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Optimal Node Placement in Wireless Underground Sensor Networks

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Abstract

Wireless Underground Sensor Networks (WUSNs) are active and emerging area of application of Wireless Sensor Networks (WSNs), whereby sensor nodes are located under the ground environment. The communication between the nodes is done underground, with the aim of sensing events to transmit the sensed events to the sink, which is normally in the terrestrial environment. The most challenging issue in the design of wireless sensor networks for the application of localization in the underground environment, mostly for miner's location, is the sensor nodes' placement problem. In this paper, we formulate a nonlinear program to determine the optimal information extraction in a grid based wireless underground sensor network. We then carefully study the cost of transmitting a bit of sensed information in the underground environment, were we then analyse the average transmission cost (energy consumed in joules per unit distance) for both variation in transmission distance between nodes, packet size (bits), and number of nodes in the network (network node density). The result shows that through optimal node placement approach, energy consumed in the network can be minimized if nodes are selectively placed using the minimum transmission cost. This work provides an insight on average transmission cost for deploying wireless underground sensor networks for the application of underground miners' localization and protection.

Keywords: Wireless Sensor Networks, Transmission Cost, Node Placement, Packet Size, Wireless Underground Sensor Networks, Information Optimization, Grid Topology.

INTRODUCTION

The features of Wireless Sensor Network (WSN) has led to a proliferation in their use in a wide variety of applications such as traffic monitoring, target tracking, perimeter/boarder monitoring, military surveillance, environmental monitoring and many others. Different WSN applications have varying specific requirements. In [1], Rault et al. proposed a taxonomy of WSN applications and their requirements. Depending on where they are deployed, most applications require the use of sensors of tiny size. These sensor devices are often referred to as sensor nodes or just nodes [2]. The main disadvantage of a WSN is its limited lifetime. When a node's energy is depleted it stops functioning hence a WSN may be physically damaged if many nodes within the network have their limited battery energy depleted. The lifetime of a WSN depends on node placement, pattern topology and routing protocol applied [2]. Related to WSN is the concept of Wireless Underground Sensor Networks (WUSN) [3, 4]. Unlike ordinary WSN used for monitoring underground conditions which depend on buried sensor which are wired to the surface, WUSN devices are buried completely underground with no wired connection to the surface [5]. The advantages of these WUSN are; ease of deployment, concealment, timeliness of data, coverage density and reliability [6]. The fact that WUSN devices are deployed underground presents some challenges than terrestrial WSN. They major challenge is lifetime of the WUSN. On account to the lossy underground channel, WUSN devices are equipped with radios that have high transmission power compared to terrestrial WSN devices. Once a WUSN sensor's lifetime is over, it is a challenge to replace or recharge it since it is mostly difficulty to access it underground. Even though some scavenging opportunities strategies for WUSN devices are available [7, 8, 9] other simple methods such as recharging and energy harvesting are difficult if not impossible. This therefore calls for redesign of efficient communication protocols which will optimise energy usage.

RELATED WORK

Node placement is a key corner stone for successful deployment of wireless sensor network. It has a huge impact on coverage, data latency, connectivity and lifetime of the WSN. Node placement in WSN research has received a lot of attention in the past decade [10, 11, 12]. A comprehensive overview of various techniques and approaches for node place was presented in [13]. Hou et al [14] and Wang et al [15] studied a number of routing algorithms and placement strategies for two-tier wireless sensor networks. Without considering a constraint addressing WSN lifetime, Tang et al [16] formulated relay node placement as two optimization problems in a heterogeneous network. In [17], Liu et al proposed a mechanism to assist in the placement of Relay Nodes (RNs) for underground tunnel infrastructure monitoring. To achieve this they applied an accurate empirical mean path loss propagation model in conjunction with a fitted fading distribution model which is defined for the tunnel environment. Results obtained in [17] showed that the choice of a suitable path loss model and fading distribution model for a particular environment is critical in determining the number and positions of relay nodes. Liu et al further formulated and modelled the RN problem as a cluster based two-tier multi-hop network. In [18], Pan et al analysed the gateway node placement in order to maximise the lifetime of a two-tiered WSN. A greedy sensor placement strategy was proposed in [12]. This strategy minimises and balances the energy usage of each sensor.

The works above are about normal terrestrial WSNs. Recent research works have focused on Wireless Underground Sensor Networks (WUSNs) [3, 4]. WUSNs are a special form of WSNs. Unlike their counterparts (terrestrial WSNs), WUSN mainly use sensors that communicate through the soil [6]. In [5, 19] the concept of WUSN and the challenges associated with underground wireless channel were presented. In their work Yu et al [6] conducted experimental measurements with commodity sensor nodes at a frequency of 433MHz and concluded that there is a potential feasibility of WUSN by using Radio Frequency transceivers at 433 MHz frequency. Jiang et al [20] developed an efficient sensor placement strategy for tunnel wireless sensor network. The authors in [21] presented a sensor deployment strategy for chain-type wireless underground mine sensor network.

WIRELESS UNDERGROUND SENSOR NETWORK

In wireless underground sensor network, sensor nodes are fixed, and are randomly distributed in the environment to monitor personnel locations or other interesting events. If we consider the network of N sensor nodes ranging from 1, 2, 3 . . . N, relay nodes and a sink node, S, randomly distributed over the monitored underground region, we can look at the distance between nodes in the x and y-directions as D_x and D_y respectively. We randomly distribute the nodes in the underground topology as shown in Figure 1. We consider a first order radio model, which is a single hop transmission for transmitter, receiver and circuitry energy for sending information in the network as shown in Figure 2.

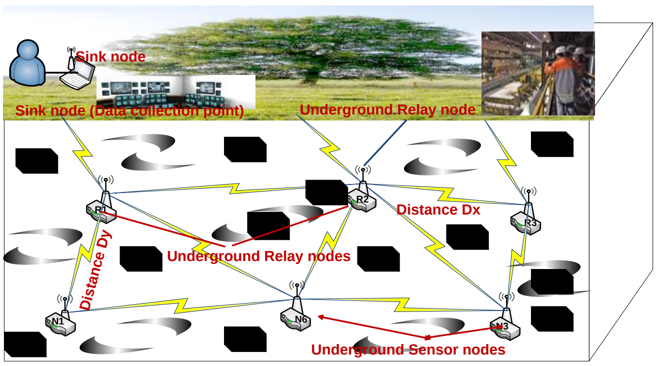

Figure 1: Topology of Wireless Underground Sensor Network

Figure 1 is a grid based topology in the underground environment, which considers sensor nodes randomly distributed to occupy all corners of the environment as it is applied to grid based topology. For the network under consideration (underground sensor network), it is important to know the distance between pairs of nodes as it will allow us to give priority to either distance or energy consumed by nodes in the network for network lifetime elongation. In general, the total amount of energy required for a packet of information or sensed event to arrive at the destination node (sink node), of which the communicating nodes are in the range of communication, is given as a function of the number of sensed events (normally measured in bits) and also a function of the square of the distance (D) between the pair of the communicating nodes. However, for a grid based topology as applied to underground environment, energy required for sending a sensed message to a nearby neighbour defined as E_{pk}, is the sum of the energy required for transmitting the sensed information, E_{tm} and that required for the reception of the same message by the neighbour node E_{rc} [22]. That is:

$$E_{pk} = E_{tm} + E_{rc} \tag{1}$$

Now, if we take the nodes transmitting in both direction, that is x and y direction, we can refer to the distance coordinate of x and y as D_x and D_y respectively. For two consecutive grid nodes, the distance between them D is:

$$D = ((D_{x1} - D_{x2})^2 + (D_{y1} - D_{y2})^2)^{\frac{1}{2}} \tag{2}$$

If we consider the underground environment as in Figure 1 with width W_x and of height W_y, we can define the horizontal and vertical hops of sensor nodes in the X and Y direction respectively as $\frac{W_x}{D}$ and $\frac{W_y}{D}$. If we carefully select distance between nodes, the average energy consumed per unit meter (average transmission cost), T_{av}, can be defined as:

$$T_{av} = \frac{\sum_{(X+Y)hops}(E_{tm} + E_{rc})}{D_s} \tag{3}$$

and,

$$D_s = ((DX)^2 + (DY)^2)^{\frac{1}{2}} = D(X^2 + Y^2)^{\frac{1}{2}} \tag{4}$$

Where D_s represents the distance for a single hop transmission between sensing nodes [22](source nodes) and the destination node (sink node). We adopt a simple radio model as used in [22]. This model is shown in Figure 2. The model shows the energy dissipation by radio, E_{elec} measured in joules per bit for transmission or reception of information using the electronic circuitry, and the transmit amplifier energy denoted by E_{amp}, also measured in joules per bit of information, are the necessary energy needed for sending any sensed event. However, for the reception of sensed events, only the radio energy, E_{elec} is required due to the fact that there is no need for amplification at the receiver ends.

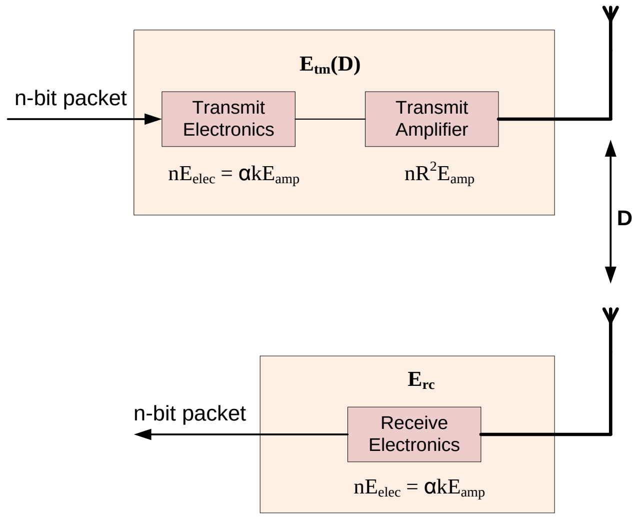

Figure 2: First order radio model (single hop transmission)

Also, a D^2 energy loss due to channel transmission is assumed. Hence, to transmit an n-bit of information over a distance D using the simple radio model [23, 24], the energy expended in transmitting an information of n-bits of data in a single hop is$(E_{tm} + E_{rc})$, and

$$E_{tm}(n, D) = E_{tm-elec}(n) + E_{tm-amp}(n, D) \tag{5}$$

Or $E_{tm}(n, D) = nE_{elec} + nD^{\lambda}E_{amp} = n\alpha E_{amp} + nD^{\lambda}E_{amp}$ (6)

Where λ represents the path-loss exponent such that $(2 \le \lambda \le 4)$. If we assume $\lambda = 2$ for a single hop transmission (minimum loss) or minimum transmission cost, then,

$$E_{tm}(n, D) = nE_{amp}(\alpha + D^2) \tag{7}$$

Where α is an amplification factor such that $\alpha = \frac{E_{elec}}{E_{amp}}$. And to receive the n-bit of message, the radio energy expended is:

$$E_{rc}(n) = E_{rc-elec}(n) = nE_{elec} = \alpha nE_{amp} \tag{8}$$

But the average energy consumed per unit distance in (3), can then be re-arranged as:

$$T_{av} = \frac{\sum_{(X+Y)hops}(E_{tm}+E_{rc})}{D_S} = \frac{(X+Y)[\alpha nE_{amp}+nD^2E_{amp}+\alpha nE_{amp}]}{D*(X^2+Y^2)^{\frac{1}{2}}} \tag{9}$$

$$= \frac{(X+Y)nE_{amp}(2\alpha+D^2)}{D*(X^2+Y^2)^{\frac{1}{2}}} \tag{10}$$

For the static grid based network used in RMASE [22], x, y, n, and E_{amp} are constant in the W_x by W_y grid topology. The upper bound for energy consumption can be achieved if the expression (10) above is set to the worst case scenario as:

$$T'_{av} = \frac{D_S}{D_S*D}\left[\frac{(X+Y)nE_{amp}(2\alpha+D^2)}{D*(X^2+Y^2)^{\frac{1}{2}}}\right] = 0 \tag{11}$$

That is, $\frac{(X+Y)nE_{amp}}{(X^2+Y^2)^{\frac{1}{2}}}\left[\frac{D_S}{D_S*D}\left[\frac{(2\alpha+D^2)}{D}\right]\right] = 0$

or $\frac{D_S}{D_S*D}[2\alpha D^{-1} + D] = 0$

And $-2\alpha D^{-2} + 1 = 0$ (12)

$\rightarrow$ $-2\alpha = -D^2$

$\therefore$ $D = (2\alpha)^{1/2}$ (13)

It then implies that, the average transmission cost occurred when $D = (2\alpha)^{1/2}$.

Information Optimization Analysis in Wireless Underground Sensor Network

This section describes optimization method for data collection using relay nodes in wireless underground sensor network. It is expected that maximum transfer of data is expected to be disseminated from the relay nodes to the collection centre (sink node) for a network whose energy resource is limited (wireless underground sensor network). In this network, we assume that all the sensor nodes including the relay nodes are randomly placed on the given environment as shown in Figure 3.

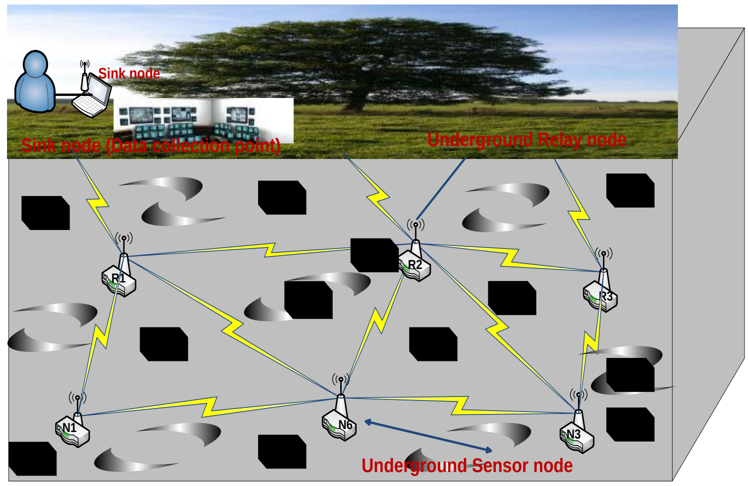

Figure 3: Node deployment in underground environment

The sensor node including the relay and forwarding node carries a limited energy supply E_{sp}, and the respective distance between each pair of sensor nodes on the underground environment is r_{ij}, where r_{ij} is the actual distance between nodes i and j on the sensor network environment. Assuming that much data is needed to be delivered to the sink node with unlimited energy resource (most sink nodes are normally plugged in to the regular power supply), via the relay and forwarding nodes with limited energy resource (most sensor and relay nodes carries limited power supply). For the network, each node consumes E_{rc} of energy per bit of received message, E_{tm} of energy per bit of transmit message, and E_{sm} of energy per bit of sensed message. Assuming that each sensor nodes that adjust both to the transmission energy per unit time and information flow rate, represented by E_{ij} and I_{ij} for the path between sensor nodes *i* and *j* respectively. The expression relating the information flow rate and transmission energy per unit time on a path is given by Shannon's capacity expression for an additive Gaussian noise (AWGN) channel [25]. For setting information flow rate along with transmission energy per unit time, it is necessary to find the coordinated operation of all nodes in the network so as to maximize the information transmitted to the sink node via the relay and forwarding nodes. As adopted in [26], and in accordance with [27], we followed same trend and assumed that there is no data aggregation in this network, meaning, all events are relayed to the sink node via relay and forwarding nodes. If the sum of energy consumed by node *i* is E_i, which comprises of both receiving, sensing, and transmitting energy, the same energy E_i should not be more than the amount of energy available for the node *i*.

Following this assumptions, we can then represent the problem as a nonlinear program as:

$$Max \sum_{j=1}^{K} I_{jK+1}$$

Such that,

$$\sum_{j=1}^{K+1} I_{ij} - \sum_{j=1}^{K} I_{ji} \geq 0 \tag{14}$$

$for\ i = 1{:}K$

That is, $$\sum_{j=1}^{K+1} I_{ij} - \sum_{j=1}^{K} I_{ji} \leq M \sum_{j=1}^{K} I_{jK+1} \tag{15}$$

K is the available bits of data that is generated and sent via the relay node to the sink. If we assume a square-law signal decay d_{ij}^{-2}, a noise of ζ on the communication channel, with the assumption that all transmissions are scheduled either through frequency-division multiplexing or time-division multiplexing, and that interference is avoided, we then model the network environment such that the total energy consumed at node *i*, $E_i \leq E_{sp}$. That is to say that:

$$E_i = \sum_{j=1}^{K+1} E_{ij} + E_{rc} \sum_{j=1}^{K} I_{ji} + E_{sm}\left(\sum_{j=1}^{K+1} I_{ij} - \sum_{j=1}^{K} I_{ji}\right) \leq E_{sp} \tag{16}$$

$$for\ i = 1{:}K$$

and $$I_{ij} \leq log\left(1 + \frac{E_{ij} d_{ij}^{-2}}{\zeta}\right) \tag{17}$$

$$for\ i = 1{:}K, j = 1{:}K+1$$

such that, $$I_{ij} \geq 0,\ E_{ij} \geq 0 \tag{18}$$

$$for\ i = 1{:}K, j = 1{:}K+1$$

The expression (16) defines total energy consumed as a function of the cost in sensing the information that is sent to the sink node via the relay node as "E_{sm}", and the cost of transmitting events among all pairs of nodes *i-j*, which is a function of the energy node *i* spent in transmitting (E_{ij}), and the cost node *j* spend in receiving $E_{rc}I_{ji}$. As seen in expression (16), it is expected that the total energy for each node should be greater than the whole sum of energy used in receiving, sensing and transmitting information or sensed events. If we sum the total energy consumption of node *i* in the network with the aim of also extracting as much information as possible in the sensor network, we will then have the overall energy consumed by the sensor nodes as a function of event or message. The summation of all the energy consumption for every node *i* in the network is given as:

$$\begin{aligned}\sum_{i=1}^{N} E_i &= \sum_{i=1}^{K}\left[E_{sm}\left(\sum_{j=1}^{K+1} I_{ij} - \sum_{j=1}^{K} I_{ji}\right) + \sum_{j=1}^{K+1} E_{ij} + \sum_{j=1}^{K} E_{rc} I_{ji}\right] \\ &= E_{sm}\sum_{i=1}^{K} I_{iK+1} + \sum_{i=1}^{K}\sum_{j=1}^{K+1} E_{ij} + E_{rc}\sum_{i=1}^{K}\sum_{j=1}^{K} I_{ij} \\ &= \sum_{i=1}^{K}(E_{sm} I_{iK+1} + E_{iK+1}) + \sum_{i=1}^{K}\sum_{j=1}^{K}\left(E_{rc} I_{ij} + E_{ij}\right)\end{aligned} \tag{19}$$

The expression in (19), clearly show that the maximum message or information that can be gotten from the sensor network, depends on the total available energy of the network nodes. That is to say that, to achieve maximum throughput in terms of message extraction from the network, we can look at the network having at least I_{min} message received by the sink node. This statement can be used to replace expression (16) by a more generalized expression as:

$$E_i = min \sum_{i=1}^{K}(E_{sm} I_{iK+1} + E_{iK+1}) + \sum_{i=1}^{K}\sum_{j=1}^{K}\left(E_{rc} I_{ij} + E_{ij}\right)$$

such that,

$$\sum_{j=1}^{K+1} I_{ij} - \sum_{j=1}^{K} I_{ji} \geq 0 \tag{20}$$

$$for\ i = 1{:}K$$

and, $$\sum_{j=1}^{K+1} I_{ij} - \sum_{j=1}^{K} I_{ji} \leq M \sum_{j=1}^{K} I_{jK+1} \tag{21}$$

$$for\ i = 1{:}K$$

That is, $$\sum_{j=1}^{K} I_{jK+1} \geq I_{min} \tag{22}$$

$$for\ i = 1{:}K$$

It then implies that, $$I_{ij} \leq log\left(1 + \frac{E_{ij} d_{ij}^{-2}}{\zeta}\right) \tag{23}$$

$$for\ i = 1{:}K, j = 1{:}K+1$$

Such that, $$I_{ij} \geq 0,\ E_{ij} \geq 0 \tag{24}$$
$$for\ i = 1{:}K, j = 1{:}K+1$$

Average Transmission Cost of a Grid Based Wireless Underground Sensor Network

This section tends to analyse and show the effect of change in parameters on transmission cost of wireless underground sensor network. From Figure 4 through Figure 6, which is a result gotten from the computational analysis of Eqn. (10), it is observed that the energy consumed in joules per unit meter (transmission cost), depends directly on both the distance between two consecutive nodes (*D*), packet size (*n*), and the number of movement of nodes (hops) in the *X* and *Y* directions. Figure 4 describes the behavioural pattern of the effect of transmission distance on the energy consumption per unit meter. It is evidence that, when there is an increment in transmission distance (*D*), energy consumed per node increase as well. The sharp increase in energy consumed per unit meter (transmission cost) is due to the proportionality between the energy consumed per unit meter (transmission cost) and the transmission distance (*D*) as can be seen in the expression (10). For a well-known wireless sensor nodes produced by Libelium (Waspmote) [28], a node has the capacity transmit information up to a maximum distance of 500 meters, for Crossbow MICAz, a maximum of 100 meters is expected, and for the intel product (Intel IMote2), we expect a maximum of 30 meters. This simply means that, multihop or relaying method should be encouraged for evenly distribution of energy in the network for prolonging the network lifetime. Shown in Figure 5 is behavioural pattern of the effect of increase in packet size in bits on the energy consumption per unit meter. In this behaviour, it was also observed that, for every bit of packet increase. The energy consumed per unit meter (increase in transmission) increases linearly as well. This idea can be coined from an expression (10), of which the energy consumed per unit meter also depends on the number of bits of information (*n*) transmit in the network. it should be noted that, a typical sensor node has low memory in addition to low or limited storage capacity, of which each frame of sensed data or event occupies an average of approximate 100bytes (800bits). Waspmote sensor nodes having a low memory of 8KB SRAM, necessitated low overhead transmission, this is to give enough space for data or message transmission. As can be seen, we compute the transmission cost to a maximum of 900bits of information, of which every increase in bits also corresponds to an increase in transmission cost. Figure 6, shows the behavioural pattern of the effect of increase in number of nodes in the network on the energy consumption per unit meter. The increase in the network nodes density considered both X and Y directions on the topology. It is also seen that, as we increased the number of nodes participating in the sensing and forwarding of information in the network, the energy consumed per unit meter (transmission cost), increase as well. This is an evidence as can be seen in expression (10), due to the fact that, the energy consumed per unit meter (transmission cost), also depends on the number of hops in the *X* and *Y* directions on the topology.

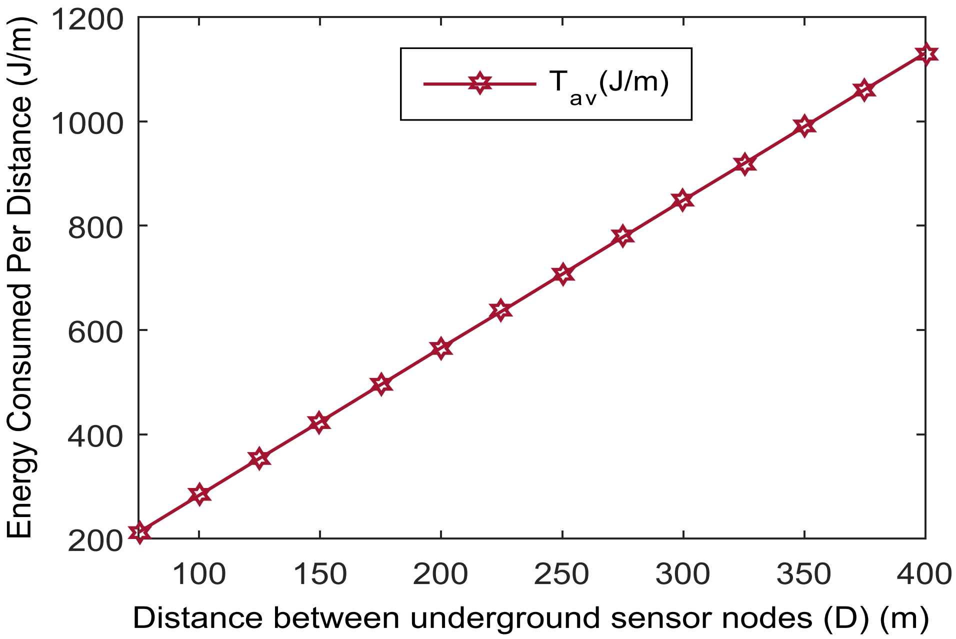

Figure 4: Effect of Transmission distance on the energy consumed in joules per unit meter (transmission cost) for a grid based wireless underground sensor network

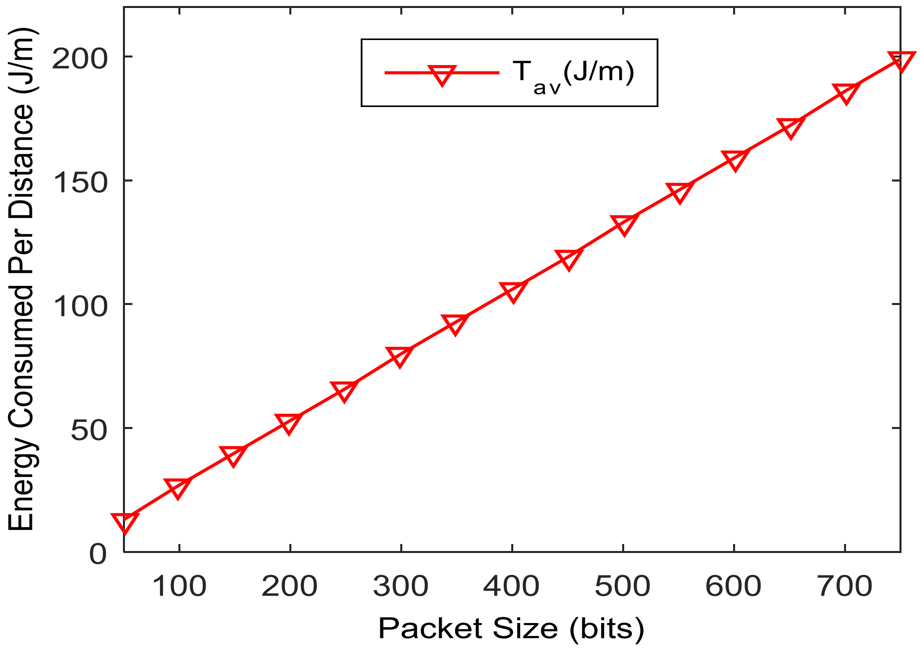

Figure 5: Effect of Packet Size on the energy consumed in joules per unit meter (transmission cost) for a grid based wireless underground sensor network

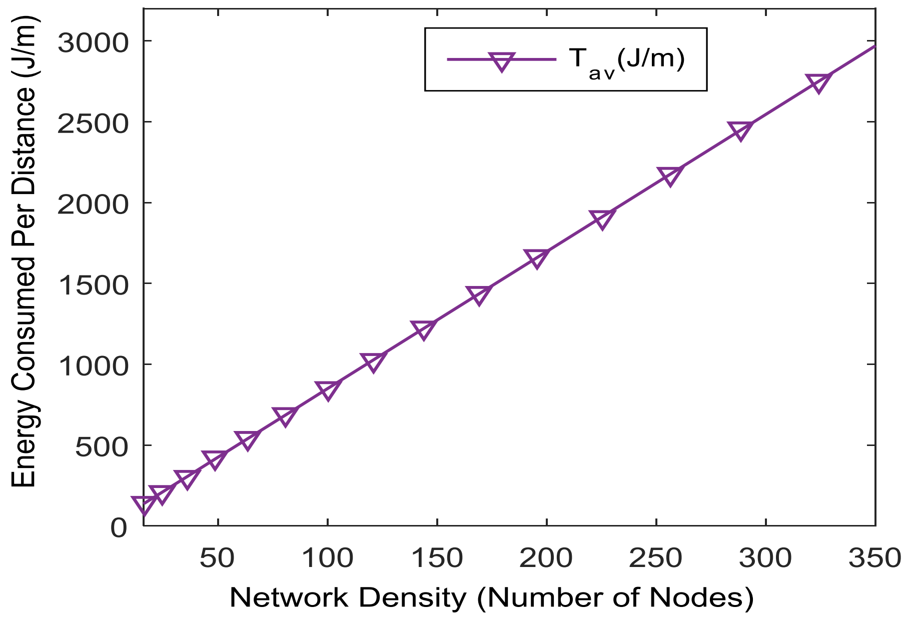

Figure 6: Effect of Number of Nodes on the energy consumed in joules per unit meter (transmission cost) for a grid based wireless underground sensor network

CONCLUSIONS

In this paper, we provide an insight to optimal placement of nodes in the wireless underground sensor networks. The environment considered is a tunnel which act as a grid based topology with sensor nodes randomly distributed in the environment. We therefore, addressed the need for a systematic placement of the nodes in the network considering minimum transmission cost, which is the energy consumed in sending a sensed event in joules per unit distance. We also formulate a nonlinear program to determine the optimal information extraction in a grid based wireless underground sensor network. Through the analysis, it was observed that, when designing a sensor network, energy consumption of nodes in the network should be minimize so as to prolong the network lifetime by considering factors that correlate with it such as transmission distance, packet length, and network density. In the course of the analysis, it was clearly observed that, the average transmission cost (average energy consumed per unit distance) has strong relationship with nodes' distance apart, size of packets of information and the network density (number of nodes) in both X and Y axis in the grid based network. In Figure 4, it is observed that for increase in distance between nodes from 200m to 300m, the energy consumed per meter of nodes in the network increased linearly from about 566J/m to 990J/m. It is also evidence from Figure 5 that, as the packet size increases from 200 bits to 600 bits, energy consumed per meter increase from 53 J/m to 159 J/m. Also, from Figure 6, when the number of nodes in the network increase from 150 to 300 nodes, energy consumed per meter increase from about 1230 J/m to about 2460 J/m. Hence, the energy consumed per unit meter (transmission cost) is directly proportional to both the packet size, network density and distance between sensing and relay nodes in the network.

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AUTHORS' CONTRIBUTIONS

All Authors participated in all experiments, coordinated the data-analysis and contributed to the writing of the manuscript.

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