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Minimizing Energy Consumption in Wireless Sensor Networks using Binary Integer Linear Programming

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***Abstract*—**The important issue considered in the widespread deployment of Wireless Sensor Networks (WSNs) is an efficiency of the energy consumption. In this paper, we present a study of the optimal relay station planning problems using Binary Integer Linear Programming (BILP) model to minimize the energy consumption in WSNs. Our key contribution is that the proposed model not only ensures the required network lifetime but also guarantees the radio connectivity at high level of communication quality. Specially, we take into account effects of noise, signal quality limitation and bit error rate characteristics. Numerical experiments were conducted in various network scenarios. We analyzed the effects of different sensor node densities and distribution on the energy consumption.

***Keywords*—** Binary Integer Linear Programming, BILP, Energy consumption, Optimal node placement and Wireless sensor networks.

I. Introduction

WIRELLES Sensor Networks (WSNs) have been deployed in several data-gathering applications such as health monitoring and environmental monitoring in factories, farms and residential areas. The WSN structure consists of sensor nodes (SNs) and a sink node, usually called a base station (BS). SNs are placed in the sensing field and BS is usually located further away to collect and analyze the sensing data. Typically, SNs could send data to BS directly or indirectly via other intermediate SN(s). Since SNs usually operate by using limited energy sources such as batteries, it is undesirable to replace or recharge SNs due to high maintenance cost. In this case, Relay Stations (RSs) serve an essential role to receive and forward data from SNs to BS such that the energy-limited SNs can operate for a desired period of the network lifetime. Since RSs could be equipped with more sophisticated energy sources such as solar cells and the energy storage, the network deployment cost and lifetime could mainly depend on the number of sophisticated RSs used in the network and how the sensing data is forwarded to BS. In order to address the energy efficiency issues of WSNs, we need an effective RS planning technique, considering practical issues such as limitation of network cost, energy efficiency and the effects of noise and bit error rate characteristics of the wireless transceivers.

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Several works have paid attention on investigating the WSN design problems with special consideration on the energy consumption issues [1-10]. In [1], the authors explored factors that affect the WSN design and the communication protocol that used in each layer.

In [2], the authors classified node placement strategies for WSN design. Several studies have devoted on the relay node placement problems in which [3-6] considered no energy limitation at SNs whereas [7-10] considered energy constraints. In [3], the authors considered node connectivity and coverage with buffer overflow constraint. In [4], the multi-hop communication among SNs was considered and the mathematical formulation for RS placement problem was proposed. In [5] and [6], the authors considered the single hop communication between SNs and RSs. [5] assumed that the RSs could adjust the transmit power level where as [6] considered the connectivity constraints. In [7], the objective was to maximize the number of packets received at BS. In [8], the authors investigated definitions of network lifetime and proposed one that is appropriate for WSNs in forestry applications. In [9], the authors studied the BS placement problem that aimed to minimize energy consumption of SNs. In [10], the authors addressed the sensing coverage issue by keeping the minimum number of active SNs to save node energy. While the contributions of the previous works are significant, the existing studies did not consider the effects of noise and bit error rate characteristics of the wireless transceivers and did not provide radio connectivity guarantee. Furthermore, the network cost limitation and the energy efficiency were not considered together. For this reason, more practical and effective approaches for the WSN design with the use of relay stations are needed.

In our paper we propose a novel Binary Integer Linear Programming (BILP) model to optimally locate sufficient RSs to achieve minimum energy consumption in WSNs. In particular, we examine the problem of minimizing energy consumption of sensor nodes in the network under the network cost limitation (specified by the limited number of RSs) and the required network lifetime. Specially, our model accounts for the effects of noise and bit error rate characteristics of the wireless transceivers on the SN connectivity and the quality of communication links.

The remainder of this paper is organized as followed. Section II provides the problem definition and describes the problem formulation. Section III presents experiment setup. Section IV presents numerical result and analysis which focus on studying the network size on energy consumption. Finally, section V concludes the paper.

II. Problem Definition And Formulation

To achieve the energy efficiency in WSN deployment, this paper proposes optimal RS placement techniques, considering practical issues such as limitation of network cost, energy efficiency and the effects of noise and bit error rate characteristics of the wireless transceivers. Specially, we consider the minimum energy – RS placement problem (ME-RPP). The proposed model aims to determine optimal locations to install RSs in the target sensing field and determine optimal route to forward sensing data packet from SNs directly to BS or indirectly via RS(s) so that the energy consumption used for data transmission of SNs can be minimized and the resulting network configuration can guarantee that the network lifetime and the radio communication quality at the required bit error rate and a given budget for RS installation.

Here the network lifetime is defined as the duration from starting the network until the first SN depletes its battery power. This is a common definition of the WSN lifetime [11]. It is assumed that the SNs are distributed across the sensing field and the sensing data packets that contain sampled data from SNs are transmitted back to BS directly or indirectly via other neighbor SNs or RSs based on a synchronized schedule specified by a predefined period of time. We assume no collision in the packet transmission of SNs due to the MAC operation of IEEE 802.15.4.

TABLE I
NOTATIONS

Sets:	
I	A set of sensor nodes
J	A set of relay stations
B	A set of base stations
Decision variables:	
β_j	A binary {0, 1} variable that equals 1 if the RS is installed at site j, $j \in J$; 0 otherwise
s_{ik}	A binary {0, 1} variable that equals 1 if the SN i is assigned to SN k, i and $k \in I$, $i \neq k$; 0 otherwise
r_{ij}	A binary {0, 1} variable that equals 1 if the SN i is assigned to RS j, $i \in I, j \in J$; 0 otherwise
h_{ib}	A binary {0, 1} variable that equals 1 if the SN i is assigned to BS b, $i \in I$, $b \in B$; 0 otherwise
Constant parameters:	
E_t	Energy consumption for transmit data per round (*Joule/round*)
E_r	Energy consumption for receive data per round (*Joule/round*)
E_i	Initial energy of a sensor node (*Joule*)
P_{ik}	The signal strength that SN k receives from SN i (dBm), i and $k \in I$
P_{ij}	The signal strength that RS j receives from SN i (dBm), $i \in I$, $j \in J$
P_{ib}	The signal strength that BS b receives from SN i (dBm), $i \in I$,$b \in$B
P_{t1}	The received signal strength threshold between SNs (dBm)
P_{t2}	The received signal strength threshold between SNs and RSs (dBm)
P_{t3}	The received signal strength threshold between SNs and BS (dBm)
ω_k	Noise at SNs (dBm), $\forall k \in I$
ω_j	Noise at RSs (dBm), $\forall j \in J$
ω_b	Noise at BS (dBm), $\forall b \in B$
δ	Noise threshold for SNs (dB)
N_{RS}	The number of RSs that can be used due to the budget limitation
T	The required network lifetime

The proposed optimal RS placement problem is formulated as a Binary Integer Linear Programming (BILP) model, denoted as a ME-RPP model. Table I shows notations used in the model. ME-RPP model aims to minimize the SNs' energy consumption, including energy used for receiving and forwarding sensing data packets. This can be written as the objective function (1). We incorporate other network requirements into the mathematical model through a set of constraints written in (2) – (12).

Objective:

$$Min \quad T\Big(\sum_{\forall i\in I}\Big(E_r \sum_{\forall m\in I}^{m\neq i} s_{mi} + E_t \sum_{\forall k\in I}^{k\neq i} s_{ik} + E_t \sum_{\forall j\in J} r_{ij} + E_t \sum_{b\in B} h_{ib}\Big)\Big) \quad (1)$$

Constraints:

$$\sum_{\forall k\in I}^{k\neq i} s_{ik} + \sum_{\forall j\in J} r_{ij} + \sum_{b\in B} h_{ib} = 1 \qquad \forall i\in I \qquad (2)$$

$$\sum_{\forall k\in I}^{k\neq i} s_{ik} \le \sum_{\forall j\in J} r_{ij} + \sum_{b\in B} h_{ib} \qquad \forall i\in I \qquad (3)$$

$$\sum_{\forall j\in J} \beta_j \le N_{RS} \qquad (4)$$

$$r_{ij} \le \beta_j \qquad \forall i\in I, \forall j\in J \qquad (5)$$

$$s_{ik}(P_{ik} - P_{t1}) \ge 0 \qquad i \text{ and } k\in I, i\neq k \qquad (6)$$

$$r_{ij}(P_{ij} - P_{t2}) \ge 0 \qquad \forall i\in I, \forall j\in J \qquad (7)$$

$$h_{ib}(P_{ib} - P_{t3}) \ge 0 \qquad \forall i\in I, b\in B \qquad (8)$$

$$s_{ik}(P_{ik} - \omega_k - \delta) \ge 0 \qquad i \text{ and } k\in I, i\neq k \qquad (9)$$

$$r_{ij}(P_{ij} - \omega_j - \delta) \ge 0 \qquad \forall i\in I, \forall j\in J \qquad (10)$$

$$h_{ib}(P_{ib} - \omega_b - \delta) \ge 0 \qquad \forall i\in I, b\in B \qquad (11)$$

$$T\Big(E_r \sum_{\forall m\in I}^{m\neq i} s_{mi} + E_t \sum_{\forall k\in I}^{k\neq i} s_{ik} + E_t \sum_{\forall j\in J} r_{ij} + E_t \sum_{b\in B} h_{ib}\Big) \le E_i \qquad (12)$$
$$\forall i\in I$$

The objective function (1) intends to minimize energy consumption of SNs for receiving and forwarding sensing data packets during the required network lifetime, T. Constraint (2) states that each SN forms a path to send data packet via a neighboring SN and/or RS to BS. In order to preserve SNs' energy, we limit the sensor-to-sensor transmissions to one hop. Constraint (3) states that if SN receives data packet from other SNs, it will send the packet to RS or BS. Considering the network budget limitation, constraint (4) specifies the number of RSs to be used in the sensing field. Constraint (5) ensures that SNs send data packet to RSs that are installed. To guarantee radio connectivity between SNs, RSs and BS, constraint (6)-(8) ensures that the signal strength received at SNs, RSs and BS must be greater than the specified threshold. Here the simplify path loss model [12] is applied to evaluate radio connectivity around the sensor nodes. It is assumed symmetric connectivity in different directions around the transmitter. To guarantee the quality of radio communication at the required bit error rate, constraints (9)-(11) enforce that the signal to noise ratio (SNR) level at the receiving SNs, RSs, and BS must be greater than the specified threshold. Constraint (12) specifies the initial energy of each SN. It states that the total energy consumption of each SN for generating, receiving, and transmitting all data packets during the network lifetime cannot exceed the initial energy.

III. Experimental Setup

Our experiment consists of two phases of WSN network design. In the first phase we use ME-RPP model to obtain the optimal sites to install RSs and the optimal packet transmission path from SNs to the selected RSs or BS. In the second phase we use the results obtained from the first phase to derive the optimal path between RSs and BS and to select suitable antenna for RSs by using the algorithm based on minimum spanning tree. We use the Yagi antenna for transmission and the Omni-directional antenna for receiving data. Table II contains the antenna parameters [16].

We use the simplify path loss model [12] to calculate the received signal strength to guarantee sufficient signal strength that can ensure the radio communication between nodes in WSNs. Here the radio connectivity around the sensor nodes is assumed symmetric in different directions around the transmitters. The energy model presented in [15] is used to compute the energy consumption for transmitting and receiving signal of SNs.

The WSN standards IEEE 802.15.4 are considered in our experiments. Table III shows the parameters used in the mathematical experiments. The received signal strength threshold to ensure the radio communication between nodes in the network is set to -90 dBm [13]. The SNR level to guarantee the quality of radio communication is set to 2 dB in order to achieve bit error rate (BER) at 10^{-6} [14]. The period of time to transmit a sensing data packet is 5 minutes/round. Here we consider the required network lifetime of 47 days (13,631 rounds).

In numerical experiments, we consider the sensing field of size 500m×500m and BS is located at the center of the area. Fig. 1-3 has shown the example of sensor node's distribution in the network of size 30, 50, and 80 nodes, respectively.

We input the set of RS candidate sites, the required network lifetime, and other parameters to the model. Then, we solve the problem by implementing the ME-RPP model with the ILOG-OPL development studio and solving with CPLEX 12.2 optimization solver. Computations are performed on an Intel Core™ i5-2410M 2.3 GHz 64 bit and 4 GB of RAM.

IV. Numerical Results and Analysis

In this section we present numerical study and analysis demonstrating the optimal RS placement using the proposed ME-RPP model in the first phase and the results of algorithm to find connection of RS in the second phase.

TABLE II
GAIN AND COMMUNICATION RANG OF ANTENNA

Antenna	ID	Gain (dBi)	Communication range(m)
Transmit	1	7	188
	2	8	199
	3	15	298
	4	16	315
Receive	1	8	199

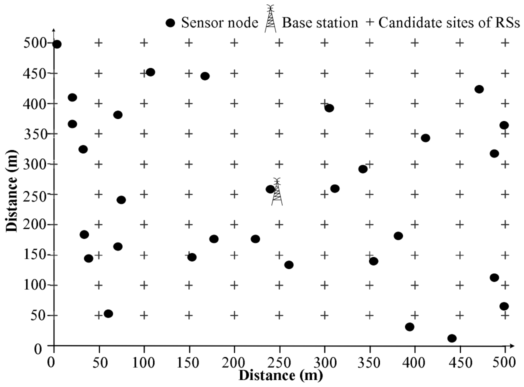

Fig. 1 Network 30 SN

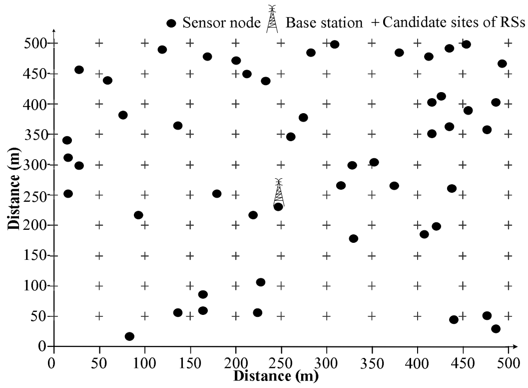

Fig. 2 Network 50 SNs

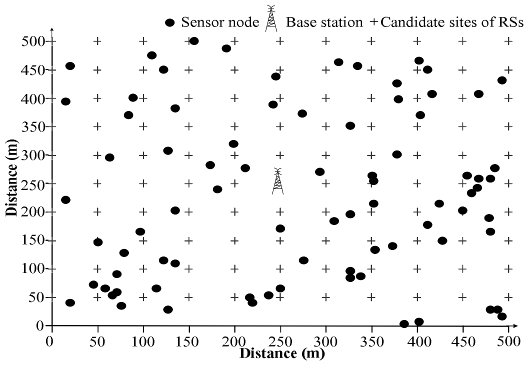

Fig. 3 Network 80 SNs

TABLE III
PARAMETERS USED IN NUMERICAL EXPERIMENTS

Parameters	Value
Receiver sensitivity threshold	-90 dBm
Operating frequency	2.4 GHz
Initial energy of sensor nodes	61,560 joules
Transmit power	32 mW
Reference distance	2 m
Path loss exponent	4
SNR	2 dB
Packet size	200 bits
Network lifetime	13,631 rounds (47 days)

TABLE IV
NUMBER OF RS INSTALLED IN THE NETWORK

Network	Number of relay station (node)					
	Test 1	Test 2	Test 3	Test 4	Test 5	Average
30 SNs	7	9	8	8	8	8
50 SNs	10	10	10	10	9	9.8
80 SNs	10	11	9	8	8	9.2

TABLE V
ENERGY CONSUMPTION OF SENSOR NODES (AVERAGE AND S.D.)

Network	Energy consumption of SN in network (Joules)					
	Test 1	Test 2	Test 3	Test 4	Test 5	Average (S.D.)
30 SNs	73637.42	48077.26	31986.56	40580.75	49286.75	48713.61 (15555.37)
50 SNs	56849.37	82258.65	72660.69	50103.76	58029.74	63980.44 (13117.4)
80 SNs	110615.56	157300.98	119743.29	166478.57	153219.76	141471.63 (24688.82)

Fig. 4-6 shows the optimal locations of RSs and the optimal packet transmission paths from SNs to RSs and the transmission path between RSs to BS. Table IV shows the number of relay stations that are selected to install in each network. We can see that the number of RSs required does not depend on the network size. The network of 50 SNs uses more RSs than that used in the network of 80 SNs. The reason is that to install RSs, the sufficient number and the suitable locations are selected based on the distribution of SNs in the sensing field. In some area where SNs are out of transmission range from other nodes, RS(s) is needed to receive and forward the packet to BS.

Table V reports the energy consumption of SNs during the required network lifetime. We can see that although the same network size in test 1 to 5, the energy consumption is not the same. The reason is that in each test, SNs are located in different positions. However, the networks containing more number of SNs tend to consume more energy than others. As we can see that the energy consumption in the network of 80 SNs is highest.

Fig. 7-9 show cumulative distribution function of the energy consumption in the network of 30, 50 and 80 SNs, respectively. Fig. 10 compares the energy consumption in those networks. We can observe that SNs in the network of size 50 consume least energy compared with the other networks. This means that the energy consumption of SNs does not solely depend on the number of SNs in the network but it also depends on how the SNs are distributed in the sensing field.

V. CONCLUSION

In this paper, the optimal relay station planning problems for minimum energy consumption in wireless sensor networks are investigated. We propose new mathematical formulation as a Binary Integer Linear Programming (BILP) model that can determine the optimal locations to installed relay stations and the packet transmission path from sensor nodes to the base station under a set of constraints on the radio communication range, the signal quality requirement in term of bit error rate limitation and the required network lifetime. Various network scenarios considered in the numerical experiments illustrate that the energy consumption of sensor nodes in the network depends on not only the density of the sensor nodes in the area but also how the sensor nodes are distributed in the sensing field. Our ongoing works investigate performance and effectiveness of the proposed model.

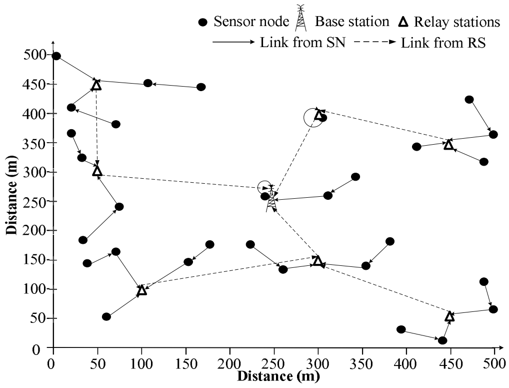

Fig. 4 Packet transmission path in the network of 30 SNs

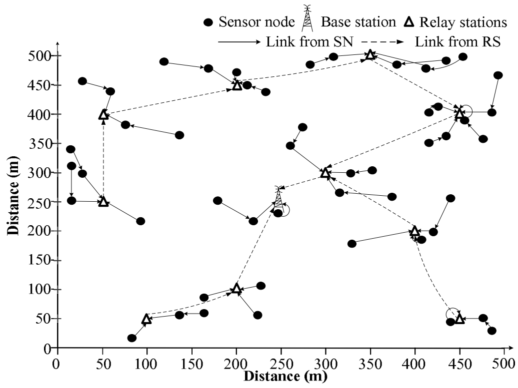

Fig. 5 Packet transmission path in the network of 50 SNs

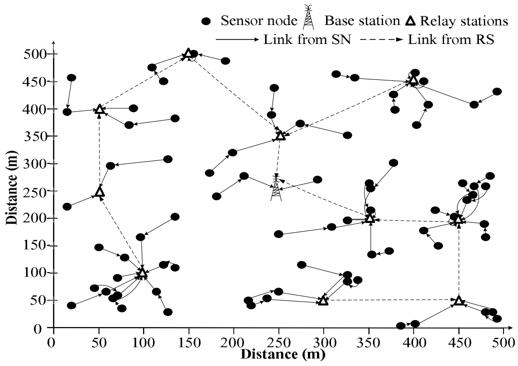

Fig. 6 Packet transmission path in the network of 80 SNs

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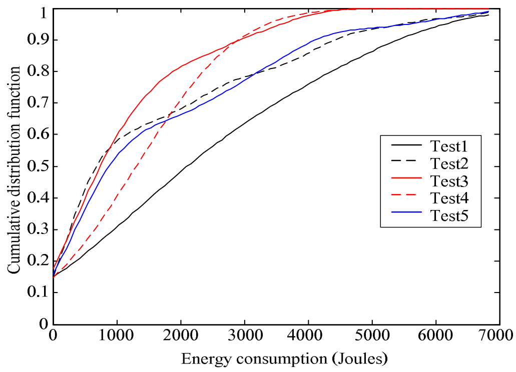

Fig. 7 CDF of energy consumption in network of 30 SNs

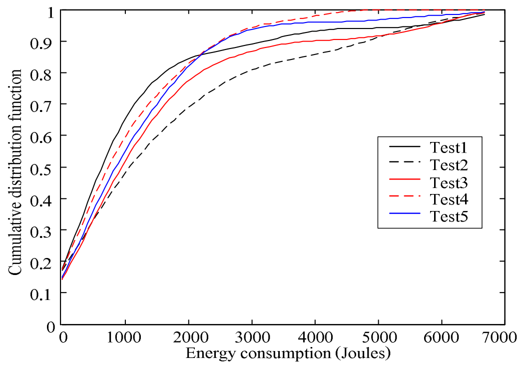

Fig. 8 CDF of energy consumption in network of 50 SNs

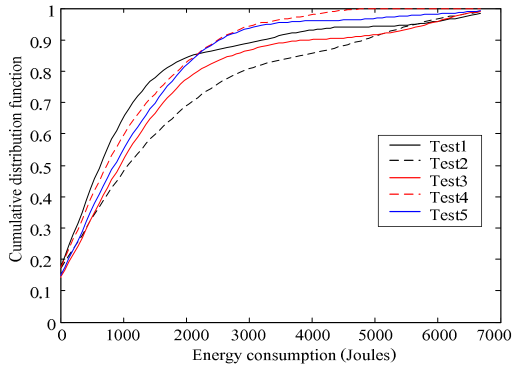

Fig. 9 CDF of energy consumption in network of 80 SNs

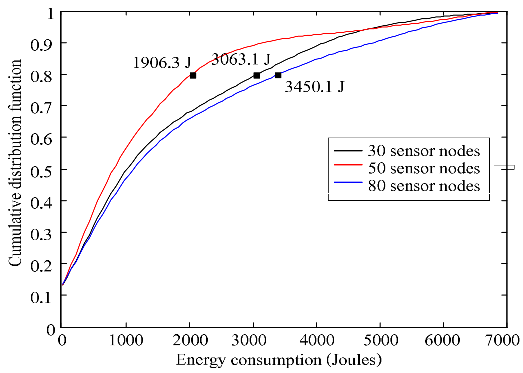

Fig. 10 CDF comparison of energy consumption