Mobile Netw Appl (2008) 13:186–197
DOI 10.1007/s11036-008-0027-7

On Relay Node Placement and Assignment for Two-tiered Wireless Networks

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Published online: 29 March 2008

Abstract Wireless networks that operate on batteries are imposed with energy constraints and long distance communications between nodes are not desirable. Implementing Relay Nodes (RNs) can improve network capacity and save communication energy. A two-hop relay routing scheme is considered, in which the RNs are temporarily placed and have energy constraints. This paper investigates a joint optimization problem on Relay Node Placement (RNP) and route assignment for two-tiered wireless networks. A recursive Weighted Clustering Binary Integer Programming (WCBIP) algorithm is proposed to maximize the total number of information packets received at the Base Station (BS) during the network lifetime. We first present an optimization algorithm based on Binary Integer Programming (BIP) for Relay Node Assignment (RNA) with the current node locations. Subsequently, a weighted clustering algorithm is applied to move the RNs to the best locations to best serve their respectively associated Edge Nodes (ENs). The algorithm has the complexity of $O(2^n)$. The simulation results show that the proposed algorithm has significantly better performance than the other two relay placement schemes. Both theoretical analysis and practical design procedures are also presented with details.

Keywords two-tiered wireless network · optimal relayed path · packet reception rate · BIP · relay node placement

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1 Introduction

Wireless sensor networks have been used in a wide range of applications. As one example of disaster communications, spatially distributed temperature sensors in an ablaze forest can provide critical information about fire distribution, which helps to control the fire diffuse. Another example can be found on the farms. Farmers use transducers to gather information about environmental parameters in their greenhouses. In both scenarios, Edge Nodes (ENs), such as sensors and transducers, are deployed at strategic positions with fixed sensing and transmit power, thus they can sustain a fixed length of lifetime. In addition to the deployment of ENs, a Base Station (BS) is needful to collect data from the sensing field. However, due to geographic reasons, sometimes the BS could only be established far away from the sensing field, resulting in very low data reception rate if there is any. To address this problem, a small number of Relay Nodes (RNs), as energy-limited as ENs, can be placed between the sensing field and the BS to forward data packets. Here we only consider two-hop relay routing from ENs to the BS. It is assumed that the power of RNs can be adjusted to amplify the faded signals received from ENs and forward it to the BS. Therefore, the ENs, RNs, and BS build up a two-tiered wireless network in such applications.

There is a renewed interest in research on relayed communication networks [4]. In this paper, we consider two-tiered wireless networks that can be used for a wide range of applications, such as disaster area communications, farm humidity information gathering, etc. Such realistic scenarios share similar characteristics: task-based ENs are distributed on the desired spots for sensing and sending local information; RNs, placed between ENs and the BS, receive information packets from ENs and forward them to the BS; the BS, which is located distant away from the sensing field as in Fig. 1, collects all the data from RNs and processes the information to make a decision. The RNs are battery powered, as energy-limited as ENs, and are temporally placed to enhance the network performance. However, since each RN has to forward many more packets than each EN transmits in the two-tiered wireless network, we assume that when the last RN depletes its energy, all the ENs are still kept alive.

Many recent research efforts are focused on maximizing the lifetime of wireless sensor networks [1, 2, 10, 11, 12], while others try to address the problem of maximizing the capacity or throughput in Wireless Local Area Networks (WLANs) [5]. The strategies they adopt consist of power control, RN placement, etc. However, few studies available in the literature investigate approaches to maximize the absolute amount of information packets received during the network lifetime, which is a joint problem of maximizing the lifetime and the capacity, and is the most straightforward and performance-oriented measure to evaluate the design of such task-based wireless sensor network applications. For instance, in a burning forest, the amount of temperature information from widely distributed sensors matters as much as the extent to which firefighters can control the fire; farmers can well adjust the environmental parameters if they obtain much feedback information from greenhouse transducers. Therefore, instead of studying solely network lifetime elongation or network throughput optimization, we propose to investigate the joint problem of both on how to maximize the network data reception within the network lifetime. As a result, the proposed approach can be applied to many other task-based data-oriented wireless networks.

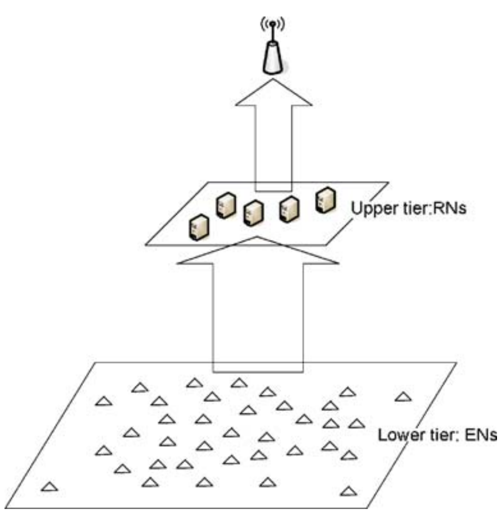

Figure 1 A two-tiered wireless network

In our proposed network scenarios, ENs are distributed on various spots to collect local information, thus their positions can not be altered in the sensing field. Moreover, the transmit power and data generation rate for all ENs remain as constants over the network lifetime. The BS represents the data sink and is stationary. The RNs are quasi-stationary and are deployed between the sensing field and the BS. Each RN is associated with different ENs at times, thus is subject to its exact location with adjustable transmit power. While the system parameters of the ENs and the BS are fixed, the location and transmit power of each RN as well as the dynamic assignment among the ENs and RNs are yet to be determined.

To define relayed network designations, we have to specify the RN placement and the corresponding dynamic mapping from ENs to RNs. These two issues are highly interdependent. Directly applying the optimization techniques to solve the joint problem is unrealistic due to a large number of varying parameters. Therefore, we resort to developing an efficient iterative algorithm, called Weighted Clustering with Binary Integer Programming (WCBIP). It is a three-step iterative process: (1) based on the current locations of RNs, calculate the optimal power for each RN to maximize its capability to transmit data, then compute the network lifetime; (2) determine the optimal relay routing table using Binary Integer Programming (BIP), which provides the dynamic mapping from ENs to RNs; (3) update each RN's position using weighted clustering method based on the current routing table. These three procedures are executed recursively until the algorithm converges.

The main contributions of this paper are as follows: *first*, we present a two-tiered wireless network architecture in which RNs are temporarily added to overcome the long distance communications between the ENs and the BS and the RNs are energy constrained; *secondly*, a joint-optimization problem is defined and analyzed for relay node placement and assignment; *thirdly*, an elegant yet practical solution is proposed using BIP and weighted clustering techniques; *finally*, the simulation results are presented to demonstrate that the WCBIP algorithm outperforms other relay placement schemes.

The rest of this paper is organized as follows. In Section 2, we review the related work about RN placement problem. In Section 3, we describe the network model and formulate the RN placement problem. In Section 4, we present the BIP together with its implementation to figure out the optimal association between ENs and RNs. In Section 5, we present the WCBIP algorithm to solve the

RN placement problem. The simulation results are demonstrated in Section 6, followed by conclusion in Section 7.

2 Related work

There are many researches focusing on the RN placement problem for sensor wireless networks. In [2], a joint problem of energy provisioning and relay node placement for wireless sensor network is considered to maximize the network lifetime. In [10], the authors seek to deploy a minimum number of relay nodes such that all the network nodes are connected, when sensor nodes and relay nodes have different communication ranges. In [11], the problem to deploy a minimum number of relay nodes to guarantee connectivity of sensor nodes and the base station is studied. The network modeling also considers communication range of sensors and relay nodes. In [13], the relay node placement problem in two-tiered wireless sensor network is considered. The objective is to place minimum number of relay nodes to forward packets from sensor nodes to the sink. Likewise, communication ranges for sensor nodes and relay nodes are also considered in the network modeling. Few papers focus on the amount of data reception at the BS during the network lifetime.

Concerning techniques utilized in RN placement in wireless networks, many researches have done significant achievements that motivate us to pursue our goal. In [16], the optimal power is calculated for peer to peer communication with respect to fixed Signal-to-Noise ratio. Besides, many heuristic and iterative approaches are employed to solve the RN placement problems with different objectives. For example, A heuristic algorithm is presented in [8] for energy provisioning and RN placement in wireless sensor networks. In [5], an integer programming optimization formulation and an iterative approach are proposed to compute the best placement of a fixed number of RNs. In [14], a novel BIP formulation of the BS placement problem is proposed to find the optimal BS position in an interference-limited indoor wireless system.

Not only in sensor network area, RNs have also been used in cellular networks and WLAN. In [3], the iCAR architecture is introduced to use RNs to redirect the cellular communication traffic from congested cell to its neighboring cells. Another aspect of relay network applications is wireless LAN. Relay points [5] with access to power supply are strategically placed to improve the throughput of wireless LAN.

In [15], we studied the optimal relay association problem to maximize the data reception during the network lifetime. The RNs in the network scenario have fixed positions. In this paper, based on the previous work, we investigate the RN placement problem by iteratively moving the RNs to "better" locations based on the optimal relay routing assignment of the current network scenario.

3 Network modeling and problem formulation

3.1 Network architecture

We focus on a two-tiered architecture for wireless sensor networks. As shown in Fig. 1, there are three types of nodes in the network: ENs, RNs and the BS. ENs, constituting the lower tier of the network, are portable or quasi-stationary user terminals that are usually battery powered and are equipped with wireless transceivers. They could also be low-bandwidth application-specific sensor devices. As ENs are responsible for collecting local task-based information, we assume that ENs are pre-deployed in the field at strategic positions. The operation mode for ENs is very simple: Once triggered by an event, each EN sends an F-bit packet directly to a relay node in one hop per time period using a constant transmit power. Each EN may select a different path to BS by choosing a different RN from time to time. Therefore, the ENs associated with each relay may change over time. Since RNs are supposed to be energy constraint, we assume that ENs keep alive before all the RNs die. It should also be noted here that because ENs are very close to each other and the BS is far away from ENs, multi-hop routing among ENs is not necessary as it will not bring any distinct benefits to the data transmission.

The upper tier of a network is made up of RNs. During each period, each RN simply forwards all packets received from ENs to the BS. RNs share equivalent receiving power, but differ with each other in the aspect of transmit power. Since RNs are deployed between ENs and the BS, and are associated with different ENs during the network lifetime, their optimal locations are subject to the distribution of ENs and location of the BS to yield the best performance. Suppose their initial energy levels are the same, RNs may deplete their energy at different time because of different traffic load and transmit power. When one RN runs out its energy, the ENs associated with this RN in the previous period may switch to another RN to send packets in the next period. Here we also disregard multi-hop data transmission among RNs, because the transmit power of RNs are adjustable to amplify the signals to reach the BS. Moreover, as it is easily understood that more RNs would achieve a larger amount of packets received at the BS, a fixed and moderate number of RNs are introduced in this network model.

The data sink in a two-tiered wireless network is the BS. As the BS collects all information packets forwarded by the RNs from the ENs, it is assumed that the BS has sufficient energy provided by a large or constantly reprovisioned battery source. It is also assumed that the BS has a fixed position as an information gathering center.

3.2 Joint problem of RN placement and assignment

As an ultimate goal, RNs should be placed in locations resulting in the largest amount of data reception at the BS within the network lifetime. For a two-tiered wireless network with every node placed at certain fixed position, the optimal association between ENs and RNs needs to be computed such that the amount of correct packets received at the BS is maximized. It is obvious that different network topologies could yield different maximized amount of data reception. Then for a network with a BS, a group of ENs, and a given number of RNs waiting to be deployed, the question becomes: where should we place these RNs and what are the optimal associations between ENs and RNs, such that the total amount of correct packets received at the BS during the network lifetime is maximized?

From the above analysis, we can see that the two issues of RN placement and the corresponding dynamic mapping from ENs to RNs are highly interdependent. As we are desirous of finding the optimal RN placement, we should also consider the corresponding association between ENs and RNs for the node locations as well as the maximized amount of data received at the BS.

In the definition of system objective and constraint functions, Table 1 contains all adopted conventions.

Since packets are transmitted through a two-hop transmission, the total number of correct packets received at the BS would be $\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{T} PRR(e_i, r_j)PRR(r_j, BS)x_{ij}^t$.

Table 1 Notation

Symbol	Definition
$\{e_1,e_2,\ldots e_n\}$	The set of ENs
$e_i(x,y)$	The *XY* location of e_i
$\{r_1,r_2,\ldots r_m\}$	The set of RNs
$r_j(x,y)$	The *XY* location of r_i
$s(x,y)$	The *XY* location of BS
PRR (*a*, *b*)	Packet reception rate (PRR) between node *a* and node *b*
T	Network lifetime in periods
X_{ij}	Number of times that e_i sends packets to r_j during the network lifetime *T* periods
x_{ij}^t	If e_i sends data to r_j in the *t*th period, $x_{ij}^t = 1$; else $x_{ij}^t = 0$
buffer (*j*)	Number of packets that r_j can transmit;
Pt_j	Transmit power of r_j
N_{total}	Total number of packets received within network lifetime

RNA problem For a two-tiered wireless network, $e = \{e_1, e_2, \ldots e_n\}$ are placed at $e_i(x,y)(i = 1, 2\ldots n)$; $r = \{r_1, r_2, \ldots r_m\}$ are placed at $r_j(x,y)(j = 1, 2\ldots m)$; the BS is placed at $s(x,y)$;

$$\max \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{T} PRR(e_i, r_j)PRR(r_j, BS)x_{ij}^t$$

s.t.

$$\sum_{j=1}^{m} x_{ij}^t = 1$$

$$\sum_{i=1}^{n}\sum_{t=1}^{T} x_{ij}^t \leq buffer(j)$$

RNP problem Given a deployment of ENs and one BS, find the positions for a fixed number of RNs, such that the maximum number of correct packets from ENs can be received at the BS.

4 Technical approach for RNA

In this section, we present a BIP method based on power control for RNA problem. Given a two-tiered topology with known locations of all nodes, we can calculate the optimal power for all the RNs and compute the network lifetime. Then we can obtain two constraints and adopt the BIP method with the constraints to find a solution for RNA problem under current network deployment.

4.1 Optimal power control for RNs

4.1.1 Path loss model

The RNA solution depends heavily on the relationship between transmit power and packet error rate, which can be modeled using path loss channel model in physical layer. In this paper, the following path loss model is used.

$$P_0 d_0^{\alpha} = P_1 d_1^{\alpha} \quad (1)$$

where P_0 and P_1 are the signal power measured at d_0 and d_1 meters away from the transmitter, respectively. α denotes the path loss exponent. If we set d_0 to be 1 meter, thus P_0 is the reference signal power measured at 1 meter away from the transmitter. Then Eq. 1 is simplified as $P_1 = \frac{P_0}{d_1^{\alpha}}$. P_a can be calculated using the free space propagation model as:

$$P_0 = G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \times P_t \quad (2)$$

Where P_t is the transmit power, G_t and G_r are the transmitter and receiver antenna gains respectively, $\lambda = c/f$

is the wavelength of the transmitted signal, and c is the velocity of radio-wave propagation in free space, which is equal to the speed of light.

Then the received power P_r at a distance d meters away from the transmitter can be calculated as:

$$P_r = \frac{G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \times P_t}{d^\alpha} \tag{3}$$

Suppose P_{noise} denotes the power of noise, then the signal-to-noise ratio (SNR) at the receiver end is:

$$SNR = \frac{P_r}{P_{noise}} \tag{4}$$

The bit error rate can be determined by the SNR based on the error probability model. For illustration purpose, we take BPSK [6] as the modulation scheme and the bit error rate is given by

$$P_b = \frac{1}{2} e^{-\frac{1}{2}SNR} \tag{5}$$

Assuming bit error rate occurs independently, the packet reception rate (PRR) is

$$PRR = (1 - P_b)^F = \left(1 - \frac{1}{2} e^{-\frac{1}{2}SNR}\right)^F \tag{6}$$

where F is the packet size.

4.1.2 Optimal power control

Considering a peer-to-peer communication between a relay r_i and the BS, there is a certain distance d_i between r_i and the BS. We assume r_i uses transmit power Pt_i, and it relays z_i^t packets to the BS in time period t, or there are z_i^t ENs sending packets to r_i in the tth period. Using above-mentioned error probability model, the total number of packets that the BS receives from r_i is:

$$M_i = \sum_{t=1}^{T} z_i^t \left(1 - \frac{1}{2} e^{-\rho \frac{Pt_i}{d_i^\alpha}}\right)^F \tag{7}$$

where $\rho = \frac{1}{2} G_t G_r \left(\frac{c}{4\pi f}\right)^2 \frac{1}{P_{noise}}$ and T is the overall number of periods, also referred as the relay network lifetime. The total number of packets that can be transmitted by r_i is restricted by its energy. Then we have:

$$\sum_{t=1}^{T} z_i^t = \frac{E \cdot v}{(Pt_i + P_{elec})F} \tag{8}$$

where E denotes the total energy each RN holds, v is the transmission bit rate, P_{elec} denotes the electronic power consumed by receiving one packet.

Combining Eqs. 7 and 8 yields:

$$M_i = \frac{E \cdot v}{(Pt_i + P_{elec})F} \cdot \left(1 - \frac{1}{2} e^{-\rho \frac{Pt_i}{d_i^\alpha}}\right)^F \tag{9}$$

To maximize M_i, we need to find the optimum power Pt_i. Take a derivative of M_i with respect to Pt_i, and set the derivative to zero, we get the following characteristic equation from convex theory:

$$\frac{1}{2}(Pt_i + P_{elec}) \cdot F \cdot e^{-\rho \frac{Pt_i}{d_i^\alpha}} \cdot \frac{\rho}{d_i^\alpha} + \frac{1}{2} e^{-\rho \frac{Pt_i}{d_i^\alpha}} - 1 = 0 \tag{10}$$

Let us set Ω to be the collection of all solutions to Eq. 10. By optimization theory, the optimal point Pt_i^* maximizing the function $M_i(Pt_i)$ must lie in the union of the set Ω and boundary points of Pt_i. Note that Eq. 10 is transcendental and may not have closed form solutions. Numerical solutions for an experimental setup will be provided in Section 5.

4.2 Fixed relay network lifetime

Based on the analysis above, each RN has an optimal transmit power Pt_i^* setup for best energy efficiency. Given the total energy constraint E, the total number of packets that r_i can relay is:

$$buffer(i) = \frac{E \cdot v}{(Pt_i^* + P_{elec})F} \tag{11}$$

Relay network lifetime is defined as the total number of network operating periods, represented by T. The total number of packets received from ENs equals to the total number of packets forwarded by all RNs. Thus,

$$T = \frac{1}{n} \sum_{i=1}^{m} \frac{E \cdot v}{(Pt_i^* + P_{elec})F} \tag{12}$$

Where m denotes the number of RNs and n denotes the number of ENs. For r_i with fixed location in a two-tiered wireless network, Pt_i^* can be determined from Eq. 10. Therefore, the relay network lifetime T is fixed if the energy levels of RNs are known.

4.3 BIP optimization

4.3.1 Description of BIP optimization

BIP optimization is a linear programming (LP)-based branch-and-bound algorithm. The algorithm searches for an optimal solution to the BIP problem by solving a series of LP-relaxation problems. The branch-and-bound method is described briefly below. More details can be referred to [7].

The algorithm creates a search tree by repeatedly adding constraints to the problem, called "branching." At a branching step, the algorithm chooses a variable x_j whose current value is not an integer and adds the constraint $x_j = 0$ to form one branch and the constraint $x_j = 1$ to form the other branch. This process can be represented by a binary tree, in which the nodes represent the added constraints.

At each node, the algorithm solves the LP-relaxation problem using the constraints at that node and decides whether to branch or to move to another node depending on the outcome. There are three possibilities: (1) If the LP-relaxation problem at the current node is infeasible or its optimal value is greater than that of the best integer point, the algorithm removes the node from the tree, after which it does not search any branches below that node. The algorithm then moves to a new node according to the pre-specified method. (2) If the algorithm finds a new feasible integer point with lower objective value than that of the best integer point, it updates the current best integer point and moves to the next node. (3) If the LP-relaxation problem's optimal value is not an integer and the optimal objective value of the LP relaxation problem is less than the best integer point, the algorithm branches below this node.

As the algorithm could potentially search all 2^n binary integer vectors, the running time for BIP is $O(2^n)$. n is the number of variables that need to be specified. As future work, we can transform the Binary Integer Programming problem into a linear optimal distribution problem [18] by generating a directed graph, to reduce the computation complexity to only $O(n^3)$.

4.3.2 Optimizing the RNA Problem

Suppose the PRR from r_i to the BS is R_i, then the total number of packets received correctly at the BS can be presented as:

$$N_{total} = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{t=1}^{T} PRR(e_i, r_j)PRR(r_j, BS)x_{ij}^t \tag{13}$$

The constraints are listed in Eqs. 14 and 15: (1) e_i associates with one RN in one period; (2) the total packets sent to r_j can not exceed the buffer size of r_j.

$$\sum_{j=1}^{m} x_{ij}^t = 1(i = 1, 2....n, t = 1, 2...T) \tag{14}$$

$$\sum_{i=1}^{n} X_{ij} \leq buffer(j)(j = 1, 2, ...m) \tag{15}$$

In practice, we define the coefficient vector as:

$$\mathbf{f} = [\mathbf{Y_1}, \mathbf{Y_2}, ..., \mathbf{Y_n}] \tag{16}$$

$$\mathbf{Y_i} = [\underbrace{\mathbf{Q_i}\mathbf{Q_i}...\mathbf{Q_i}}_{T}],\ i = 1, 2, ...n \tag{17}$$

$$\mathbf{Q_i} = [PRR(e_i, r_1)PRR(r_1, BS), ..., PRR(e_i, r_m)PRR(r_m, BS)],\quad i = 1, 2, ..., n \tag{18}$$

The solution vector is given as:

$$\mathbf{U} = [\mathbf{S_1}, \mathbf{S_2}, ..., \mathbf{S_n}] \tag{19}$$

$$\mathbf{S_i} = [\mathbf{K_{i1}}, \mathbf{K_{i2}}, ...\mathbf{K_{iT}}],\ i = 1, 2, ..., n \tag{20}$$

$$\mathbf{K_{ij}} = \left[x_{i1}^j, x_{i2}^j, ...x_{im}^j\right],\ j = 1, 2, ..., T \tag{21}$$

where x_{ij}^t can only take the values of 0 or 1, and $x_{ij}^t = 1$ means e_i send one packet to r_i during the tth period indicated by the superscript.

To implement equality constraint, we define the coefficient matrix $\mathbf{A_{eq}}$ as in Eq. 22 and the result vector $\mathbf{b_{eq}}$ as in Eq. 23.

$$\mathbf{A_{eq}} = \begin{bmatrix} \underbrace{111...11}_{m}|\underbrace{000...00}_{m}|000..00|..........|000...00 \\ 000...00|\underbrace{111...11}_{m}|\underbrace{000...00}_{m}|.........|000...00 \\ 000...00|000..00|\underbrace{111...11}_{m}|..........|000...00 \\ .... \\ 000..00|\underbrace{000...00}_{m}|......|000....000|\underbrace{111...11}_{m} \end{bmatrix} \tag{22}$$

$$\mathbf{b_{eq}} = (1, 1, 1, ...1)^T \tag{23}$$

Where $\mathbf{A_{eq}}$ is $n \times T$ by $m \times n \times T$ matrix and $\mathbf{b_{eq}}$ is vector with length $m \times n \times T$.

Similarly, we define the coefficient matrix $\mathbf{A}$ and the result vector $\mathbf{b}$ as in Eqs. 24 and 25, respectively, in order to implement the inequality constraint.

$$\mathbf{A} = \begin{bmatrix} \underbrace{100...00}_{m}|\underbrace{100...00}_{m}|100..00|..........|100...00 \\ 010...00|\underbrace{010...00}_{m}|\underbrace{010...00}_{m}|.........|010...00 \\ 001...00|001..00|\underbrace{001...00}_{m}|..........|001...00 \\ .... \\ 000..01|\underbrace{000...01}_{m}|000....01|.........|\underbrace{000...01}_{m} \end{bmatrix} \tag{24}$$

where $\mathbf{A_{eq}}$ is m by $m \times n \times T$ matrix.

$$\mathbf{b} = (buffer(1), buffer(2), ...buffer(m))^T \tag{25}$$

Then the RNA problem can be redefined as in the form below:

$$\text{maximize } \mathbf{f} \times \mathbf{U^T} \text{ such that } \mathbf{A} \times \mathbf{U^T} \leq \mathbf{b}, \mathbf{A_{eq}} \times \mathbf{U^T} = \mathbf{b_{eq}} \tag{26}$$

5 WCBIP: an iterative approach for RNP

In this section, we first provide an analysis on how to maximize the amount of correct data reception with respect to different relay node placements. Then the analysis results are used to bring forward an efficient algorithm called WCBIP.

5.1 Analysis on RNP problem

Section 4 gives a detailed description on how to assign ENs to RNs within a fixed scenario, such that the amount of correct packets received at the BS can be maximized. Each relay node functions as a cluster head to forward packets from its cluster members. As we observe this two-tiered network system in this cluster view, maximizing the total number of correct packets received at the BS is tantamount to maximizing performance of each cluster. Because within the current network scenario, the ENs are immobile while the RNs are temporarily placed. Intuitively, we construct the clustering function for relay node r_j as:

$$\begin{aligned} f_{\text{cluster}-j} &= \sum_{i=1}^{n} \frac{X_{ij}}{buffer(j)} PRR(e_i,r_j) PRR(r_j,BS) \\ &= \sum_{i=1}^{n} \frac{X_{ij}}{buffer(j)} \left(1 - \frac{1}{2} e^{-\rho \frac{Pt_{edge}}{d_{ij}^{\alpha}}}\right)^F \left(1 - \frac{1}{2} e^{-\rho \frac{Pt_j}{d_j^{\alpha}}}\right)^F \end{aligned} \tag{27}$$

where Pt_{edge} denotes the constant transmit power of ENs. d_{ij} represents the distance between edge node e_i and relay node r_j. $f_{cluste\text{-}j}$ is a function of the x–y location of relay node r_j. The weighted factor $\frac{X_{ij}}{buffer(j)}$ denotes the contribution each edge node makes to the overall cluster performance. As we move r_j, we can search for the position where the clustering function reaches its maximal value.

5.2 Implementation of WCBIP

Based on the relay placement analysis, we propose an iterative procedure to search for the optimal positions of all RNs so that the maximum amount of correct packets can be received at the BS.

Step 1: Initial placement. According to the EN deployment, RNs are evenly distributed within the coverage area.

Step 2: Obtaining two constraints for BIP. Calculate optimal power for each RN and compute the network lifetime;

Figure 2 Pseudo code of the WCBIP algorithm

```
WCBIP algorithm:
1. Initialization: evenly distribute RNs;
2. Compute the optimal power for each RN;
3. Calculate the network lifetime in periods;
4. Apply BIP method with two constraints to find a solution χ to RNA;
5. The total number of correct packets received at the BS at this optimal point is N_total ;
6. Set iterations=1, nonincrease=0 ;
7. While( iterations < M and nonincrease < C_th ){
8.      for (j=1; j<No. of RNs ; j=j+1) {
9.              Construct f_cluster-j ;
10.             update r_j(x,y) to maximize f_cluster-j ;}
11.     Compute the optimal power for each RN;
12.     Calculate the network lifetime in periods;
13.     Apply BIP method with two constraints to find a solution χ_new to RNA;
14.     The total number of correct packets received at the BS at this optimal point is N_total-new ;
15.     If ( N_total-new <= N_total ) {
16.             nonincrease=nonincrease+1;
17.     else    nonincrease=0 ; }
18.     N_total = N_total-new ;
19.     iterations=iterations+1;                        }
20.     Output χ_new and N_total-new ;
21.     Task ends.
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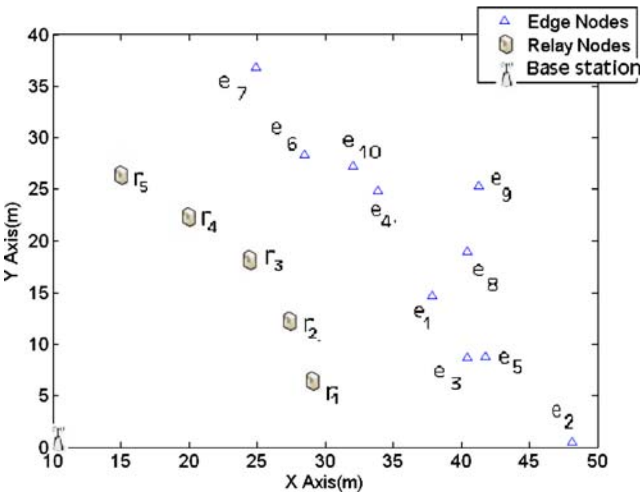

Figure 3 A scenario setup to show network nodes geographic positions

Step 3: BIP optimization for RNA. With respect to current node locations (the positions of ENs, RNs and the BS), BIP is applied to obtain the RNs' assignment result and the total number of correct packets received at the BS at this optimal point is N_{total}.

Step 4: Setting RNs to new positions. According to the assignment result, for each relay node r_j, construct the clustering function $f_{cluste\text{-}j}$, as a function of $r_j(x,y)$. Search for the maximal value of $f_{cluste\text{-}j}$, move r_j to the new position.

Step 5: Iteration and termination. The algorithm terminates when any one of the following conditions are true:

a. M iterations are completed.
b. N_{total} has not increase for C_{th} consecutive times.

Otherwise, the procedure goes back to Step 2. The pseudo code is shown as in Fig. 2.

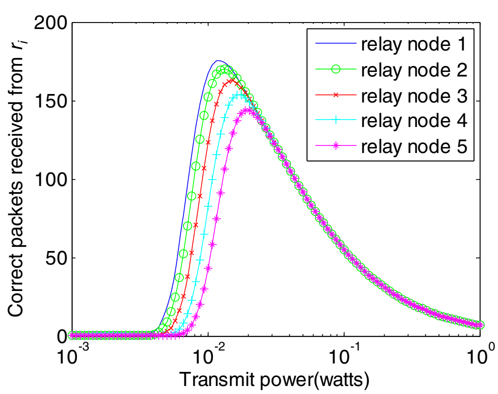

Figure 4 Total number of packets correctly received at the BS from relays using different transmit power

6 Simulation results

6.1 Experimental study on RNA problem

6.1.1 Experiment parameters

For experimental setup, we establish the network scenario as follows: ten ENs are randomly distributed within one sixth of circles with their center located at (0, 0), and radius varying between [40, 50]; the RNs, with the equal radians between each other, are also placed within the same set of concentric circles with their radius at 30. The BS is placed at *XY* coordinate (10, 0), as shown in Fig. 3.

The assumptions and experimental parameters are: unit gain for both the transmitter and receiving antenna; the frequency of the electromagnetic signal is 2.4 GHz; the noise power is 2.15×10^{-10} W; the electronic power for receiving one packet is 2.53×10^{-2} W; the size of one packet is 80 bits; the ENs each use a constant transmit power of 10^{-2} W; the rate with which the RNs send data is 11Mb/s [8]; the total energy for one relay node is 5×10^{-5} J (we render the energy of RNs so small for simulation purpose).

6.1.2 The optimal power of RNs

Given the fixed positions of the RNs and the BS, we can draw the number of packets that r_i can forward with different transmit power based on Eq. 10. Transmission at the optimal power provides the best energy efficiency for the RNs.

As shown in Fig. 4, for each relay node, the optimal transmit power can be obtained at the peak point. It can also be observed that the optimal transmit power is larger if the relay is further away from the BS.

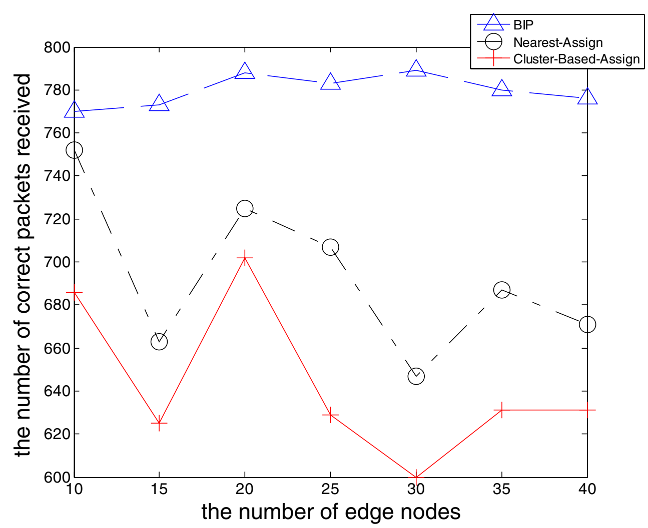

Figure 5 The number of correct packets received using three different assignments

Table 2 Assignment results of three methods for ten ENs

	Our work(BIP)					Nearest-relay-assign [17]					Cluster-based-assign [2]				
	r_1	r_2	r_3	r_4	r_5	r_1	r_2	r_3	r_4	r_5	r_1	r_2	r_3	r_4	r_5
e_1	0	21	65	0	0	0	70	0	7	7	86	0	0	0	0
e_2	86	0	0	0	0	61	9	0	7	7	0	0	0	0	86
e_3	13	73	0	0	0	61	9	0	7	7	86	0	0	0	0
e_4	0	0	23	63	0	0	0	58	19	7	0	86	0	0	0
e_5	86	0	0	0	0	61	9	0	7	7	0	0	0	0	86
e_6	0	0	0	16	70	0	0	0	77	7	0	0	86	0	0
e_7	0	0	0	0	86	0	0	0	0	84	0	0	0	86	0
e_8	0	86	0	0	0	0	70	0	7	7	0	86	0	0	0
e_9	0	0	86	0	0	0	12	58	7	7	0	0	0	86	0
e_{10}	0	0	0	86	0	0	0	58	19	7	0	0	86	0	0

6.1.3 Comparison of the proposed method and other assignment schemes

To demonstrate the advantages of the proposed method, we compare it with two other assignment schemes under the current network topology. One scheme is called the nearest relay assignment method [17], based on which every edge node sends its packets to the nearest active relay node. The other scheme requires that all RNs manage their members (ENs) as cluster heads [2]. The RNs are assigned ENs according to their capacity. Technically, the number of ENs assigned to r_i is in inverse proportion to $\left(Pt_i^* + P_{elec}\right)$ based on the energy constraint as in Eq. 9. Figure 5 shows the performance of these three methods when the number of ENs varies from 10 to 40.

For each experimental setup, the locations of ENs are placed almost randomly. Therefore, the packet reception rates from ENs to RNs change. The number of packets correctly received at BS varies. But for any given experimental cases, Fig. 5 clearly shows that the BIP method results significantly more information packets received at the BS than the other two techniques.

Table 2 lists the assignment results of these three methods for the case of ten ENs. Each row denotes an edge node, and each column corresponds to a relay node. The numbers in the table represent the number of periods during which the edge node selects the relay node to forward its packets.

6.2 Experimental study on WCBIP for RNP problem

The BIP method can be used to find the fixed relay scheme to maximize the number of correct packets received at the BS. The WCBIP method incorporates the BIP for each relay as part of iteration, and in every iteration searches for a “better” location to improve the value of each clustering

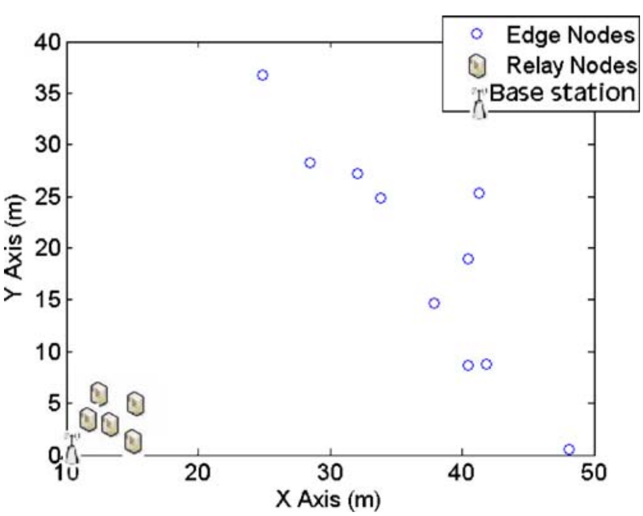

Figure 6 Network scenario at convergence using WCBIP

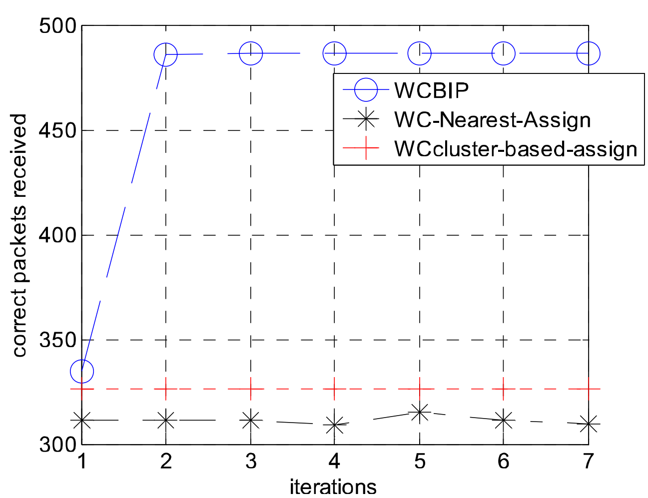

Figure 7 Iterations vs. Total number of received packets for three weighted clustering-based methods

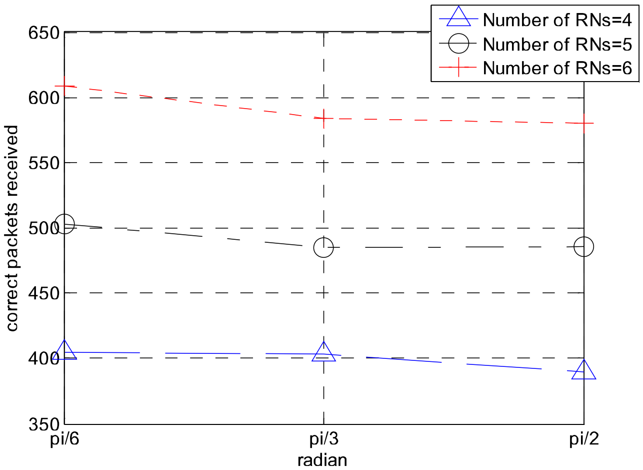

Figure 8 Number of received packets with respect to different Ranges of ENs in radian and number of RNs

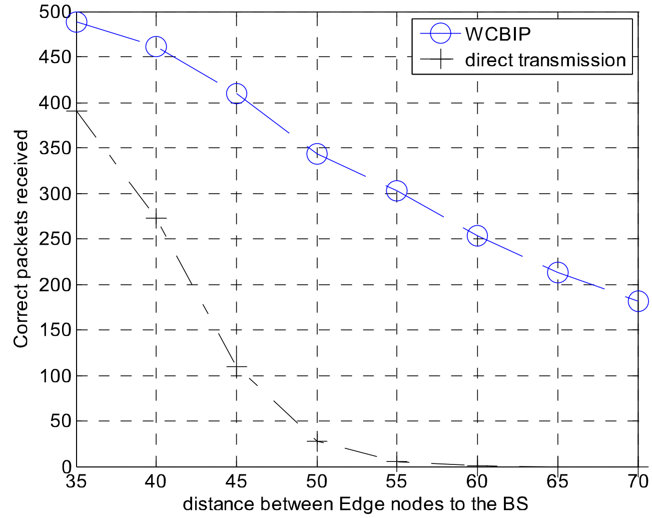

Figure 9 Correct packets received with respect to the distance between ENs and the BS

function. The search function we choose is the simplex search method [9], as one kind of unconstrained nonlinear optimization. In our simulations, we adopt the fminsearch function in Matlab to implement this optimization method.

As an example, using WCBIP (here we change the energy level for RNs to 2×10^{-5} J), the network scenario is initialized as Fig. 3 and the ultimate deployment of RNs is shown in Fig. 6. The total number of correct packets received at each iteration is demonstrated in Fig. 7. To demonstrate its advantage, we also adopt the other two methods, called as weighted clustering (WC) nearest assign and weighted clustering (WC) cluster-based assign. As they are named, these methods update the placement of RNs similarly as WCBIP, but based on their own association tables. For WCBIP, the number of correct packets received increases greatly after the first iteration, followed by small improvement in the next a few iterations. This is because the first iteration has already moved each relay node close to its optimal place. As shown in Fig. 7, WCBIP algorithm has the advantage of quick convergence with significant performance improvement. In contrary, results for the other two methods remain much lower.

We also consider the impact that the range of ENs in radian has on the data reception performance. From Fig. 8, we can see the total number of packets received increases as the number of RNs increases. This is because more RNs induce more energy to transmit data. Besides, as the radian of range increases, the number of packets received at the BS decreases slightly. The reason is that with a larger range, every packet would travel longer distances thus decreases its own reception rate.

To demonstrate the relationship between ENs' locations and the number of packets received, we set up another network scenario as follows: 20 ENs are evenly distributed on one sixth of a circle with its center located at (0, 0), and radius changing. The BS is placed at *XY* coordinate (0, 0).

Table 3 RN placements with respect to different EN locations

Distance to BS (meters)	RN's final placements				
	r_1	r_2	r_3	r_4	r_5
35	(4.9, 1.2)	(6.4, 0.8)	(5.8, 3.6)	(3.4, 3.0)	(4.7, 5.2)
40	(8.4, 0.6)	(8.1, 2.4)	(7.3, 4.0)	(6.6, 5.6)	(5.1, 6.6)
45	(12.2, 3.6)	(12.4, 1.0)	(11.1, 6.0)	(9.6, 8.2)	(7.5, 10.0)
50	(17.0, 1.4)	(16.5, 4.9)	(15.2, 8.1)	(13.1, 11.1)	(10.5, 13.6)
55	(21.8, 1.7)	(21.1, 6.3)	(19.4, 10.6)	(16.6, 14.2)	(13.3, 17.2)
60	(26.7, 2.1)	(25.9, 7.6)	(23.4, 12.6)	(20.3, 17.4)	(16.4, 21.3)
65	(31.6, 2.5)	(30.7, 9.1)	(28.0, 15.1)	(24.5, 20.8)	(19.4, 25.1)
70	(37.0, 2.8)	(35.5, 10.5)	(32.5, 17.7)	(28.1, 24.0)	(22.7, 29.6)

We employ the WCBIP method to place five RNs between the BS and ENs. The placement results are shown in Table 3. Each of the dual numbers represents the *XY*-location of the corresponding RN when ENs are placed at the corresponding distance away from the BS. As can be seen from the table, the RNs' positions become further away from the BS as the ENs are placed at a larger distance away. Figure 9 depicts the number of correct packets received with respect to WCBIP and direct transmission from ENs to the BS without data relay when ENs are placed at different distances away from the BS. From Fig. 9, it can be seen that introducing a tire of RNs increases the number of packets received. Although results for both methods decreases as the ENs are placed further away from the BS, the number of packets received through direct transmission goes down much more rapidly than the case that RNs are placed with WCBIP to help forward packets from ENs.

7 Conclusion

In this paper, we investigate the joint problem of RNA and RNP for two-tiered wireless sensor networks. Since these two problems are highly interdependent, we developed an efficient iterative algorithm, called as WCBIP to find the optimal the RN placement to maximize the data received at the BS within a network lifetime. This approach firstly derives the optimal transmit power for each RN as well as the fixed relay network lifetime. Subsequently, we determine the dynamic optimal RNA in every period using BIP such that the BS receives the maximum number of effective information packets. Then we update each RN's position by optimizing their data transmission performance under current assignment results using a weighted clustering method. These three steps are executed iteratively until the algorithm converges. Experimental results show that within a fixed network scenario, the proposed BIP method yields much better performance than the other two schemes, nearest relay assignment and cluster-based assignment. The simulation results demonstrate that RNs can send the most information packets when taking the optimal transmit power. Moreover, we observe that WCBIP converges within a few steps, yielding better results than other two weighted clustering methods and direct data transmission from ENs to the BS. Finally, we quantify the effects of EN locations, with respect to angle and distance from the BS, on RNP and the maximum number of information packets received.

For future work, we will pursue the following directions: relaxing the constraints on network energy model of edge nodes and relay nodes; extending our algorithm such that it can be applied to a multi-tiered multi-hop network; reducing the complexity by transforming the BIP-based method to a low-cost approach, such as the Linear Optimal Distribution method [18].

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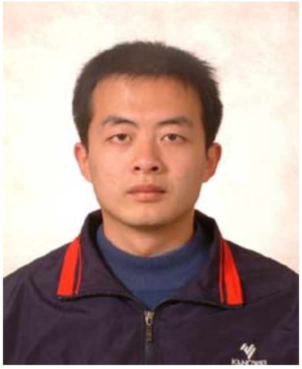

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