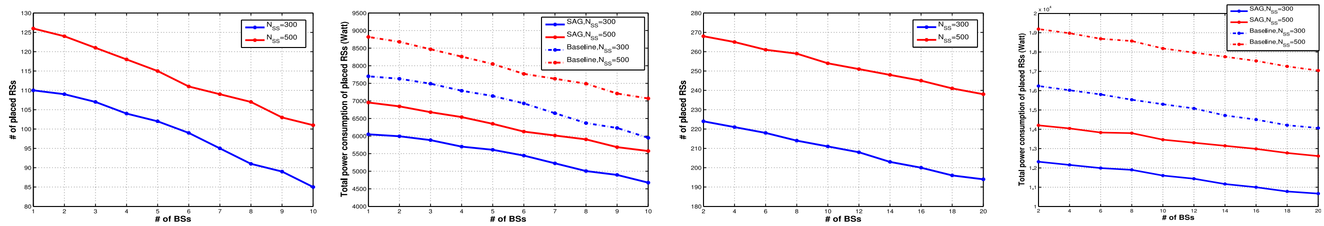


Fig. 15. SAG performance in $5\,km \times 5\,km$ field.



(a) $3km \times 3km$ field (b) $3km \times 3km$ field (c) $5km \times 5km$ field (d) $5km \times 5km$ field

Fig. 16. Impact of the number of BSs.

constraint into consideration). Fig. 14 and Fig. 15 confirm that our design SAG is not only a feasible but also an energy efficient relay deployment strategy for hot-trended wireless relay networks.

Figs. 16a, 16b, 16c, and 16d show the impact of the number of BSs on the network energy consumption. In a $3\ \mathrm{km} \times 3\ \mathrm{km}$ field (Figs. 16a and 16b), we increase the number of BSs from 1 to 10 and observe that, with more BSs deployed in the field, less number of RSs are needed relaying traffic while guaranteeing the SNR for each subscriber. Furthermore, the total power consumption of the placed RSs is decreased as well with more BSs. From Fig. 16b, we can see that more BSs lead to more power cost savings. This is consistent with practical deployment. An area with dense BS deployment needs less RSs to relay the traffic since more traffic can go to BSs directly. We place *relay RSs* on the edges of a minimum spanning tree, the less RSs to place, the less power cost savings could be achieved against the *baseline*. For $5\ \mathrm{km} \times 5\ \mathrm{km}$ field (Figs. 16c and 16d), we increase the number of BSs from 2 to 20, similar results are observed. Fig. 16 also confirms that our SAG design outperforms the baseline.

8 Conclusion

In this work, we studied the *SNR*-Aware Green relay placement problem, which sought the multi-hop relay node placement with channel capacity and *SNR* constraints in wireless relay networks. This problem was further divided into two sub-problems, *Lower-tier Coverage Relay Allocation* problem and *Upper-tier Connectivity Relay Allocation* problem. For LCRA problem, we provided two approximation algorithms, SAMC and PRO, to solve the problem in two phases. Similarly, for UCRA problem, we proposed a solution consisting of a minimum spanning tree based approximation algorithm MBMC and an optimal power optimization algorithm UCPO. With solutions to the lower-tier and upper-tier, we combined these solutions of the LCRA and UCRA and presented a solution framework of SAG. Extensive numerical results have been conducted to support our theoretical analysis and showed good performances of our solutions.

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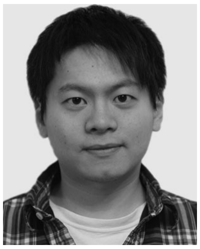

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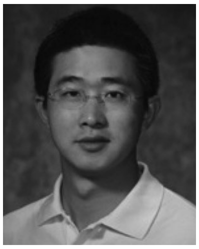

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