A Joint Design Approach for Communication Schedule and Layout of Wireless Sensor Networks

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Abstract— **This paper considers the problem of designing the layout geometry of a wireless sensor network to extend network lifetime. The communication pattern between sensor nodes and their associated base station is exploited in building an efficient network structure prior to network deployment. Such an approach is feasible for sensor networks whose installation and layout can be planned ahead of time, as is possible in many sensor network applications including intrusion detection, power-line monitoring and indoor monitoring. Since sensor nodes expand energy for relaying packets, we consider the question of placement of nodes in the typical line network topology to reduce the packet forwarding load on sensor nodes closer to the base station. Similar to scheduling problems in other domains, we also exploit the problem structure to find the periods for each sensor node to keep its radio active. The novelty of our problem formulation is that it jointly determines geometric layout and idle-listening times for line topologies. We also explain how the line solution can be used as a primitive in design of networks for the coverage of two dimensional regions. Simulation results show that such a joint design approach yields significant improvements in network lifetime as compared to the conventional network design method using uniform node distribution.**

Index Terms— **Wireless sensor networks, Scheduling, Coverage, Network Design.**

I. INTRODUCTION

WIRELESS sensor networks are currently being considered for a variety of information retrieval uses, the most frequent of which involves continual monitoring of a so-called *target region*. Applications range from environmental (soil monitoring) to security (detecting movement along a border). From a networking perspective, wireless sensor networks are uniquely characteristic in several ways. First, nodes are envisioned to be small, with limited battery power. Second, because applications usually require nodes to continually report sensed data, a significant part of the network traffic is predictable, thereby enabling off-line approaches. Finally, for some sensing applications sensor nodes can be laid out in a particular geometry if it is advantageous to the application. In many cases, the layout knowledge enables design of a fixed communication pattern that can be exploited by protocols, this is the approach used in this paper. The characteristic properties above (limited power, scheduling opportunities) motivate our work on developing a design approach for wireless sensor networks to extend network lifetime. The focus of this paper is outdoor sensor networks which require careful planning due to expensive, high precision sensor nodes and indoor surveillance sensor networks.

Consider a collection of n sensor nodes to be arranged along a line with a base station on one end, as is typical of many intrusion detection or pipeline monitoring applications. Upon detecting an important event, the nodes engage in a flurry of communication to get the sense data to the base station. At other times, in some applications, the nodes may periodically send sensed data regardless of special events. Because the energy consumed during communication significantly outweighs the energy consumed in computation, much research effort has gone into protocols and routing methods to minimize energy spent in communication. This paper considers an often neglected factor in such design problems: the geometry of sensor layout.

Clearly, nodes closer to the base station end up forwarding or relaying more packets than nodes further away. Over time, this *relay burden problem* constitutes a disproportionate share of energy consumption, leaving these “close-in” nodes with less energy and therefore the risk of prematurely terminating the network’s lifetime. At the same time, these nodes cannot afford long sleep times because they must be alert, in *idle listening mode*, to carry out their relaying function. The interplay between idle-listening time and network geometry creates an opportunity for a new joint problem formulation that finds the values for both sensor locations as well as idle-listening times in order to extend network lifetime. The problem we tackle is not only interesting but also complex, even the coverage aspect alone is NP-hard [1].

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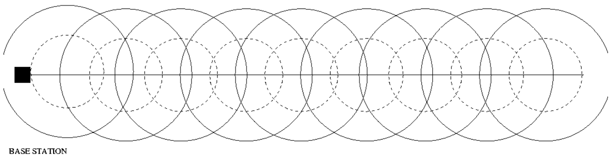

Fig. 1. A surveillance sensor network with line topology.

We observe that any approach to find sensor locations needs to be driven by a model of events that ultimately create the network traffic. Since events collectively contribute to network traffic over the lifetime of a network, a problem formulation must consider a statistical model of future possible events. In this paper we consider a Poisson model of events and determine sensor locations and idle-listening times to improve network lifetime under this Poisson model.

Our main result is that the network lifetime can be significantly increased when these parameters are determined using the proposed approach in comparison with the conventional network design method using uniform layout (equally spaced nodes) and equal idle-listening time distribution. An additional contribution of this paper relates to the solution approach. As we will show, the main problem formulation results in a mixed-integer non-linear problem, one of the difficult problem types in operational research. We show how this problem can be transformed into an approximation that is mixed-integer but linear, thereby enabling the use of well-established solution techniques, many of which are found in optimization software packages.

A. Problem Statement

This paper considers the idle listening and relay burden problems for the line network topology. The problems addressed in this paper are the following: *What is an effective placement of a given number of nodes in a line network topology for extending network lifetime?* Moreover, *what should be the idle listening period for each sensor node?* In our work, we consider the network lifetime as the time for the first node to die in the network, however, the proposed design approach can be customized for other definitions of network lifetime with minor modifications to the problem formulation. Figure 1 shows a surveillance sensor network with line topology in which nodes are placed uniformly. Sensing and transmission ranges of nodes are represented with dashed and solid circles respectively. The base station is located at one endpoint of the target region to be covered by sensor nodes. Then, sensor nodes collectively perform their task by relaying information about an intrusion among the target region to the base station.

An important point to note is that the problem considered in this paper is an off-line problem that should be solved prior to network deployment. However, the information of target areas is known in advance in many applications and therefore, it can be used effectively for off-line solutions. In addition, configuration information may be available at the base station that can then support individual sensors with their latest schedules.

B. Related Work

A significant amount of research has been carried out on the energy consumption of mobile devices [2], [3]. Similarly, several research efforts have addressed various aspects of energy consumption, ranging from low-power circuit design to applications that offload partial computations to wired servers. In comparison with these previous efforts, this paper focuses on the area of network protocols that reduce power consumption attributed to data transmission, a considerable portion of the overall power consumption of wireless sensor nodes [4]. Such protocols are complementary to efforts that use hardware techniques such as clock-speed variation.

Facility location [5] and network design, especially base station placement in cellular networks, has been a popular problem in the wireless research field. The goal is to find the optimum placement of a fixed number of base stations such that average signal strength or coverage is maximized. The key difference with the approach proposed in this paper is that there is no energy constraint on base stations and terminals are mobile. Base stations do not have to communicate with each other using wireless media due to the existence of wired infrastructure. In contrast, the problem of *coverage with connectivity* is solved in this paper. Many optimization methods have been proposed for the base station placement problem in the literature. Typical examples are genetic algorithms [6], simplex method [7] and simulated annealing [8]. For wireless sensor network design, an incremental installation method is introduced in [9] which makes use of Voronoi diagrams to find the regions of low observability from sensor nodes. Coverage of such regions is improved by deploying additional sensor nodes. In [10], authors quantify coverage as ”exposure”, the average ability of the network to observe an object moving through a trajectory over a time period, in order to measure the effectiveness of a sensor network design. In contrast to our work, the design methods of [9] and [10] are greedy in nature. Sensor network design is formulated in as a coverage problem of discrete grid points placed over the target area in [11]. However their approach is not feasible for dense grids and has the typical loss of efficiency drawback due to discrete problem domain.

Virtual communication backbone algorithms in Mobile Ad-hoc Networks (MANETs), MAC protocols [12], [13] and packet distribution protocols use scheduling for data transmission. SPAN [14] is a topology based model in which each node knows its 2-hop neighbors. GAF [15] is a location-based model which requires each node to be aware of its own position and the grid it resides. In both of these approaches, only a subset of nodes keep their radio active while preserving data dissemination capability of the network to solve the idle listening problem. However, both SPAN and GAF are developed in the context of MANETs, where traffic-flow may originate from any node to any other node in contrast to dominant network to base station data flow in sensor networks. In [16], the authors deal with the problem of scheduling packet transmissions in a wireless sensor network in order to find the optimum schedule of data distribution with directional and omnidirectional antennas. However, only packet delivery latency is optimized and relay burden problem, which is critical for network lifetime, is overlooked since nodes are placed with equal intervals on the line network as in Figure 1. Similar to the approach in this paper, the problem is first solved for the line network topology and then extended to two dimensional networks.

Coverage preserving scheduling in wireless sensor networks has recently gained attention of researchers. The distributed coverage maintenance protocol proposed in [17] identifies redundant nodes for coverage and turns off their sensing units while keeping network coverage confidence above the desired level. The work in [18] makes use of the concept of ”sponsored coverage” based on absolute location information to turn off the sensing units of nodes whose sensing regions are covered by neighbor nodes. A coverage configuration protocol is presented in [19] which arranges the network to the coverage degree requested by the application. In [20], a minimum set of sensors is identified for a given query such that sensing regions of the selected set of sensors cover the geographical region of the query, and the selected set of sensors form a connected communication graph. In comparison with our approach, these protocols are not considered in the design phase of the network, instead they focus only on the operation of the network after deployment.

The rest of the paper is organized as follows. Section II-A describes the system model. Section II-B introduces the terminology used in the problem formulation. In Section II-C, initial nonlinear problem formulation is presented. Section III-A transforms the formulation to Mixed Integer Programming (MIP) domain for computational efficiency. Section IV explains how the design for line network topology can be used for developing general network topologies. Section V discusses the performance evaluation and Section VI presents the concluding remarks.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

This paper assumes that the transmission radii of the nodes are fixed and identical, as is typical of inexpensive sensor nodes. A sensor node’s radio can switch among four modes, *sleep, idle, transmit* and *receive* [14], [15], [21]. In *sleep mode*, no communication takes place since radio of the sensor node is turned off. In *idle mode*, the radio of the sensor node is active even if the sensor node does not communicate. The transmit and receive modes are used when the node sends or receives a packet respectively. We assume a perfect capture model (low error rate) in which a sensor node can receive a packet from another one if their distance is less than or equal to the transmission range. Fixed length packet format is used during communication. Then, the energy spent for transmitting a packet is calculated by multiplying the duration of the packet by the power spent in transmit or receive mode.

We assume that an event is detected by the closest sensor. In order to simulate intrusions among sensor nodes, an event model is used, where the number of intrusions in a generic time interval has a Poisson distribution. The location of the intrusions is randomly distributed along the target region. If a sensor node’s radio is turned off and it senses an event, corresponding information is stored until its radio becomes active. All nodes have the same initial residual energy at the beginning. Finally, sensor nodes farther away from the base station are labelled with higher numbers in the formulation.

B. Problem Parameters

The following notation will be used in the problem formulation:

- n: the total number of nodes in the network ;
- P_t: the transmit power in Watts ;
- P_r: the receive power in Watts ;
- P_i: the idle (listening) power in Watts ;
- l: the total length of the target region to be covered by the network in meters ;
- E_j: the initial energy level of node j in Joules, $j = 1..n$;

- ΔE_j: the total energy consumption of node j in Joules up through to the moment when the first node in the network dies, $j = 1..n$;
- λ: the Poisson parameter for number of intrusions ;
- t_p : Time to transmit a single packet in seconds ;
- τ: the time to transmit a single packet in seconds ;
- r_s: the sensing range of nodes in meters ;
- r_t: the transmission range of nodes in meters ;
- ρ: the minimum separation required between adjacent nodes in meters ;
- k_j: a Boolean (with value zero or one) variable indicating whether node j can communicate directly to the base station or needs a closer node as relay, $j = 2..n$;
- σ_{ji}: a Boolean variable representing whether node j is using node i as a relay node at any time instant during network lifetime, $j = 2..n,\ i = 1..(j-1)$;
- t_{ji}: the duration that node j is using node i as a relay node in seconds, $j = 2..n, i = 1..(j-1)$;
- t_j: the total listening duration of node j in seconds, $j = 1..n$;
- x_j: the distance of node j from the base station in meters, $j = 1..n$. Together with the t_j's, these form the variables of the problem ;
- T: the lifetime of the network in seconds. This is the measure we wish to maximize.

C. Problem Formulation

The constraints of the problem are divided into several categories and explained below:

1) Bound Constraints:

- (B.1) $0 \leq x_j \leq l,\ j = 1..n$.
  Coordinate bounds.
- (B.2) $\sigma_{ji} \leq (1 - k_j),\ j = 2..n,\ i = 1..(j-1)$.
  If a node can communicate with the base station directly, it should not use any relay node.
- (B.3) $t_j = \sum_{(i=j+1)}^{n} t_{ij} * \sigma_{ij},\ j = 1..(n-1)$.
  The total listening duration of a sensor node is determined by the number of nodes choosing it as relay and the durations it functions as relay for these nodes.
- (B.4) $0 \leq t_j \leq T,\ j = 1..(n-1)$.
  The total listening duration of a node is bounded by the network lifetime.
- (B.5) $t_n = T$.
  The last node is assumed to be operational all the time.

2) Placement Constraints:

- (P.1) $x_j \leq (x_{(j+1)}$ - $\rho)$, $j = 1..(n-1)$.
  In the ordering constraint, sensor nodes farther away from the base station are numbered higher in the formulation.
- (P.2) l - $x_n \leq$ rs.
  The farthest end of the target region from the base station should be covered by the last node in the network.
- (P.3) $x_1 \leq \min(r_s, r_t)$.
  The end of the target region closest to the base station should be covered by the first node in the network. At least first node should be able to communicate with the base station directly for the connectivity of the network.
- (P.4) $(x_{(j+1)}$ - $x_j) \leq \min(r_t, 2 * r_s),\quad j = 1..(n-1)$.
  A node should at least be able to communicate with its adjacent neighbors. The spacing between adjacent nodes should enable detection of any intrusion among the target region that reside between the nodes.
- (P.5) *if* $(k_j = 0)$ *then* $x_j > r_t$ *else* $x_j \leq r_t$, $j = 2..(n)$.
  If a sensor node can communicate directly with the base station without any relay, its distance to the base station should be smaller than the transmission range.
- (P.6) *if* $(\sigma_{ji} = 1)$ *then* $(x_j$ - $x_i) \leq r_t$, $j = 2..n, i = 1..(j-1)$.
  A node can not be used as a relay by another one if the distance between them is not smaller than the transmission range.

3) Operational Constraints:

- (O.1) $0 \leq \Delta E_j \leq E_j,\ j = 1..n$.
  This is simply the battery constraint of each node.
- (O.2) *if* $(k_i = 0)$ *then* $\sum_{(j=1)}^{(i-1)} t_{ij} * \sigma_{ij} \geq t_i,\ i = 2..(n-1)$.
  If a node can not communicate with the base station directly, there should always be a relay node listening for packets of this node.

- (O.3) $\Delta E_1 =$

$$\left\{ \begin{array}{l} P_t t_p \left(\left(\frac{(x_1+x_2)}{2l} \right) \lambda T \right) \ + \\ (P_t + P_r) t_p \left(\left(1 - \left(\frac{(x_1+x_2)}{2l} \right) \right) \lambda t_1 \right) \ + \\ P_i \left(t_1 - \left(\left(\frac{(x_1+x_2)}{2l} \right) T + 2 \left(1 - \left(\frac{(x_1+x_2)}{2l} \right) \right) t_1 \right) \lambda t_p \right) \end{array} \right\}.$$

The three terms in the summation represent the energy spent by the first node for the following operations: *(i)* transmitting packets for events that originated within node's sensing range; *(ii)* relaying packets for nodes farther away from the base station; and *(iii)* idle listening. A node can relay packets only when its radio is on, however, events within its sensing range can originate anytime. The idle listening duration is found by subtracting the time spent in receiving and transmitting packets from the total listening duration of the sensor node. The sensing region for the first node is identified based on Constraint P.3 and the assumption that a target is detected by closest sensor.

- (O.4) $\Delta E_j =$

  $$\left\{ \begin{array}{l} P_t t_p \Bigl(\Bigl(\frac{(x_{(j+1)} - x_{(j-1)})}{2l} \Bigr) \lambda T \Bigr) \; + \\ (P_t + P_r) t_p \Bigl(\Bigl(1 - \Bigl(\frac{(x_j + x_{(j+1)})}{2l} \Bigr) \Bigr) \lambda t_j \Bigr) \; + \\ P_i \, (t_j - \Bigl(\Bigl(\frac{(x_{(j+1)} - x_{(j-1)})}{2l} \Bigr) T \; + \\ \qquad\qquad 2 \Bigl(1 - \Bigl(\frac{(x_{(j)} + x_{(j+1)})}{2l} \Bigr) \Bigr) t_j \Bigr) \lambda t_p \Bigr) \end{array} \right\}$$

  $, \; j = 2..(n-1).$

  Similar to the first node's energy consumption, the terms of summation represent the energy spent by j-th node for transmitting packets for events that originated within node's sensing region, relaying of packets and idle listening. However, definition of the sensing region that a node is responsible for differs for the first, last and intermediate nodes. This is due to the fact that closer and father ends of the target region to the base station are covered *only* by the first and last nodes respectively.

- (O.5) $\Delta E_n = P_t t_p \Bigl(\Bigl(\frac{2l - x_n - x_{(n-1)}}{2l} \Bigr) \lambda T \Bigr).$

  The last node only transmits packets for events that originated within its sensing range.

The objective, naturally, is to maximize T, the expected network lifetime with respect to the locations of the nodes and the idle listening times. We note that once the idle listening intervals are known, the actual exact times can be computed as follows. Node n in the network is assumed to have listening start time of zero (corresponding to initial network deployment) and has a listening duration equal to network lifetime (Constraint B.5). Starting from node n, the listening duration of each node is divided amongst its relays according to the σ_{ji} values found. The start time for the listening period of a relay of the node therefore depends on the start time of the listening period of the node and non-overlapping listening durations of other relays of the node with smaller identifiers. Since nodes buffer their data until their radio become active, the listening times are identified with respect to *rounds* with duration based on node buffer size, instead of whole network lifetime to minimize packet transmission delay.

The formulation above is based on the following lemma which states that the listening periods reserved for serving different sensor nodes are non-overlapping in a relay node's total listening period.

Lemma.1 : If node j, $1 \leq j \leq (n-2)$, functions as a relay for two different nodes, namely node i and node k, for $i, k > j$, the listening durations reserved for these nodes in node j's total listening period, denoted by t_{ij} and t_{kj}, are disjoint.

Proof : The proof considers the last node as its starting case. Suppose node $(n-1)$ and node $(n-2)$ are the only nodes within the transmission range of the last node n. They share the relaying load such that the union of their listening durations is equal to the network lifetime. Their listening durations do not overlap with each other to prevent energy wastage. If another node m, $m < (n-2)$, is used as a relay node for them which is in transmission range of both node $(n-1)$ and node $(n-2)$, one can observe that its listening durations for nodes $(n-1)$ and $(n-2)$ are disjoint since these nodes themselves have disjoint listening durations for node n. Inductive application of the argument concludes that the condition holds for other groups of nodes in the network closer to the base station as well. ■

III. SOLUTION APPROACH

The line network design problem formulated above is a nonlinear mixed integer programming problem, due to the product terms such as the ones including coordinate and listen duration variables in the ΔE constraints. Among optimization problem types supported by solver packages, this is the least supported problem type. To improve the speed, we trade off exact optimality and transform the problem into a mixed integer programming formulation.

A. Mixed Integer Programming Approach

Mixed Integer Programming (MIP) [22] is a technique supported by many optimization packages and is designed to efficiently prune the search space during the branch and bound process by relaxation and updating the bound values in comparison with nonlinear solution methods. We now show how the nonlinear problem above can be transformed approximately into a MIP formulation. The transformation process consists of two steps; modelling the conditional constraints of the problem and representation of the nonlinear terms.

- The conditional constraints of the problem are modelled as in Equation 1. The conditions forcing zero values for the decision variables are expressed by replacing the decision variable with a term subtracting the decision variable from 1.

$$if\ (\aleph = 1) \quad then \quad (A \leq B) \longrightarrow A + U\aleph \leq U + B \quad (1)$$

where ε is a very small tolerance value, L, U are lower and upper bounds on the expression $(A - B)$ respectively. Constraints P.5, P.6, O.2 belong to this step of transformation. As an example of this transformation, the constraint P.6 is expressed as

$$(x_j - x_i) + l * \sigma_{ji} \leq r_t + l, \quad j = 2..n, i = 1..(j-1) \quad (2)$$

- In order to transform nonlinear terms, we use the method of *linked Special Ordered Sets* (SOS) [22]. A Type-1 SOS (SOS1) is a set of variables within which exactly one variable must be non-zero. In a Type 2 SOS (SOS2) problem, at most two variables from a special ordered set can be nonzero and these should be adjacent to each other [23]. The SOS theory then exploits this structure to interpolate a two dimensional nonlinear function using a grid of sample points in the function domain. This transformation is used in order to eliminate the product terms in ΔE constraints such as $(x_1 t_1)$ and $(x_2 t_2)$ in ΔE_1. For each product term $z = x * t$ included in the constraints, a uniform grid of 100 sample points (p_i, p_j), $i = 1..10, j = 1..10$ are taken from domains of corresponding variables.

$$x = \sum_{i=1}^{10} \sum_{j=1}^{10} p_i w_{ij} \quad (3)$$

$$t = \sum_{i=1}^{10} \sum_{j=1}^{10} p_j w_{ij} \quad (4)$$

$$z = \sum_{i=1}^{10} \sum_{j=1}^{10} (p_i * p_j) w_{ij} \quad (5)$$

$$1. = \sum_{i=1}^{10} \sum_{j=1}^{10} w_{ij} \quad (6)$$

$$\zeta_i = \sum_{j=1}^{10} w_{ij}, \quad i = 1..10 \quad (7)$$

$$\nu_j = \sum_{i=1}^{10} w_{ij}, \quad j = 1..10 \quad (8)$$

where $\zeta_1, .., \zeta_{10}$ and $\nu_1, ..., \nu_{10}$ are SOS2 sets. This ensures that at most four neighboring w values can be nonzero. The basic idea behind this method is to approximate the nonlinear function with closest grid points for improved accuracy. The SOS technique appears to have currency within the optimization community and has certainly helped reduce the complexity of our problem formulation. Our experience shows that it produces accurate solutions fairly quickly for modest problem sizes. For extremely large problem sizes, any integer programming approach is forced to make approximations to maintain a reasonable running time. We next consider how a solution approach for line networks may be used as a building block for two-dimensional target regions.

IV. TWO DIMENSIONAL NETWORK DESIGN

The primary topological focus of this paper is on line networks, for applications that include border intrusion detection and power-line, pipeline or road monitoring. However, we also show, in this section, how a two dimensional network can be crafted by using a collection of line networks, each of which are designed using the approach we have described in this paper. For example, as seen in Figure 2, the area to be covered is a square region with side length of l. In this case, base stations may be at any corner. Let us consider the case when two base stations are used at two opposite corners of the square region.

The placement of nodes for this topology can be found by solving a number of line network topology problems where each line network operates using a different channel based on code or frequency-division multiplexing.

The number of line networks used will determine how many nodes are assigned per line. For example, the figure shows how 20 line networks can be deployed in the square region. The line networks can be identified by a three tuple consisting of their start, "turn" and end points. The lines are $\{BS_1, A_1, P_8\}$, $\{BS_1, A_2, P_7\}$, ..., $\{BS_1, A_9\}$, $\{BS_2, B_1, P_1\}$, $\{BS_2, B_2, P_2\}$, ..., $\{BS_2, B_9\}$, $\{A_9, BS_2\}$, $\{BS_1, B_9\}$. Most of the line networks contain a "turn" to help cover the 2D space. The turn itself has no impact on the efficiency of the solution.

There are additional constraints that we introduce to the 2D version of the problem. This is due to the fact that the definition of coverage with connectivity changes with the dimension. Based on this observation, the additional constraints can be defined as follows.

- The distance between the last node placed before the breakpoint and the first node placed after the breakpoint in a line network should be smaller than $\frac{r_t}{\sqrt{2}}$ for connectivity.
- The location of breakpoint is shifted $\frac{r_s}{\sqrt{2}}$ to the right for line network instances placed adjacently as is the case for $\{BS_1, A_1, P_8\}$ and $\{BS_1, A_2, P_7\}$ where $A_2 = A_1 + \frac{r_s}{\sqrt{2}}$.
- Constraint (P.4) is modified as $(x_{(j+1)}$ - $x_j)$ $\leq min(r_t, 2 * \frac{rs}{\sqrt{2}}), j = 1..(n-1)$, to ensure that there

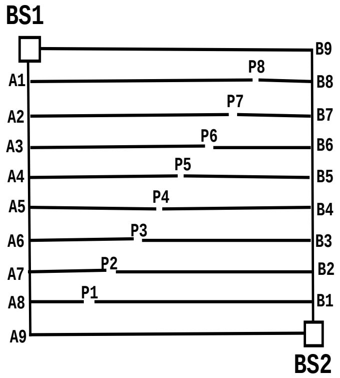

Fig. 2. Covering the conventional square shaped target region.

are no spots left uncovered in the target region between line networks.

The approach just described is one of many ways by which line networks can be used to cover a 2D region. Other ways include a single long raster-scan line, radial lines or space-filling fractal curves such as Peano curves depending on the shape of the target region to be covered. As an example, Figure 3 shows the placement methodology for consecutive line networks over a circular target region in which the radius of the target region is taken as $(l - r_s)$. For every such arrangement, the lines can be assumed independent as a first approximation. Naturally, there is a shared cost if transmission occurs between lines. A more complex problem formulation might be able to capture this interplay, but will lose the efficiency of combining solutions from the single-line sub-problems. We next turn to performance results obtained from using our approach.

V. PERFORMANCE EVALUATION

We have used the commercial optimizer ILOG that has built-in support for mixed integer programming and SOS [24]. The performance of the proposed approach is compared with that of uniform network design in which nodes are spaced equally along the line as in [16] forming a connected topology and each node's idle-listening time is distributed uniformly to its relays. The energy model of the sensor radio is given in Table-I [21]. The parameters used during the simulation are as follows

TABLE I
OPERATIONAL MODES OF THE 2.4 KBPS RFM RADIO WITH ON-OFF KEYING (OOK) MODULATION AND RANGE 20M

Radio mode	*Power Consumption (mW)*
Transmit(T_x)	14.88
Receive(R_x)	12.50
Idle	12.36
Sleep	0.016

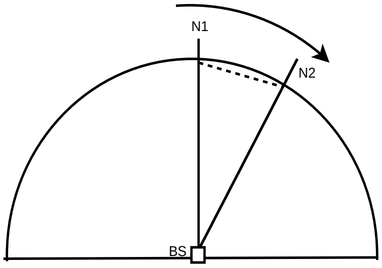

Fig. 3. Two dimensional network design for a circular target region.

- l : 100 meters ;
- rt : 20 meters ;
- rs : 20 meters ;
- ρ : 2 meters ;
- Packet size : 12 bytes ;
- E_j: 5 Joules, $j = 1..n$;

We first consider the effect of the number of nodes to be used in network design. Figure 4 compares the performance of two design approaches with respect to varying number of nodes for a constant event rate of $\lambda = 12$. The performance of the proposed design approach improves with increasing network population as compared to the uniform network design since the proposed design approach reduces the load on the most vulnerable sensor node with addition of new nodes.

Another important parameter is the transmission and sensing ranges of nodes used in design. As can be observed from the ratio of network lifetimes shown in Figure 5, in which node count and λ are kept constant at 12, robustness of the network designed with the proposed approach increases with improved transmission and sensing ranges of nodes when compared to the uniform network. The proposed network design approach exploits enhanced capabilities of sensor nodes to find better solutions in the extended solution space. This is due to the fact that improved coverage of sensor nodes relieves placement constraints and increased transmission range enables nodes to transmit further, which in turn increase relaying and scheduling opportunities.

VI. CONCLUSIONS AND FUTURE WORK

This paper presented a design approach which determines the layout and idle-listening parameters of a sensor network for the line topology. Line networks are important on their own right and have many standalone applications including border intrusion detection, power-line and pipeline monitoring. The proposed design approach also forms the basis for design of two

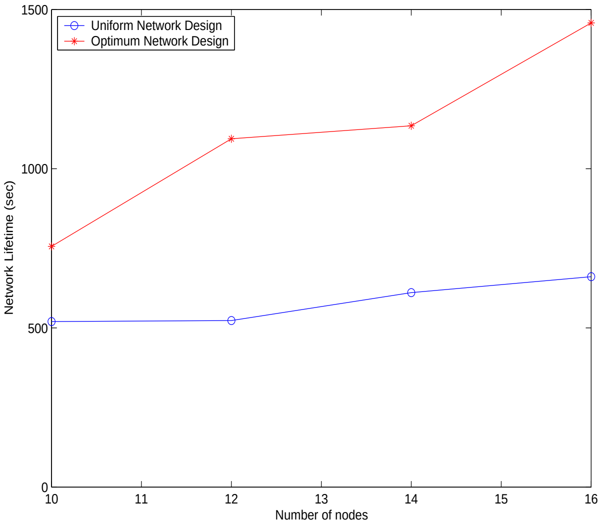

Fig. 4. Effect of number of nodes on network lifetime.

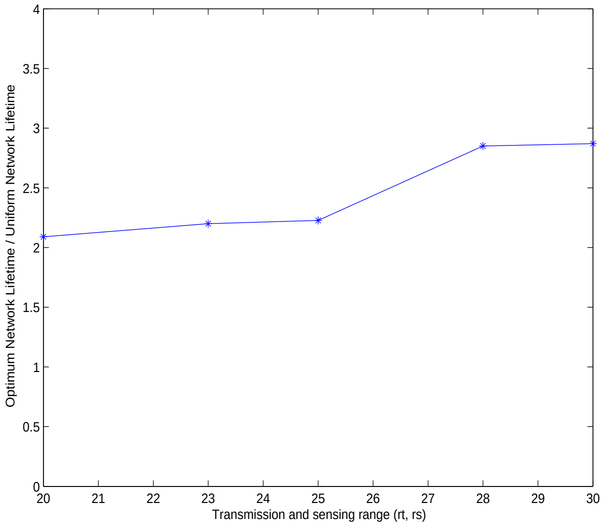

Fig. 5. Effect of sensor transmission and sensing ranges on network lifetime.

dimensional wireless surveillance sensor networks whose installation can be controlled such as indoor monitoring networks. Our work significantly improves the network lifetime when compared with the traditional network design method using uniform layouts and equal idle-listening time distribution.

As for future work, we plan to modify the formulation to include periodic data collection case in addition to the event based data retrieval. Application of distributed source coding for correlated data can be modelled with variable size packets for each node based on its distance to other nodes. The new product terms introduced to the formulation can be approximated with the same methodology used in our work.

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